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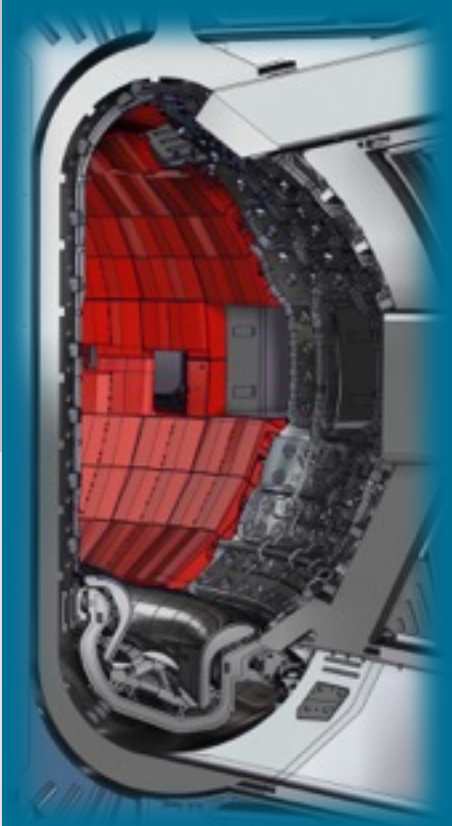
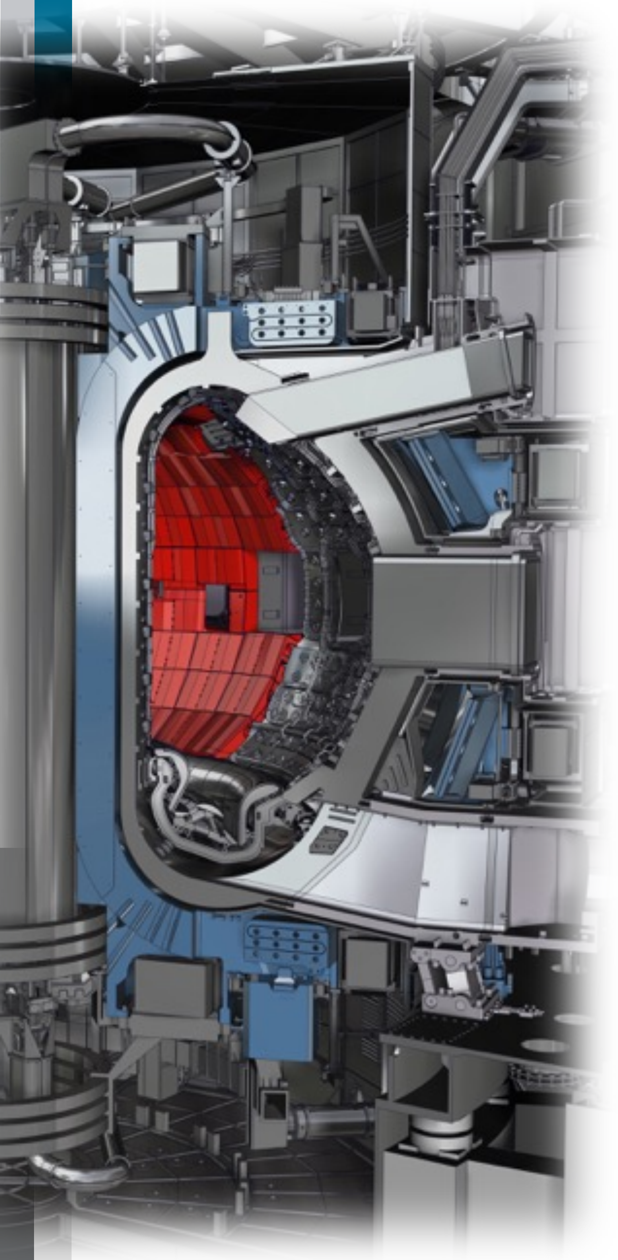
Materials and Components for Extreme Loads in Fusion 1st Wall and Divertor Applications



J.W.Coenen[1*], Ch.Linsmeier[1], S.Antusch[4], M.Aumann[1], J.Du[1], J.Engels[1], H.Gietl[2], S.Heuer[1], A.Houben[1], T.Hoeschen[2], G.Holzner[2], B.Jasper[1], F.Koch[2], M.Li[2] A.Litnovsky[1], Y.Mao[1], R.Neu[2], G.Pintsuk[1], J.Riesch[2], M.Rasinski[1], J.Reiser[4], M.Rieth[4], B.Unterberg[1], Th.Weber[1], T.Wegener[1], J-H.You[2]

[1]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung [2]Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany, [4]Karlsruhe Institute of Technology, Institute for Applied Materials, Eggenstein-Leopoldshafen, Germany .

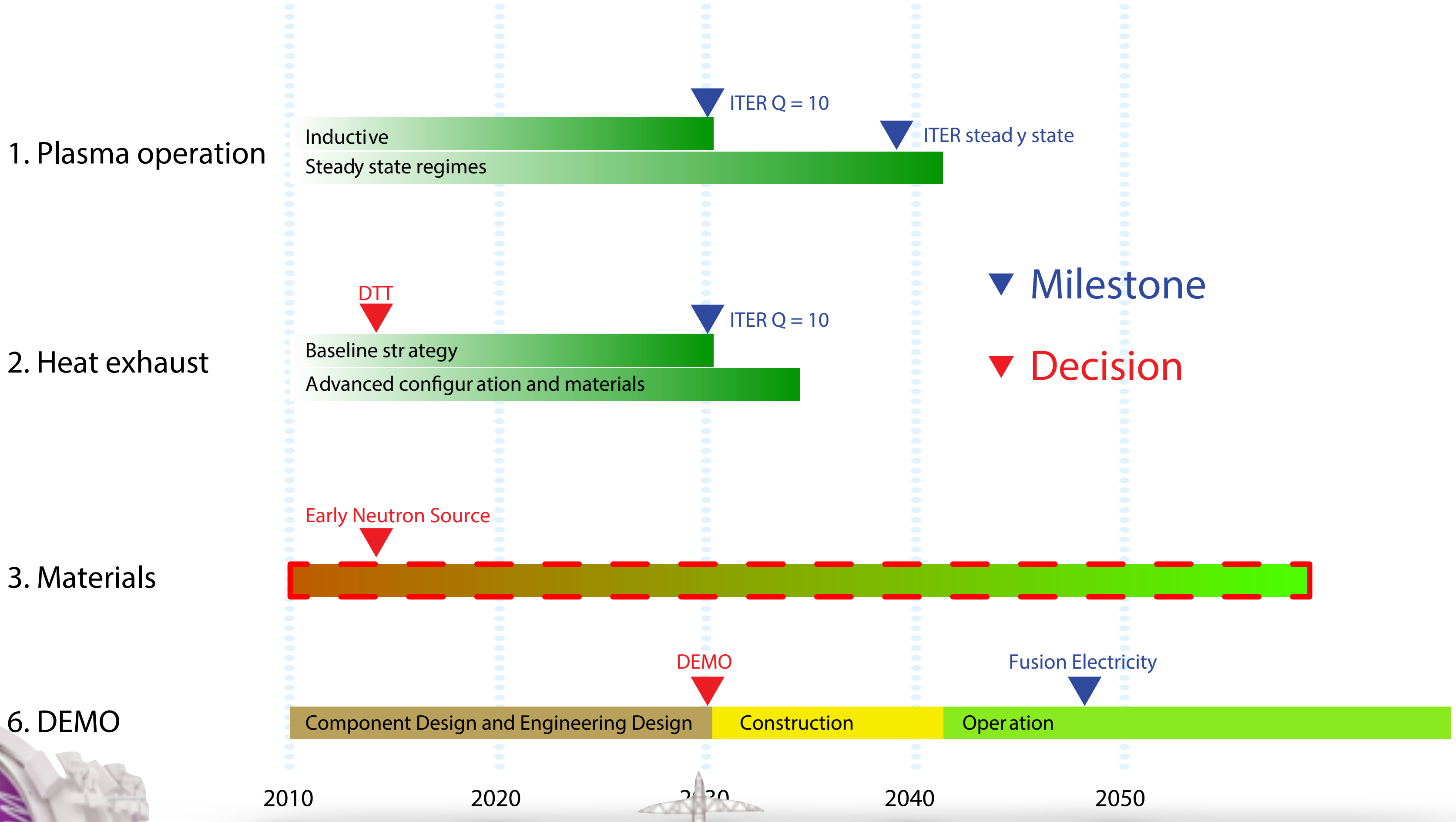
Overview

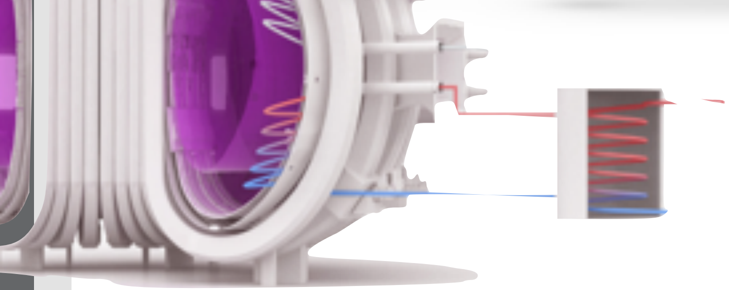


- ✦ Boundary Conditions
- ✦ Advanced Materials & PWI issues
- ✦ Conclusion

Roadmap

Fusion Electricity - EFDA November 2012





Developing new materials now will facilitate understanding of ITER operation and is necessary to ensure a viable DEMO/Reactor Design

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Boundary Conditions

All in One - Synergy

From the Fusion Plasma

Neutron loads
50-80dpa (10 MW/m^2)

Divertor fluence
$4x10^{32}m^2$

Transients - ELMs
1yr~ $2.4*10^7$s
10^9 ELMs @ 40Hz

Powerload
10 MW/m^2 - 30MW/m^2

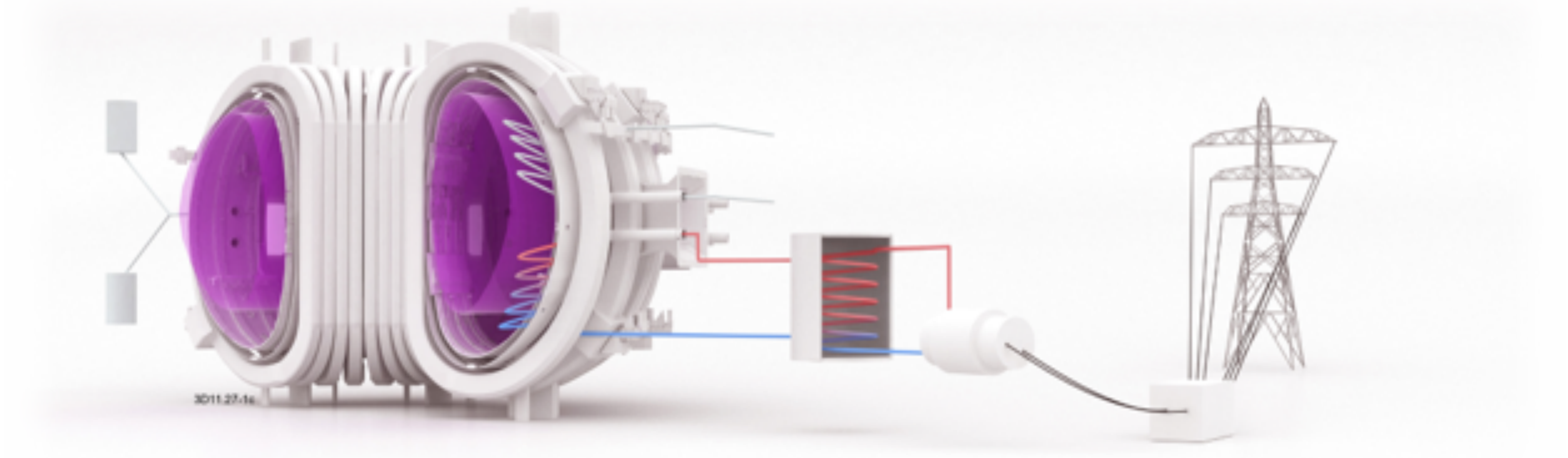
From the Material

Temperature Window
500°-1000°C

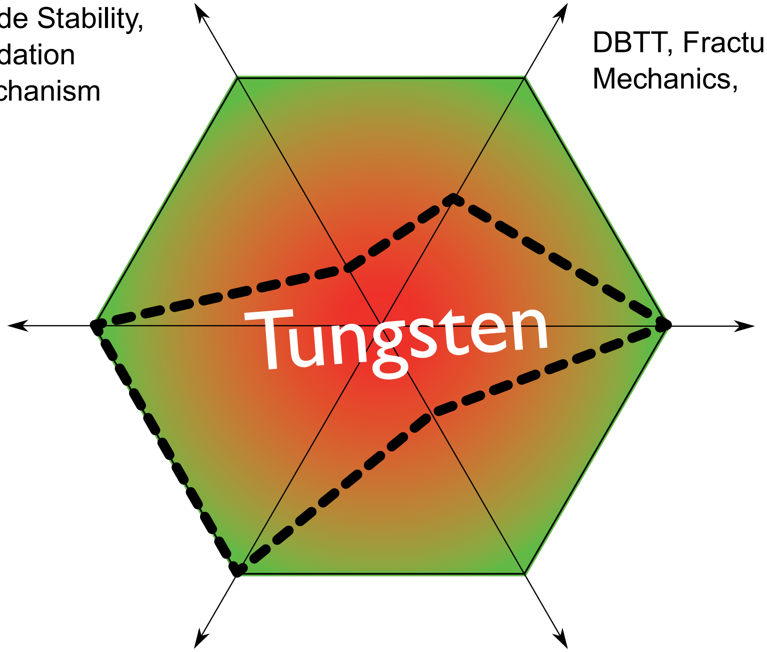
Neutron Exposure
e.g. Limits after 5 year exposure
Activation / Transmutation
change in material properties

Fuel Diffusion, Permeation
H-Embrittlement, Activation, TBR

Safety Issues & Licensing



PWI in a nutshell



Oxidation
Oxide Stability,
Oxidation
Mechanism

Mechanics
DBTT, Fracture
Mechanics,

Thermal Properties
Thermal
Conductivity,
Heat Capacity,…

D/H/T Interaction
Retention,
Diffusion,…

Sputtering
Net Erosion,
Surface Composition
Change,…

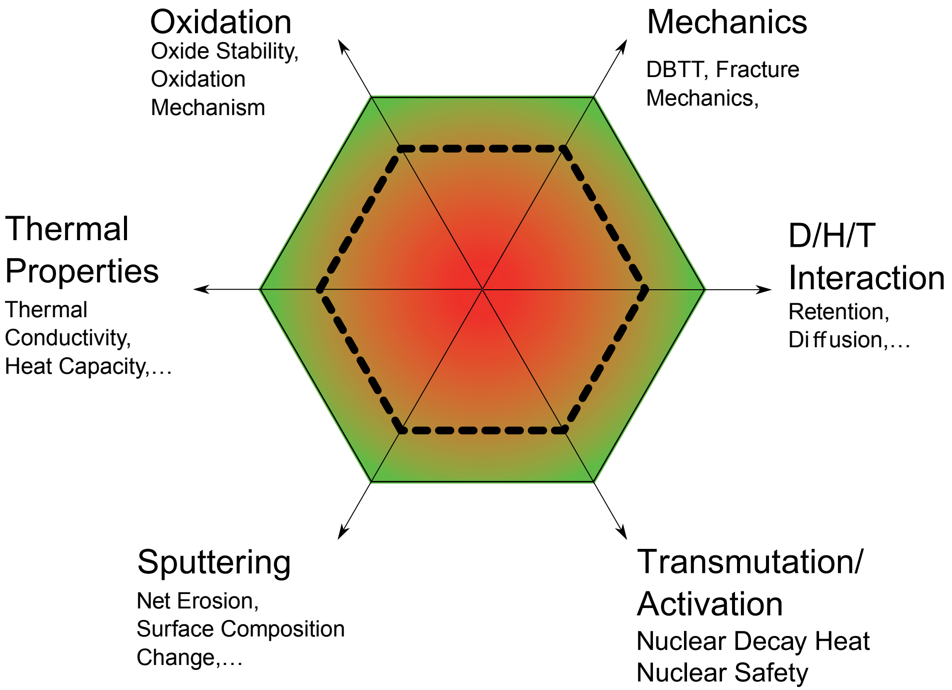
Transmutation/ Activation
Nuclear Decay Heat
Nuclear Safety

We handpick our problems - but we need to solve them in an overall approach considering the interlinked issues

Advanced Materials & PWI Issues

Advanced Materials

- Lifetime of PFCs and Joints due to erosion / creep / fatigue / embrittlement
- Thermal properties of composites and components - Maximize heatflux to coolant — „thin PFCs“
- Compatibility with tritium breeding („thin PFC“ - small coolant structure)
- Maximize damage resilience for both external as well as internal damage (e.g. cracks & neutrons)



Oxidation
Oxide Stability,
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Mechanics
DBTT, Fracture
Mechanics,

Thermal Properties
Thermal
Conductivity,
Heat Capacity,…

D/H/T Interaction
Retention,
Diffusion,…

Sputtering
Net Erosion,
Surface Composition
Change,…

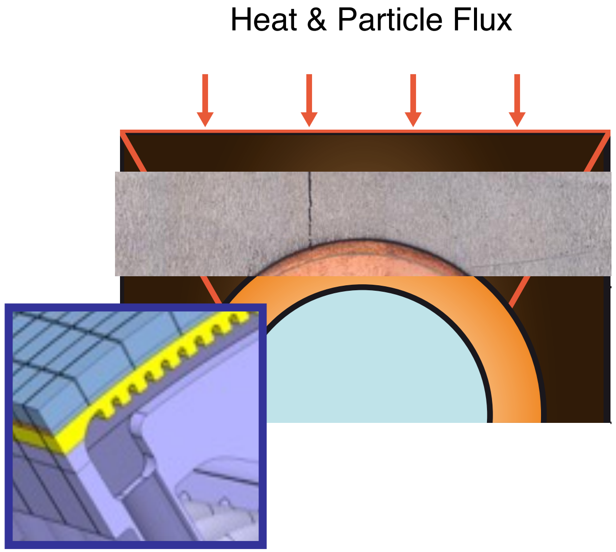
Transmutation/ Activation
Nuclear Decay Heat
Nuclear Safety

- Maintainability - Recycling of used materials / components e.g. minimize e.g. activation
- Large scale production of advanced materials / components

PFCs, HHF, and Structural Materials

… a circular argument for an integrated component…

A Plasma Facing Component



PWI defines what the materials in the wall component have to deal with

- **The PFC is a combination of the armor material protecting the structural part of the Wall component**
- **The challenge is to combine the properties of multiple materials**
- *Particle like He / H diffuse readily through metals*
- *Heat & Particle exhaust is a PFC and a structural task*
- Neutrons are an issue for both PFCs and structural materials
- **Damage resilient materials**

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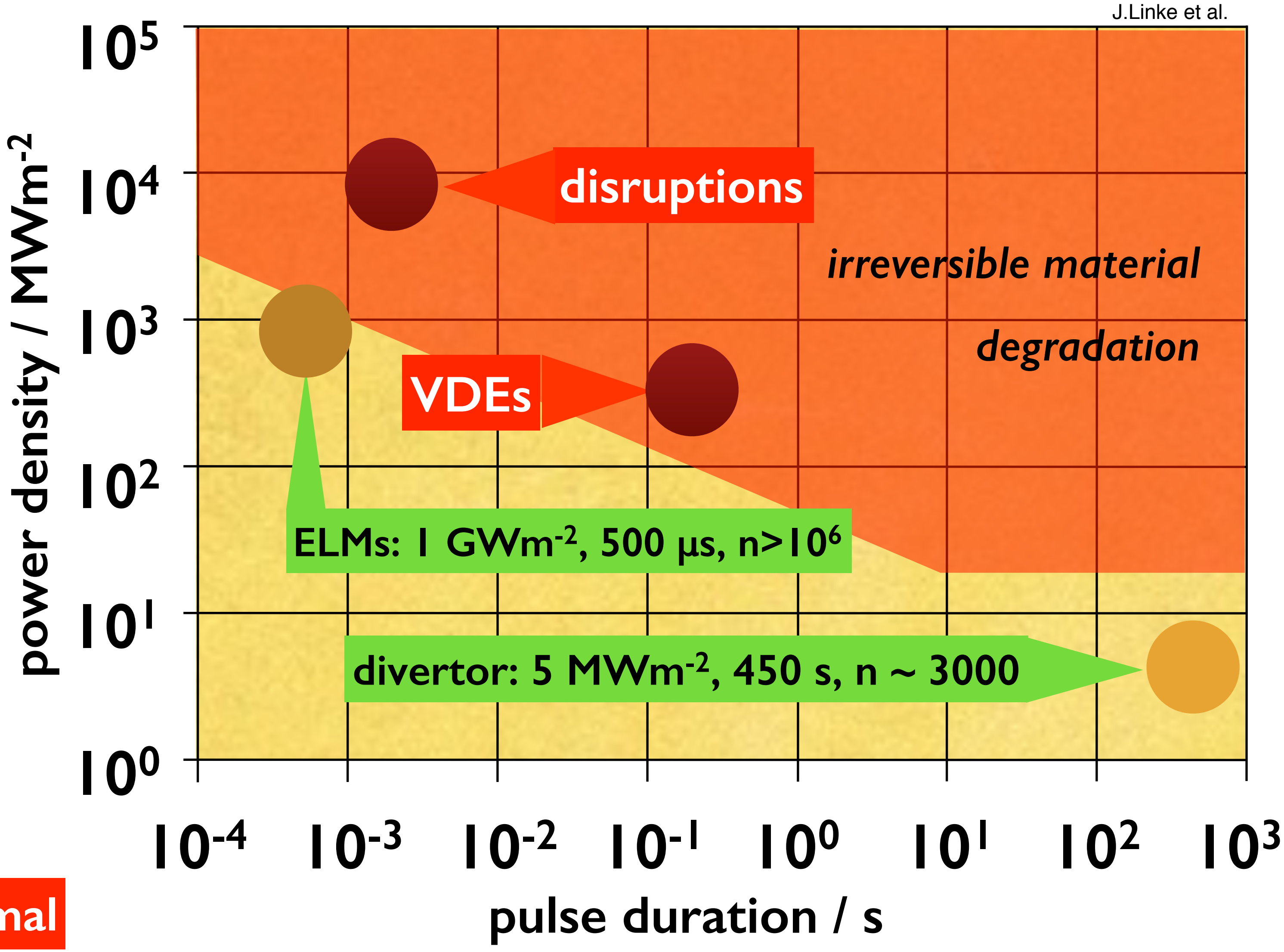
High Heat Flux & Plasma

… a circular argument for an integrated component…

Wall loads on W


J.Linke et al.

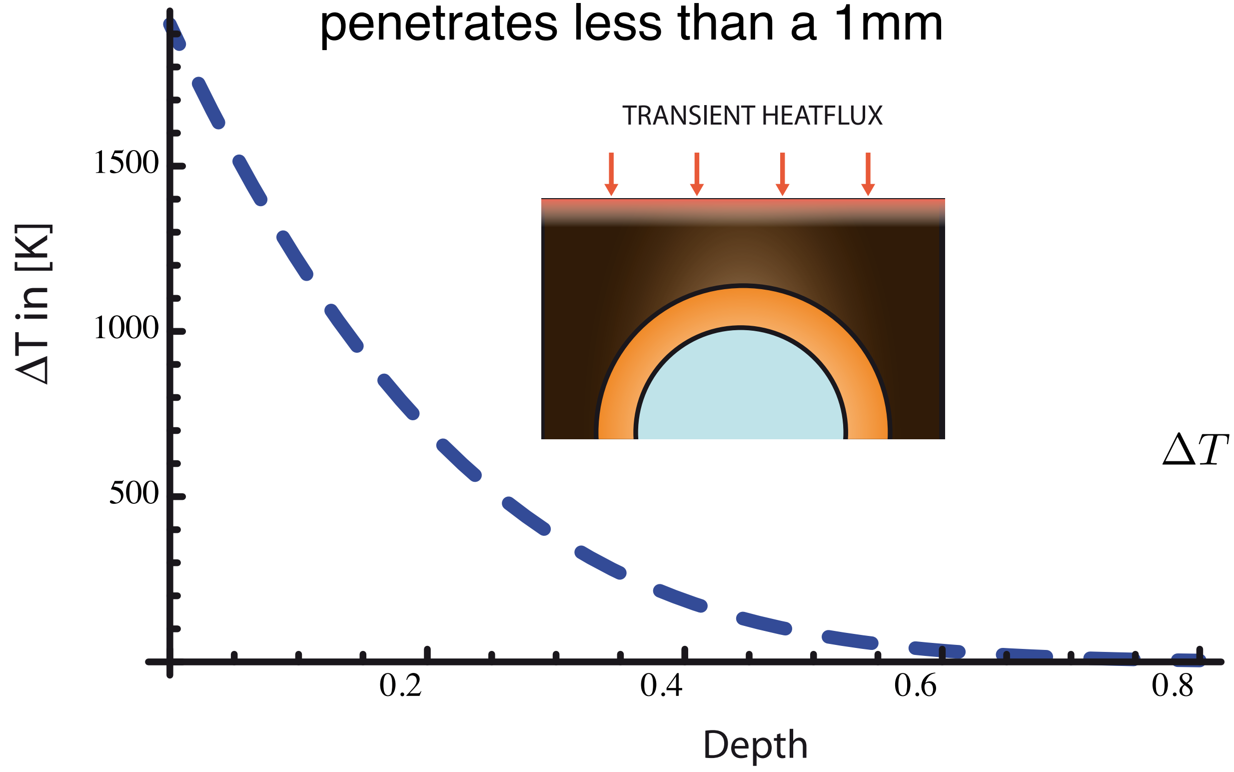
🟥 off-normal

🟩 normal

In a reactor 'normal' operation becomes challenging

Transient Heat loads

1GW/m² for 1ms
penetrates less than a 1mm



Especially large transients will induce thermal stresses and cause cracking and surface changes

Choose a crack resilient material if transients can not be avoided

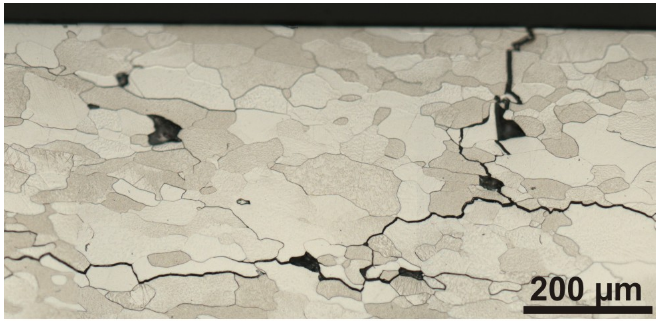
<u>Heat Penetration Coeff.</u>

$$b = \sqrt{\kappa \cdot \rho \cdot c} \quad [\frac{W \cdot s^{1/2}}{m^2 \cdot K}]$$

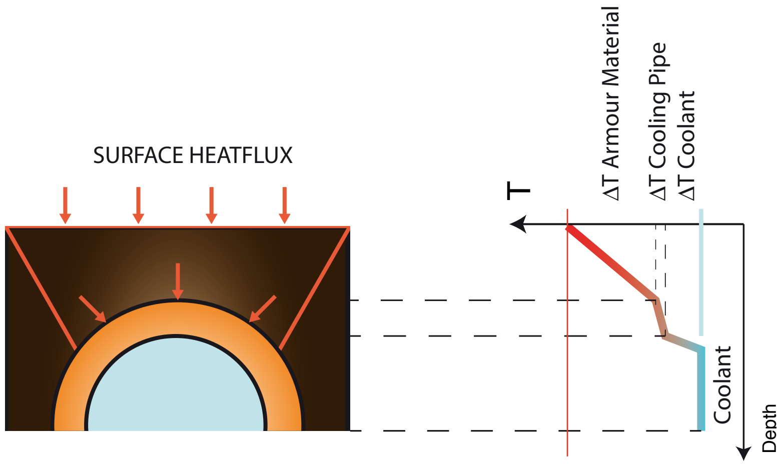
κ = Heat capacity
ρ = density
c = heat conduction

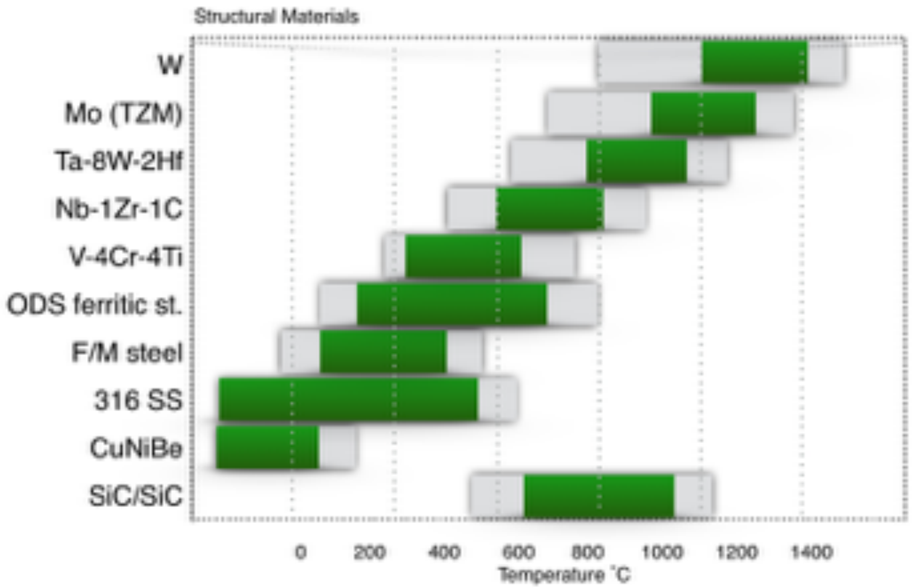
$$d = \frac{c^2}{b}$$

$$\Delta T(z,t) = \frac{q_s}{\kappa \cdot \sqrt{\pi}} (\sqrt{4 \cdot d \cdot t} \cdot e^{-z^2/(4 \cdot d \cdot t)}) - z \cdot \sqrt{\pi} \cdot (1 - \mathrm{erf}(\frac{z}{\sqrt{4 \cdot d \cdot t}}))$$



Steady State Loads





Zinkle, S. & Ghoniem, N. Fusion Engineering and Design

- The total temperature drop depends on the incidence heat flux (given) *(for a given component design)*
- ΔT in the coolant depends on the chosen coolant and its velocity
- ΔT - heat sink / armor depend on
  - **material selection (e.g. Metal Matrix Composites)**
  - **minimum allowed <u>thickness</u> <u>(lifetime vs. erosion & damage)</u>**

<u>lower limit</u>

- radiation embrittlement
- decreased fracture toughness

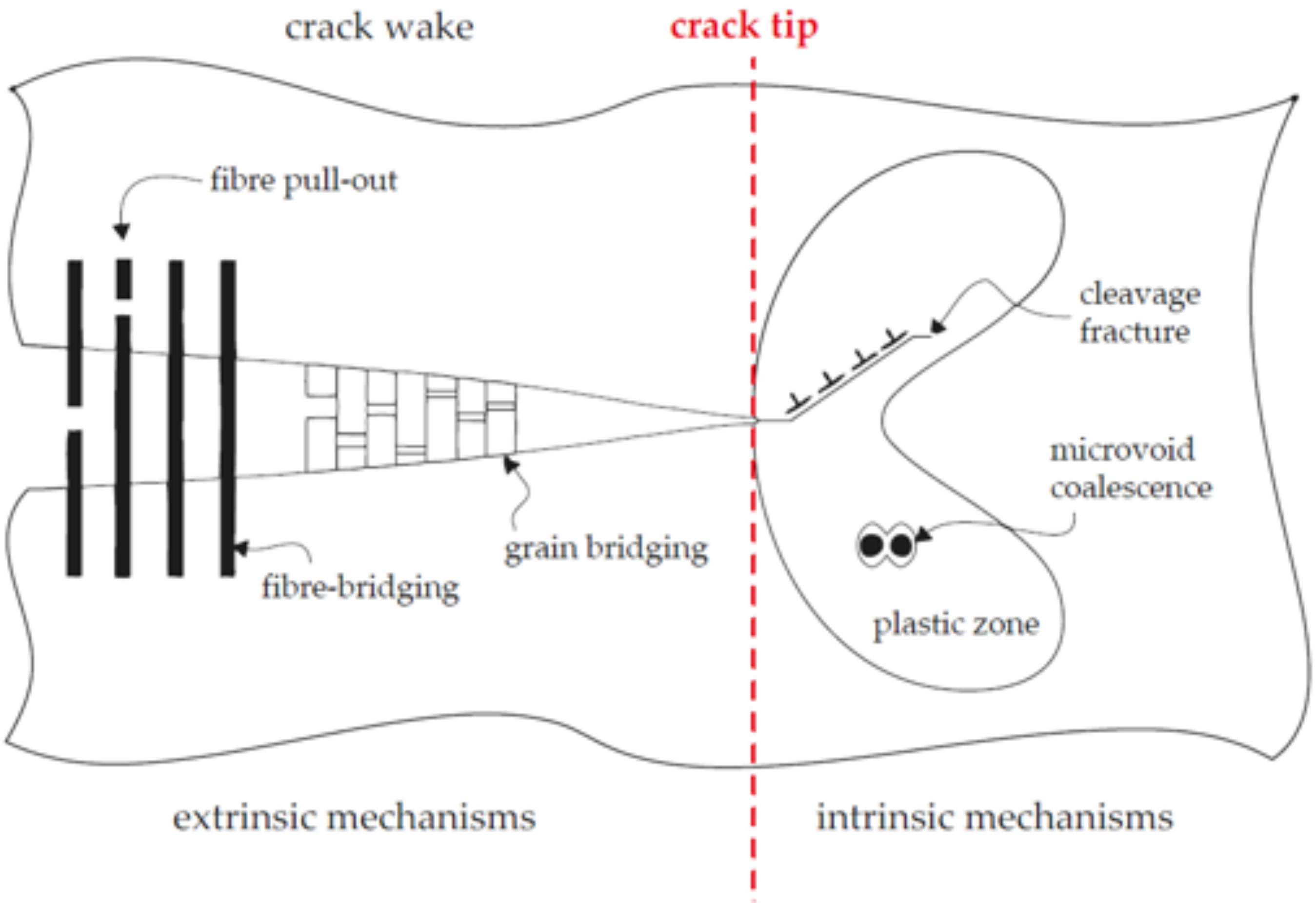
<u>upper limit</u>

- Thermal creep
- He embrittlement of grain boundaries
- Cavity swelling (esp. for Cu alloys)
- Coolant compatibility: corrosion issues.

Mechanical Properties

… a circular argument for an integrated component…

Extrinsic vs. intrinsic



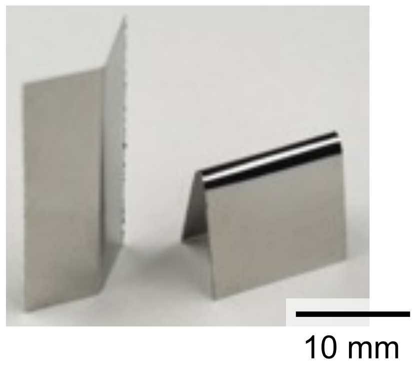
[R. O. Ritchie, Int. J Fracture, 100:55–83, 1998].

W Laminates

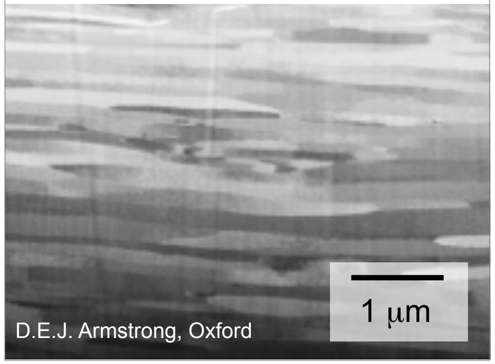
Can the ductility and the toughness of a UFG W foil be transferred to the bulk?

→ W-foil laminate materials

W-foil

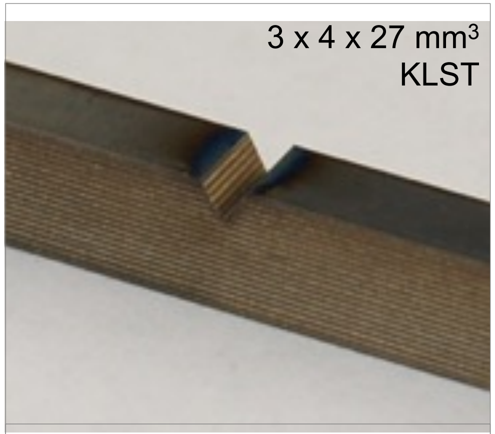


- Metal physics

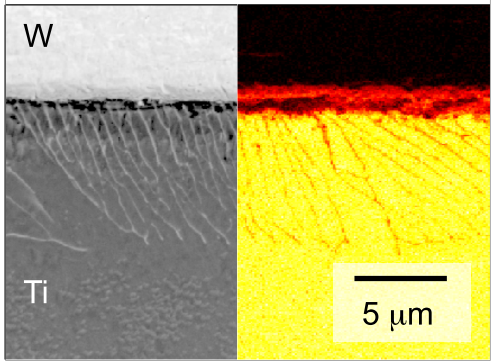


D.E.J. Armstrong, Oxford

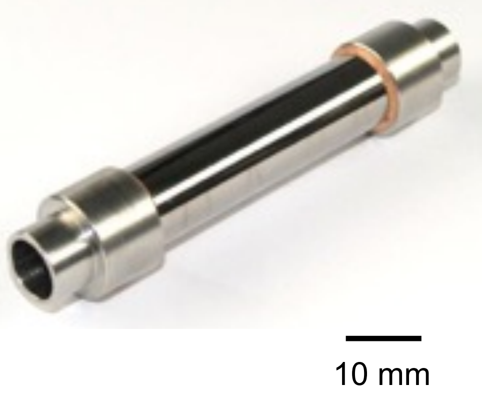
W laminate plate



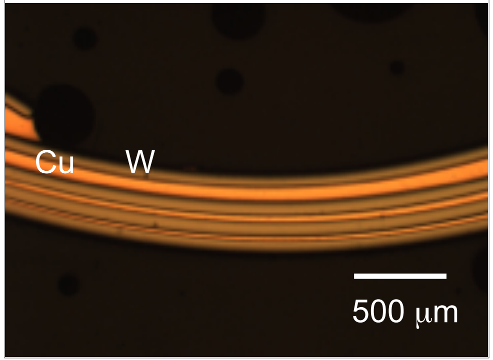
- Bonding and ageing



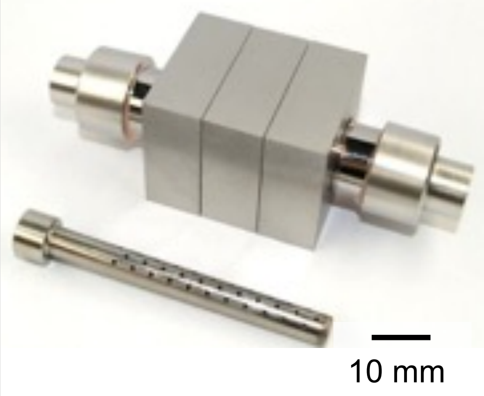
W laminate pipe



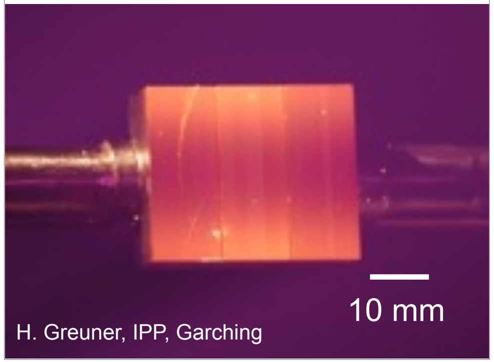
- Joining technology



Applications



- Fabrication and testing



H. Greuner, IPP, Garching

Indications for unfavorable behavior after irradiation

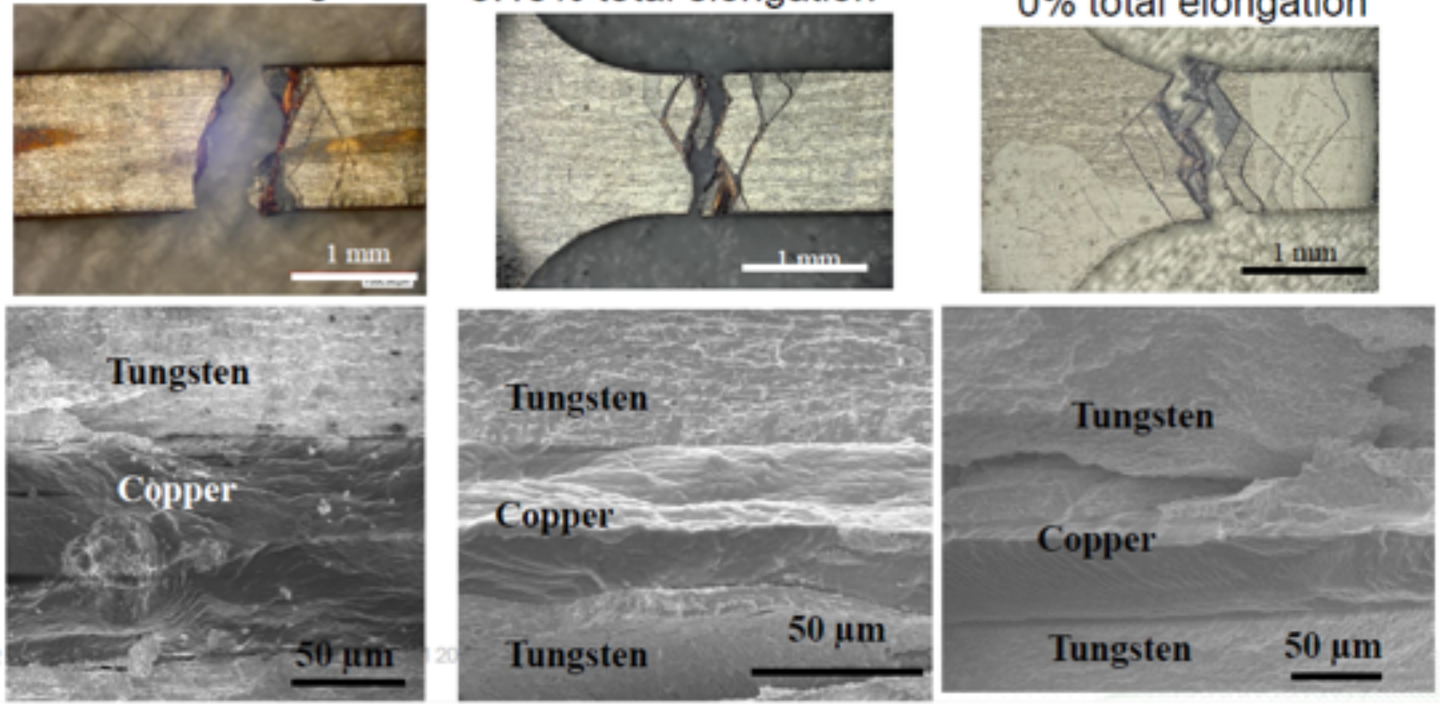
Jens Reiser KIT

Intrinsic Toughening

Fracture Surface Comparison before and after Irradiation, Tested 22°C

- All samples have ductile knife edge fracture in copper and brittle cleavage fracture in tungsten

L. Garrison (ORNL), ICFRM 2015



SW40, unirradiated
15.5 % total elongation

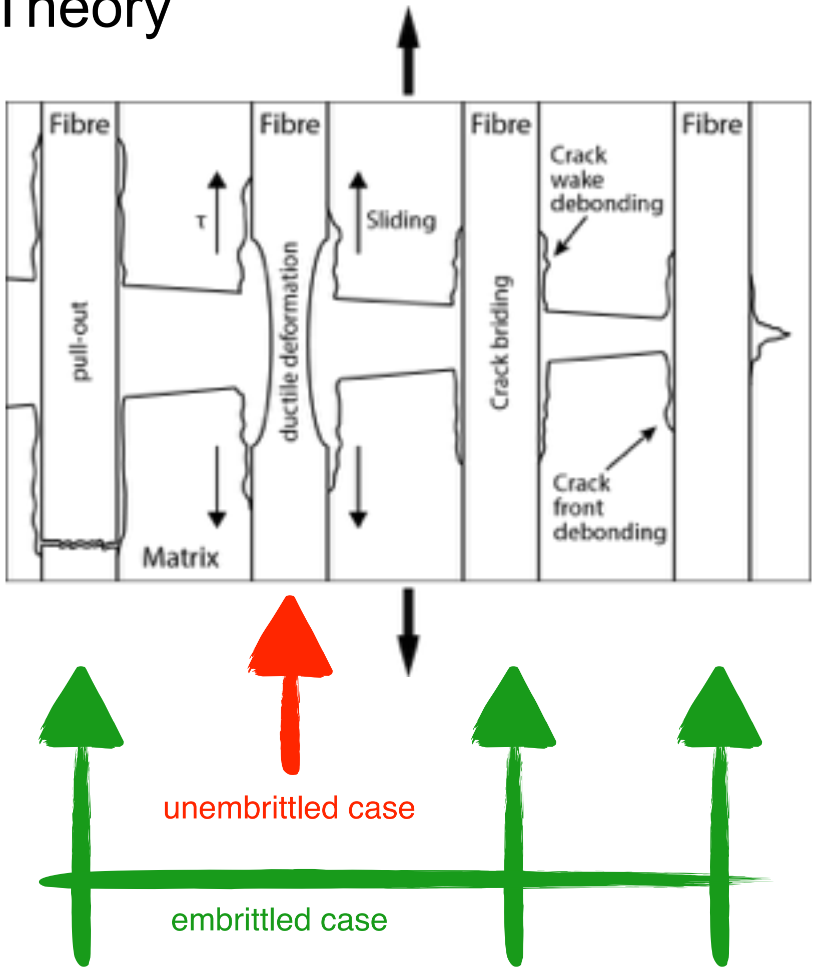
SW25, irradiated to 0.15 dpa at 760°C
0.15% total elongation

SW15, irradiated to 0.70 dpa at 710°C
0% total elongation

brittle components → global brittleness

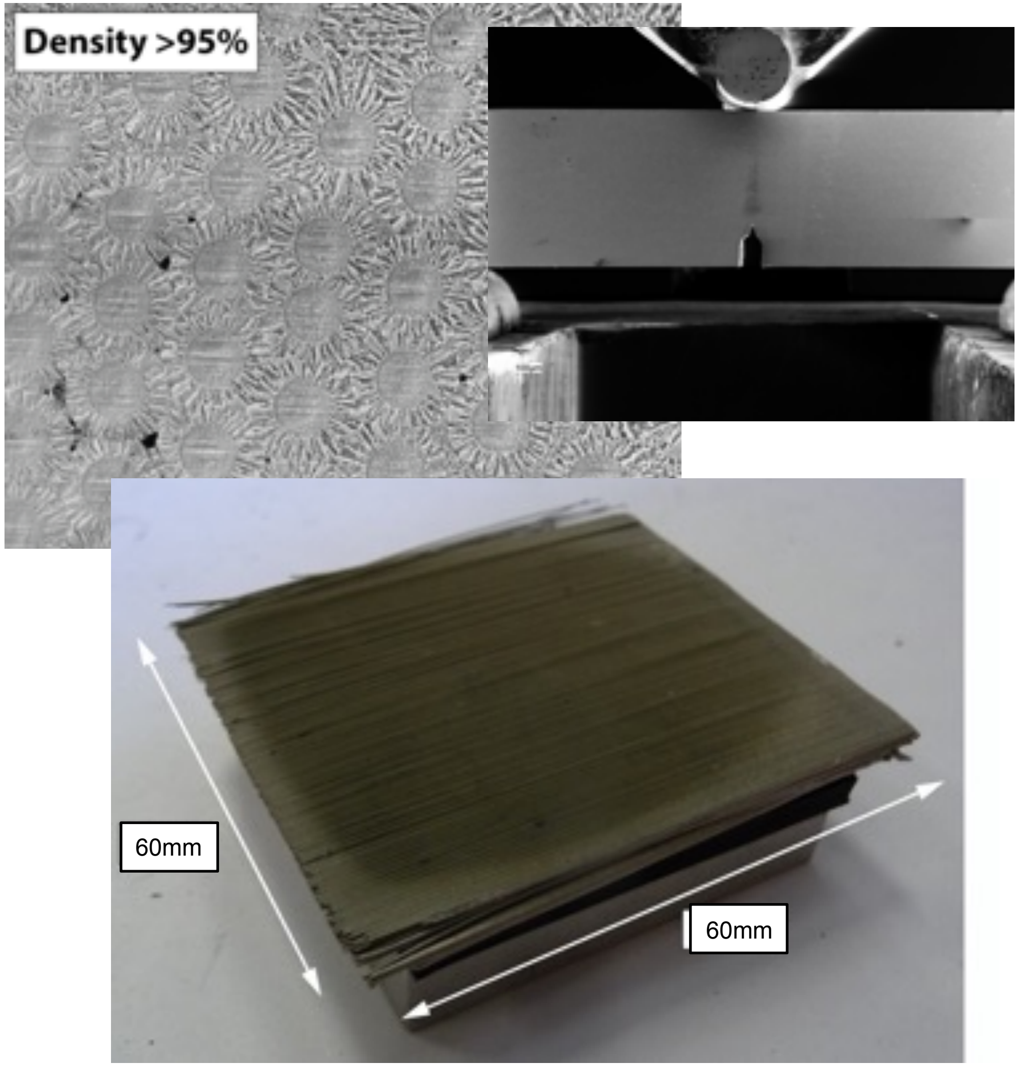
Wf/W

Theory

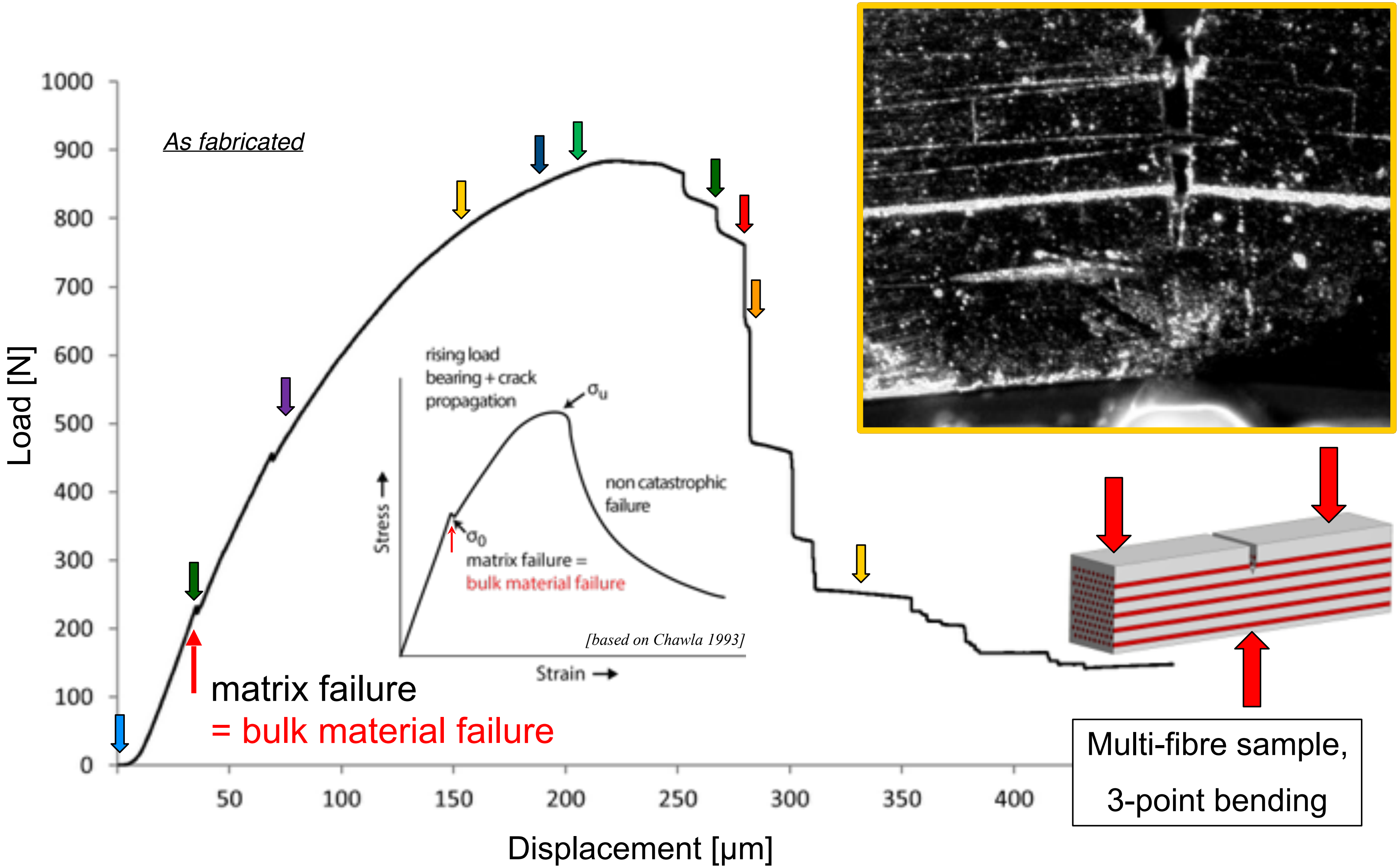


unembrittled case

embrittled case



Toughening W_f/W



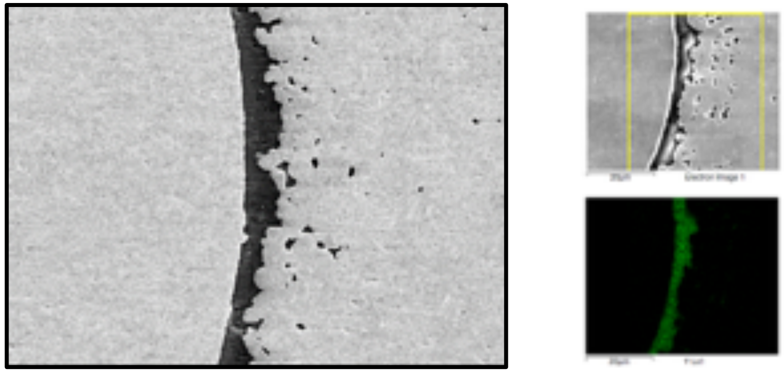
matrix failure
= bulk material failure

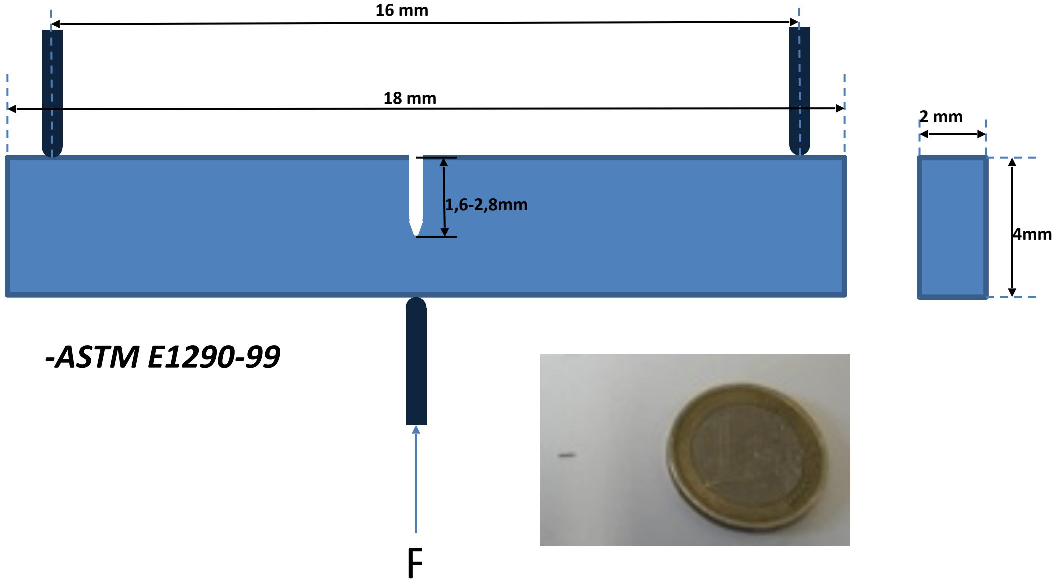
Multi-fibre sample,
3-point bending

Masterthesis G.Holzner

Short fibre PM Wf/W

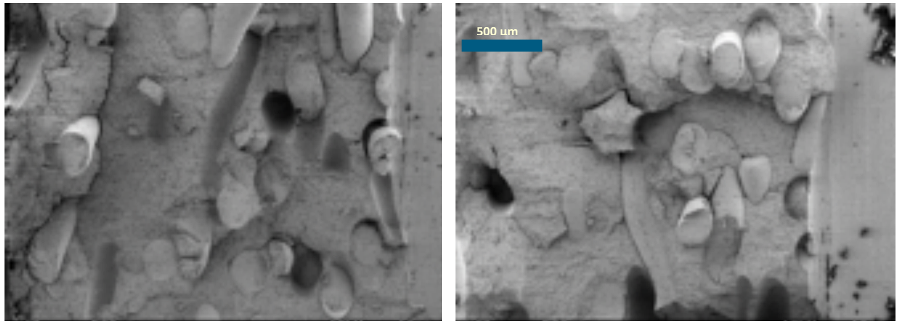
Y_2O_3 coating for the short fibers

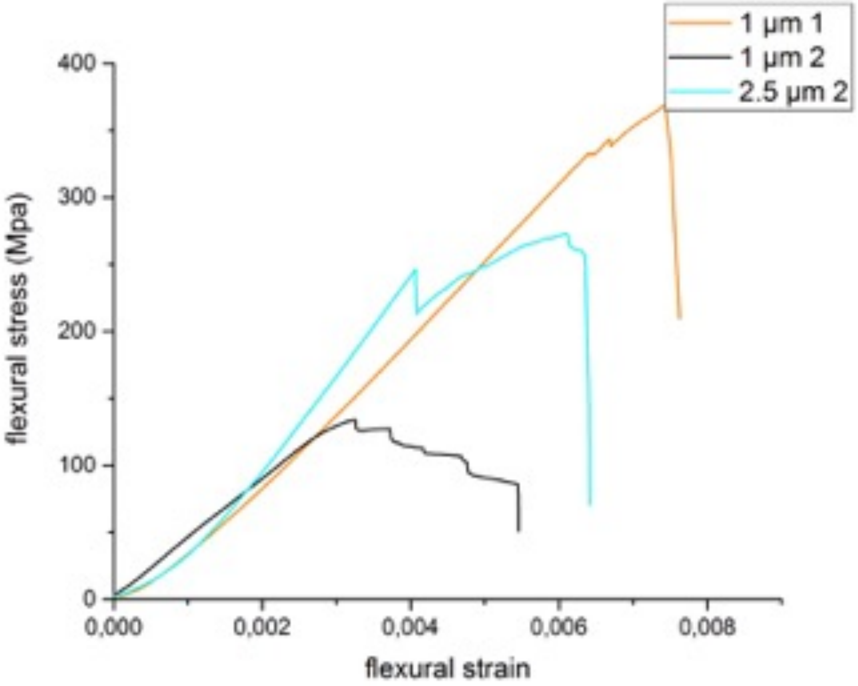




-ASTM E1290-99

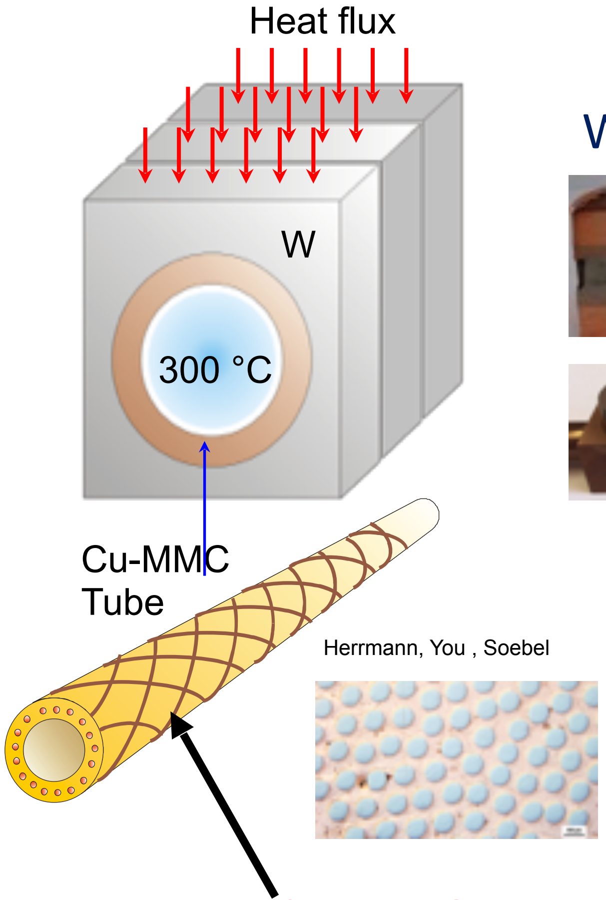
Fiber: - l/d 2.4 mm / 0.24 mm





FGMs & More

Improve thermal behavior in particular strength and expansion matching



W_f reinforced Cu

Advanced Concept W/Cu FGM

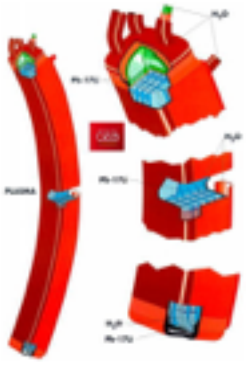
The yield strength is superior to that of a W/Cu composite owing to the hardening effect of CuCrZr alloy.

J-H . You et.al - IPP

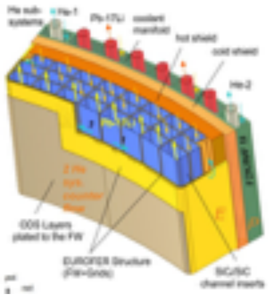
W/Cu FGM

Herrmann, You , Soebel

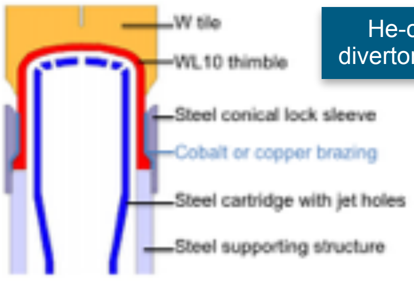
Joining W with steel – a complicated issue but required for multiple applications



WCLL TBM (Water-cooled lithium lead)



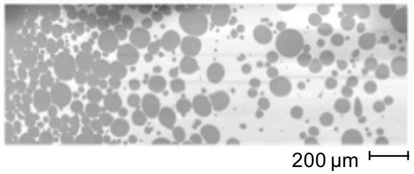
DCLL TBM (Dual-coolant lithium lead)



G. Ritz et al., Fusion Engineering and Design, 2009

He-cooled divertor concept

Resistance sintering under ultrahigh pressure

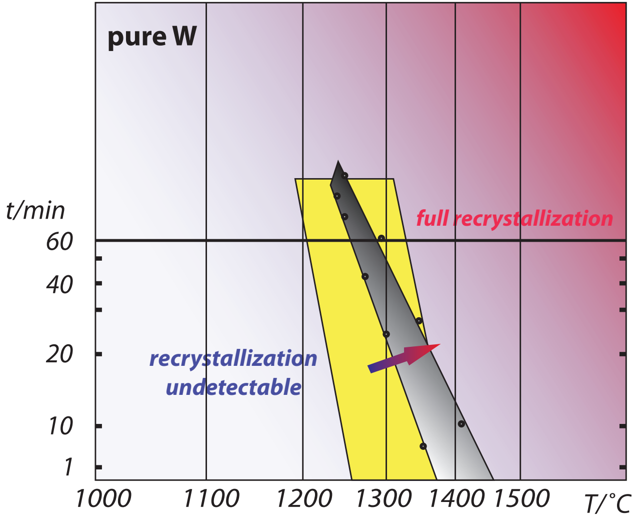


Problem - Thermal induced stresses

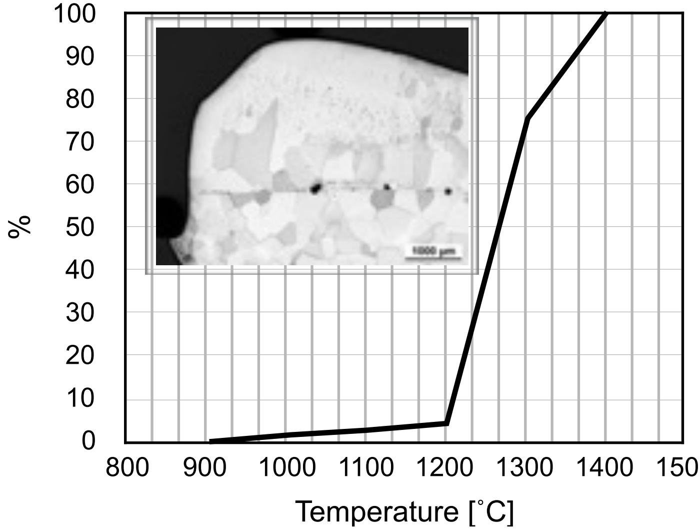
- tungsten: $\alpha = 4.4 \cdot 10^{-6}$/K
- steel: $\alpha = 12.0 \cdot 10^{-6}$/K

Recrystallisation / PIM

Recrystallization of tungsten



Tungsten Recrystallization Fraction after 1h



Springer Handbook of Materials

Samples for ASDEX Upgrade

Powder Injection Molding

Time & cost effective near-net-shape forming process with shape complexity & high final density

No recrystallisation – possible grain growth at very high temperatures only

Brittle to ductil transition for pure PIM W at 200 °C (low strain rates)

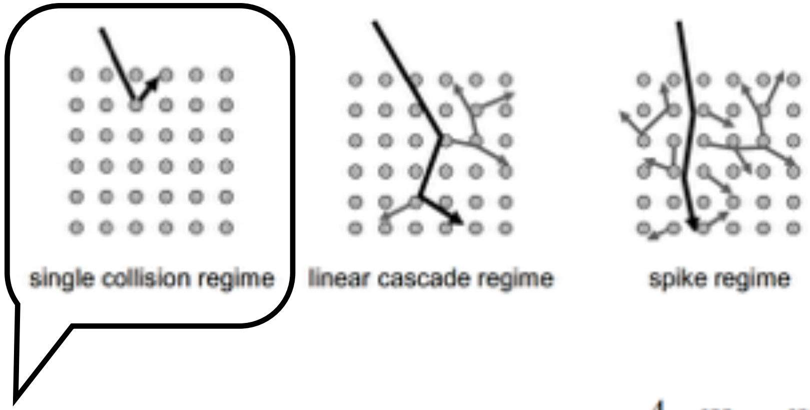
No porosities or cracks, high density (better than 99 % T.D.)

Fully isotropic material properties

Wall Erosion

… a circular argument for an integrated component…

Sputtering



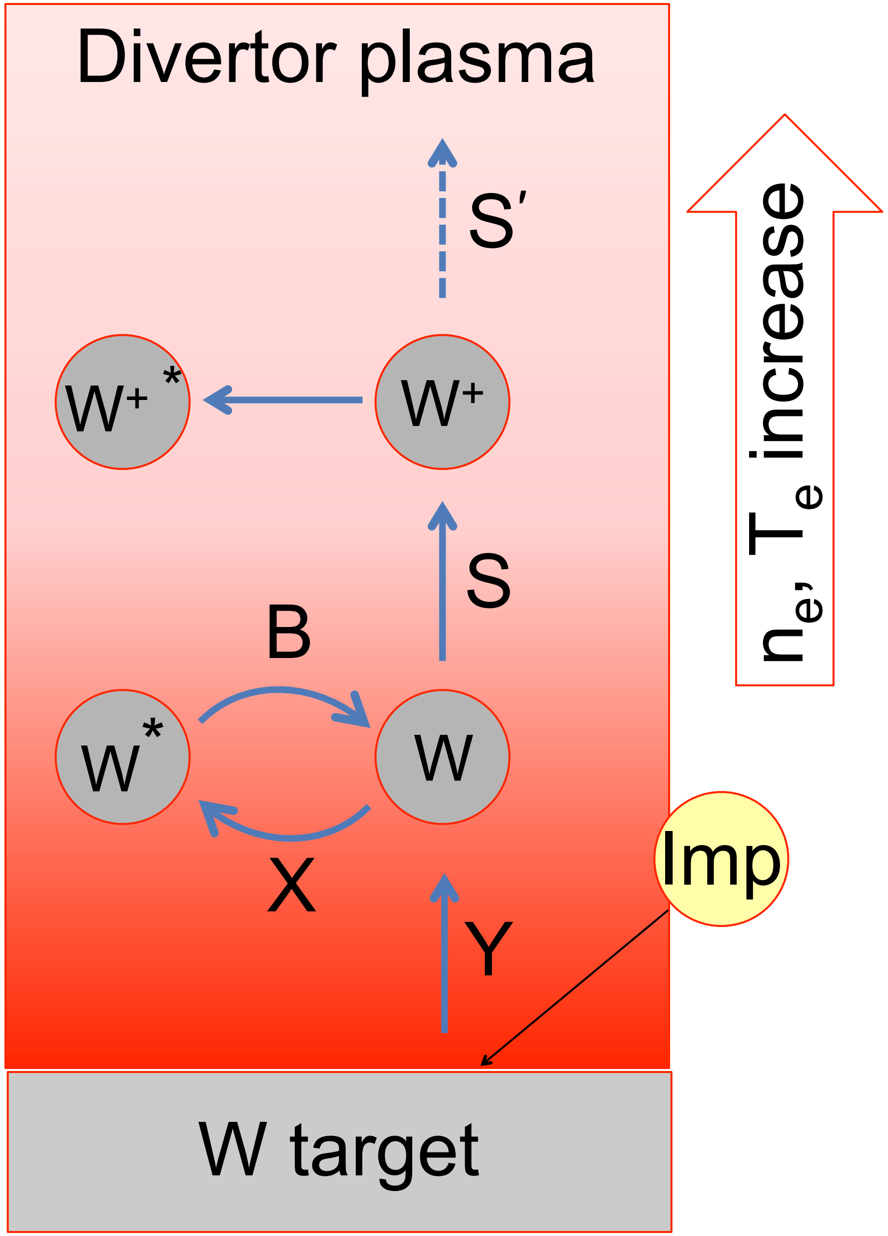
$$E_{th} = \frac{E_{sb}}{\gamma(1-\gamma)}$$

$$\gamma = \frac{4 \cdot m_1 \cdot m_2}{(m_1 + m_2)^2}$$

energy transfer factor

Tungsten has a high energy threshold due to its high mass

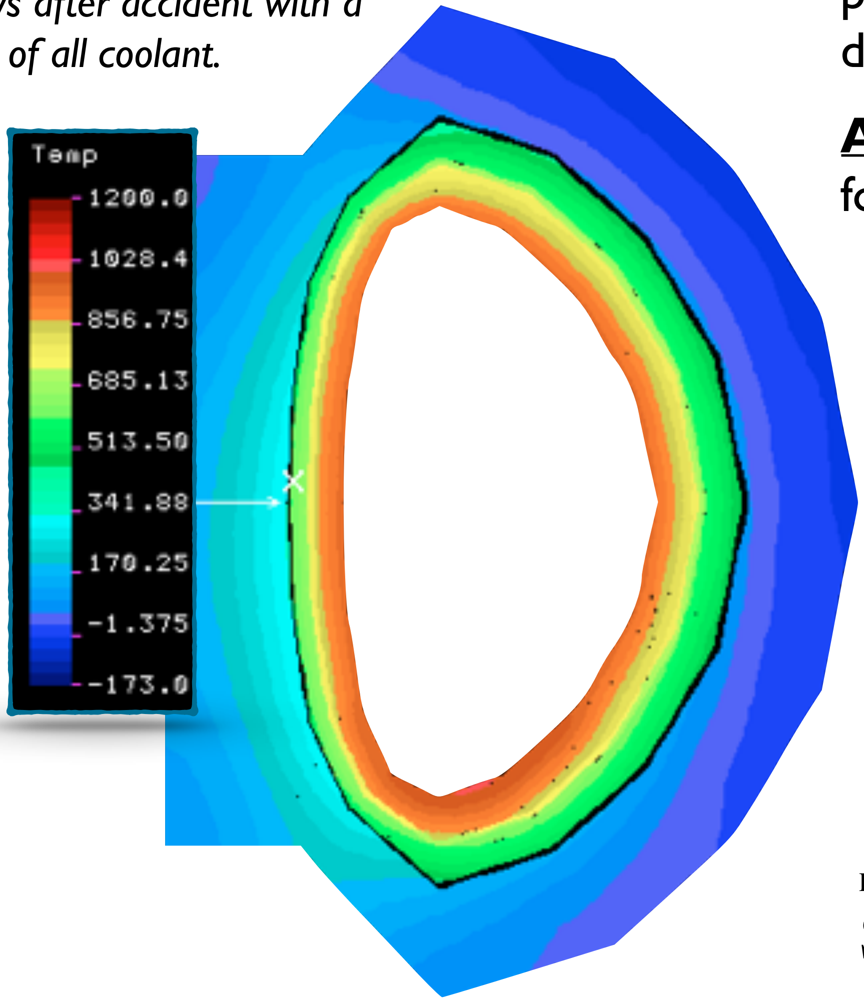
Other impurities than D will have higher sputter yields
W (E_{SB}=8.8 eV)
E_{th}=214EV (D) E_{th}=42eV (O)



A.Kirschner TRANSACTIONS OF FUSION SCIENCE AND TECHNOLOGY VOL. 53

Evaporation

Temperature profile in PPCS Model A, 10 days after accident with a total loss of all coolant.

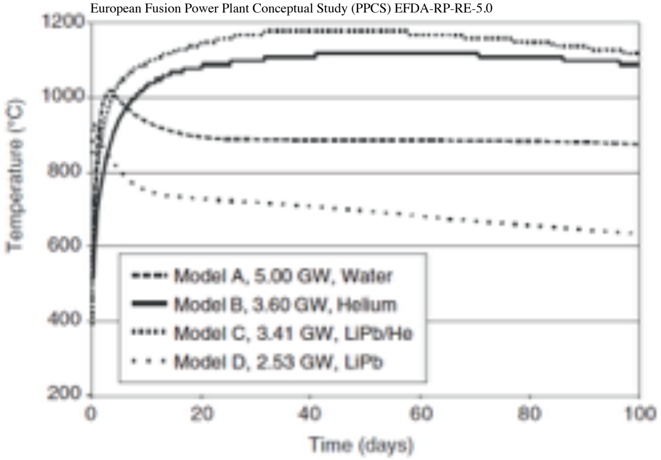


Final Report of the European Fusion Power Plant Conceptual Study,
EFDA(05)-27/4.10, 2004

Loss of Coolant Accident (LOCA):
peak temperatures of first wall up to 1200 °C due to nuclear after-heat

Additional air ingress:
formation of highly volatile WO_3 (Re, Os)

Maisonnier D et al 2005 A conceptual study of commercial fusion power plants Final Report of the European Fusion Power Plant Conceptual Study (PPCS) EFDA-RP-RE-5.0



Phys. Scr. T128 (2007) 100–105 doi:10.1088/0031-8949/2007/T128/020

Self passivating W-based alloys as plasma facing material for nuclear fusion, F. Koch and H. Bolt

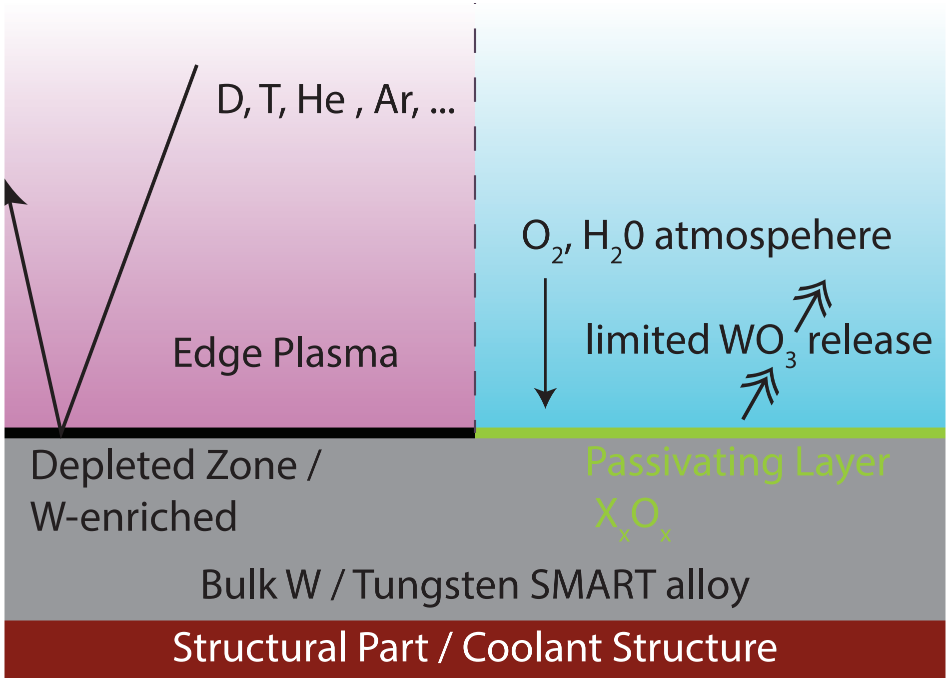
SMART Alloys

Normal operation (600°C, exposure to fusion plasmas):

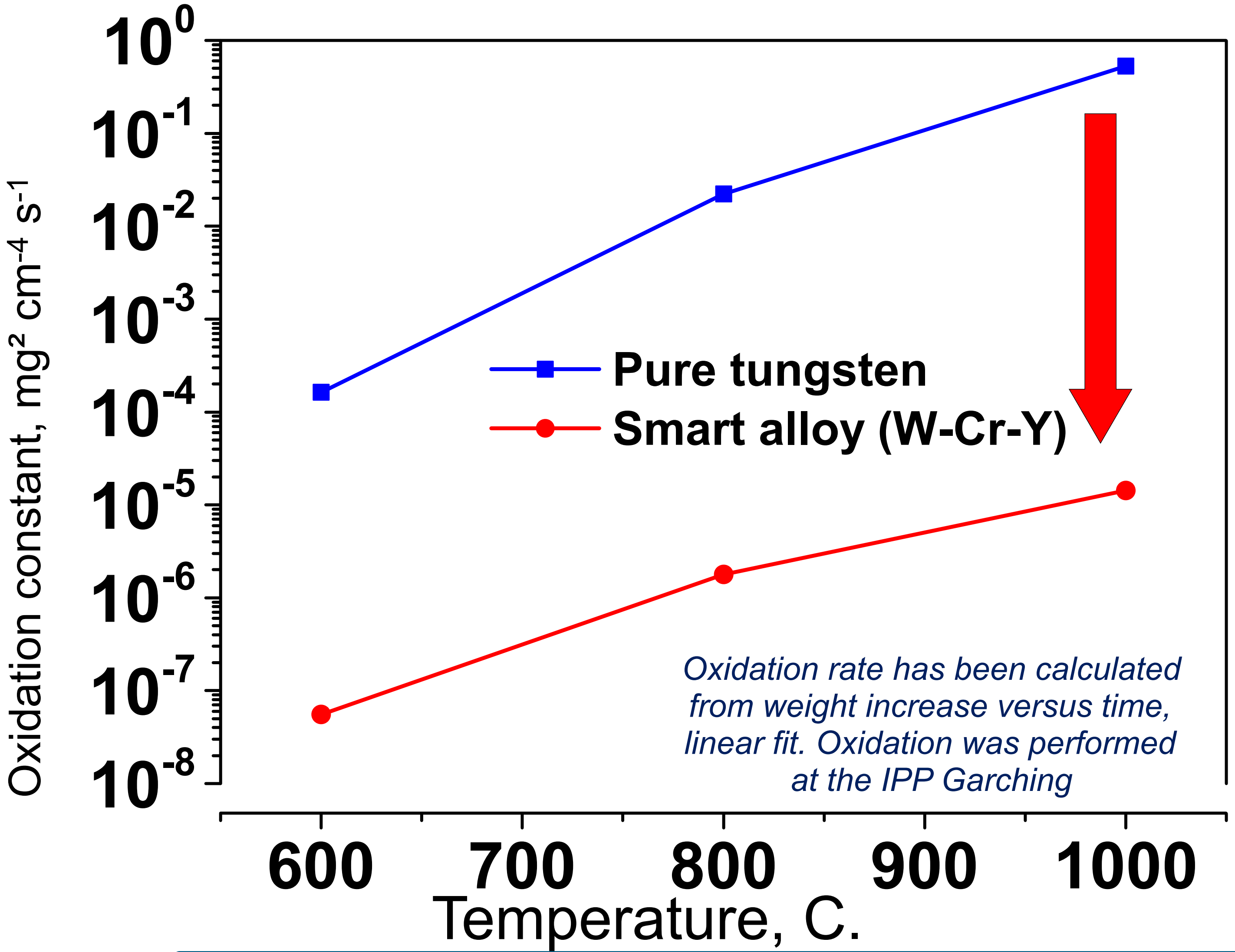
- ❖Tungsten-rich plasma-exposed surface due to preferential sputtering of light alloying elements by plasma ions

Accidental conditions (>1000°C, air):

- ❖Formation of protective layer of alloying elements on top of tungsten alloy
- ❖Suppression of tungsten oxidation



Ti-free Alloys



Oxidation rate has been calculated from weight increase versus time, linear fit. Oxidation was performed at the IPP Garching

Oxidation rates (K_p) at 1000°C:

K_p (pure W) = 0.52

K_p (smart alloy W-Cr-Y) = $1.4*10^{-5}$

- 10^4-fold suppression of tungsten oxidation due to self passivation
- Tungsten fraction in the alloy is about 70 at.%

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Hydrogen Interaction

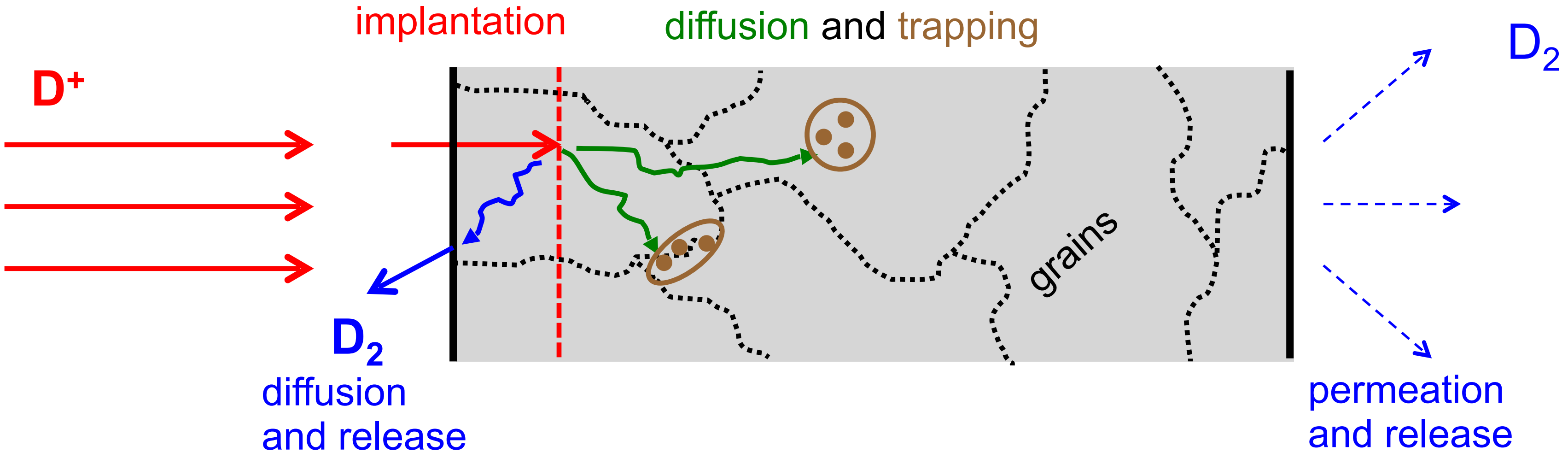
… a circular argument for an integrated component…

H Interaction

Plasma impact = ion implantation + sputtering + heat flux

Implanted H diffuses towards the surface (recombination, recycling) and into the bulk (trapping at intrinsic defects, permeation)

High fluxes/fluences = high concentrations of mobile H
= creation of defects, structural modifications

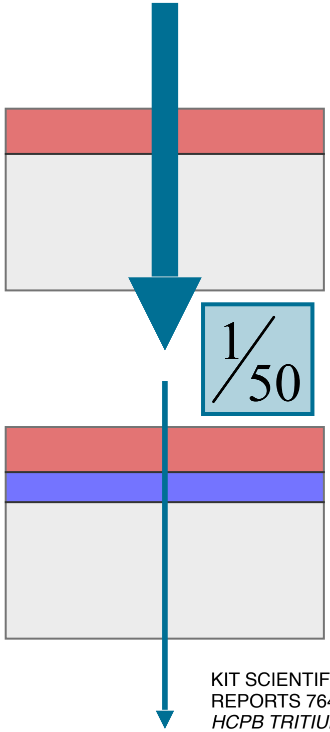


T - Barriers

- Hydrogen isotopes diffuse easily in metals
- Radioactive inventory and material embrittlement
- Permeation of T_2 into coolant
- Consider impact of Tritium inventory on TBR

$\Rightarrow$ **Reduction of permeation by a factor 50…100 necessary**

Hydrogen

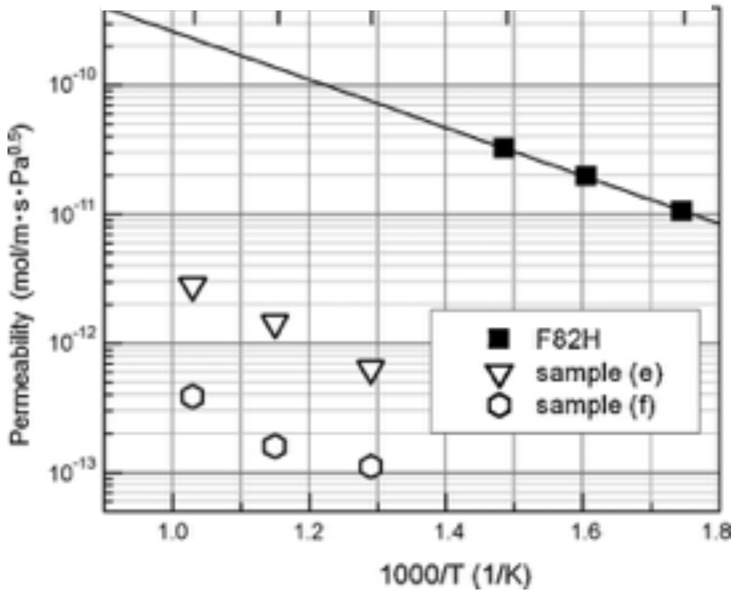


KIT SCIENTIFIC REPORTS 7642 *HCPB TRITIUM LOSSES COOLANT & ENVIRONMENT*

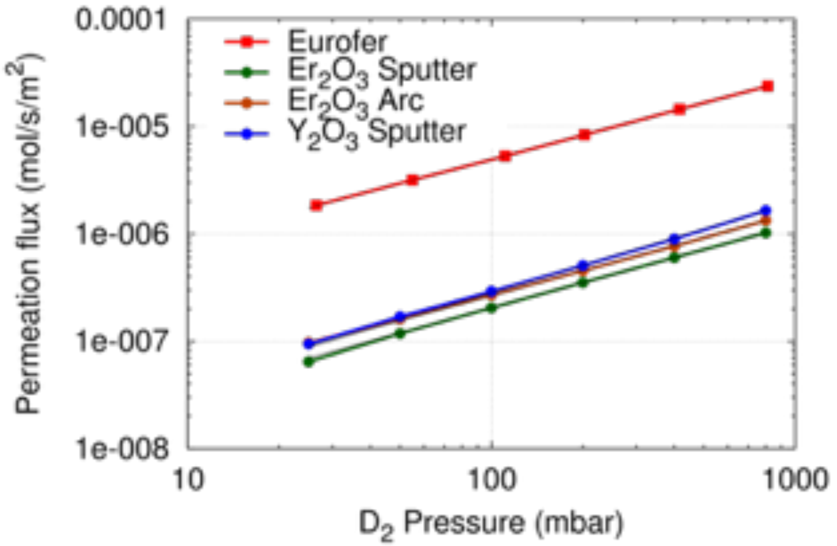
Integration of T-Barriers into components is required for a viable DEMO PFU

Permeation Data

Er_2O_3 by metal-organic decomposition



T. Chikada et al. / Fusion Engineering and Design 85 (2010) 1537–1541

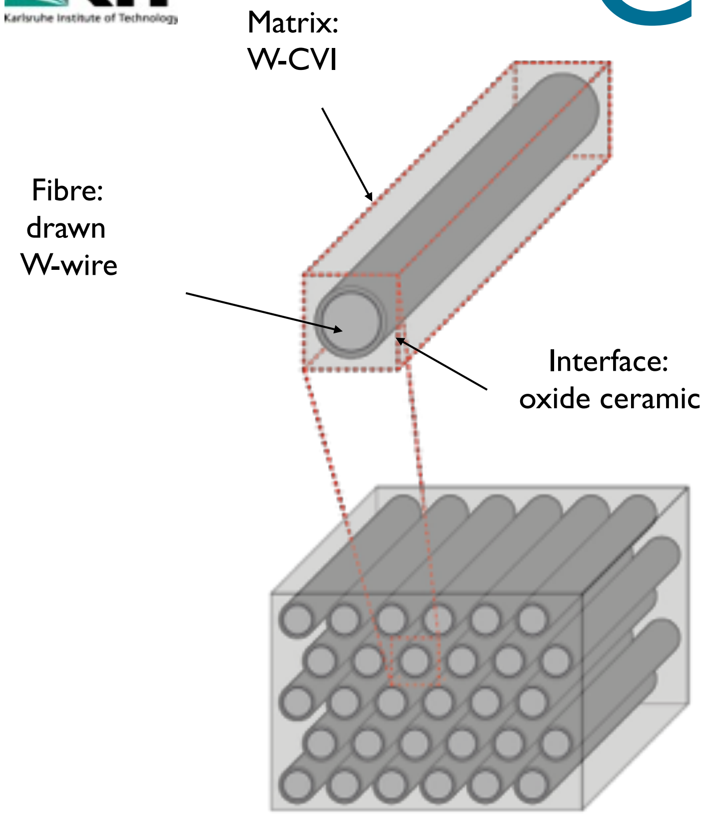


- Hydrogen permeation is drastically reduced by applying erbia, alumina or yttria

⇒ **Reduction of permeation by a factor 50…100**

Wanted as permeation barrier , unwanted in components/composites

Composites

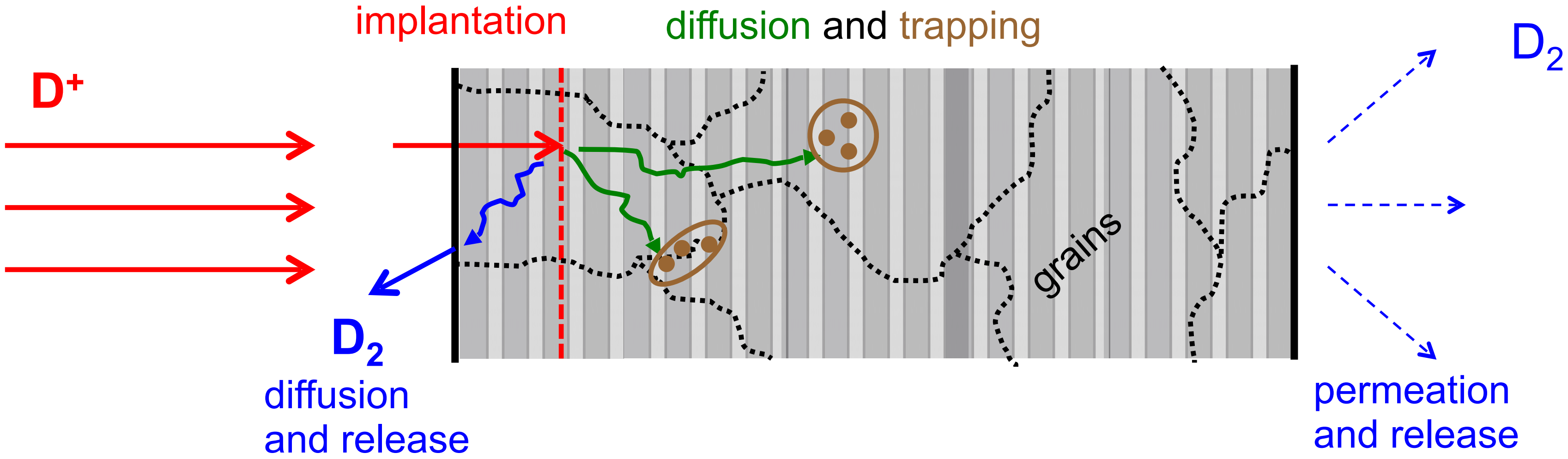


Interface & Fibre

- Erbia and Yttria both can be used as permeation barriers
- Do we consider properly the fibre as a hydrogen trap?

Matrix

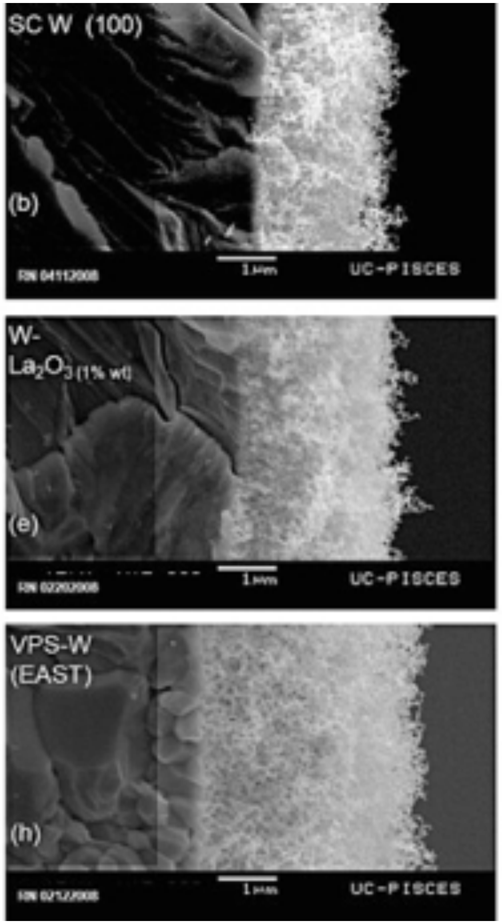
- Microstructure can facilitate H/He trapping & diffusion into the bulk.
- H-embrittlement
- Helium bubbles / voids and their impact on mechanics?

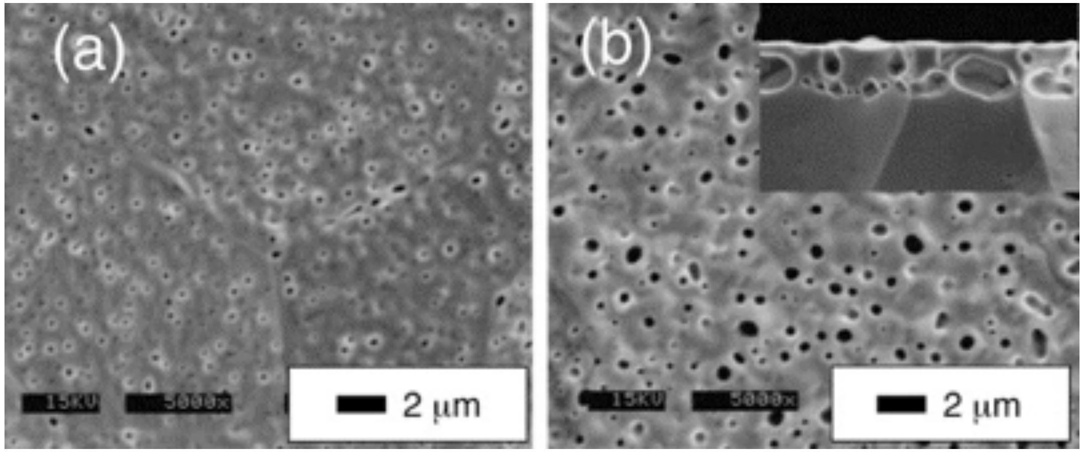


Helium Interaction

Helium Interaction

- **He blisters :** < 900K (low solubility, He can push W to an interstitial site)
- **He fuzz :** 1000K < T < 1400K , growth with ~ $t^{0.5}$ (induced mobility of He and other clusters)
- **He bubbles / holes :** T > 1400K (at large fluencies, due to capture of radiation and thermal induced vacancies)



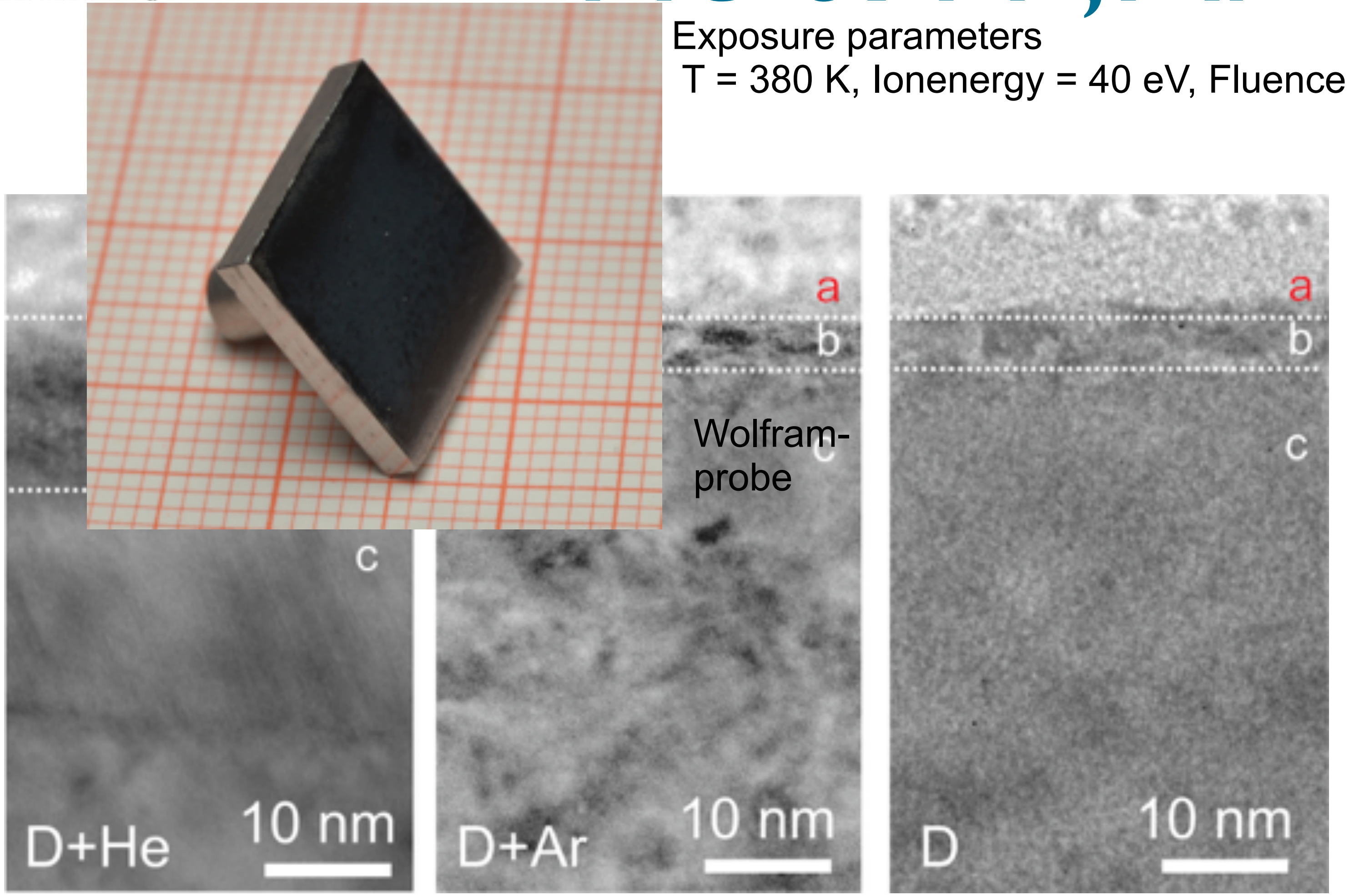


M.J. Baldwin, R.P. Doerner
Formation of helium induced nanostructure ‘fuzz’ on various tungsten grades
Temmerman, et al.
Helium effects on tungsten under fusion-relevant plasma loading conditions
Journal of Nuclear Materials , **2013**, *438, Supplement*, S78 - S83

He & H ,Ar

Exposure parameters

T = 380 K, Ionenergy = 40 eV, Fluence = 10^{26} D/m^2



TEM Images of the top layer of the W samples

a) Platinium cover
b) Modifications due to plasma exposure
c) Undamaged tungsten

D, D+Ar exposure

5 nm deep damages surface layer (~ D ion penetration depth)

D+He exposure:

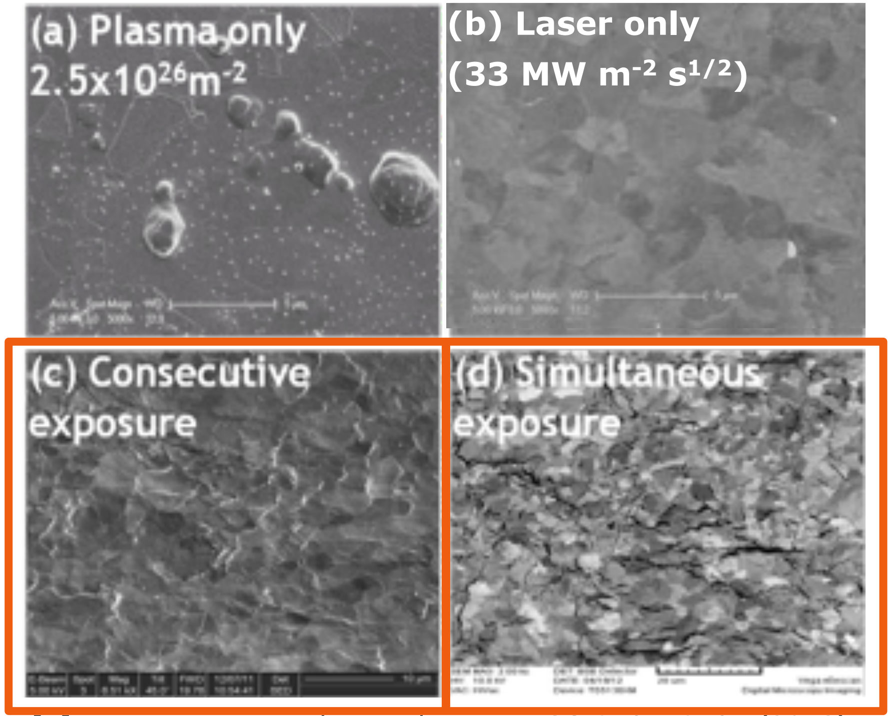
15 nm deep helium nano-bubble ayer (> D/He-ion penetration depth)

Mitglied der Helmholtz-Gemeinschaft

Synergistic Loads

Plasma & Heatflux

- Consecutive exposure shows greater roughening than laser alone
- Simultaneous exposure shows extensive cracking at much lower laser energy (20 MW m^{-2} $s^{1/2}$ vs. 35 MW m^{-2} $s^{1/2}$)
- Evidence of synergy between plasma damage and transient damage (lower lifetime for ITER PFC's than expected?)



[1] T. W. Morgan *et al J. Nucl. Mater* **438** S784–S787 (2013)

Tungsten behaves differently when exposed to plasma, heat-loads or a combination of both

Conclusion & Outlook

Development Strategy

- Idea
- Modelsystems
- Labsale - Prove of Concept

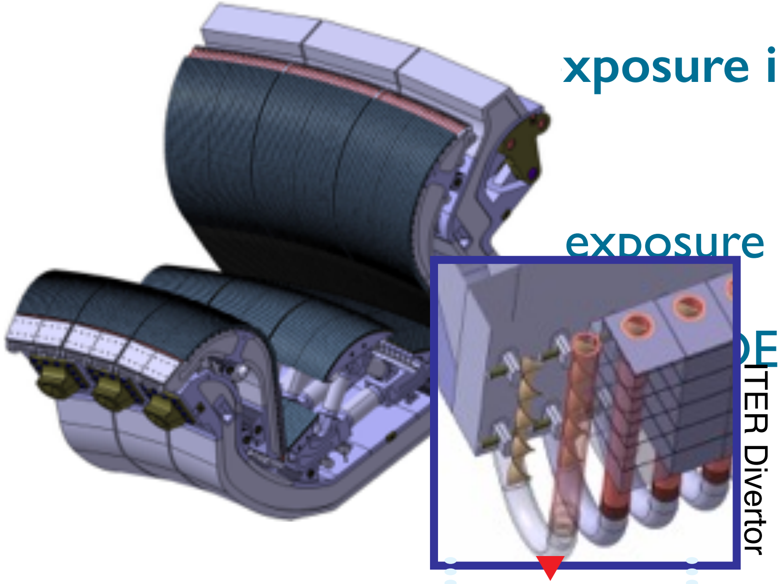
Advanced Materials add operational space to conventional approaches and might give more complex approaches (Advanced Divertors / Liquid Metal) more time to mature if they were required.

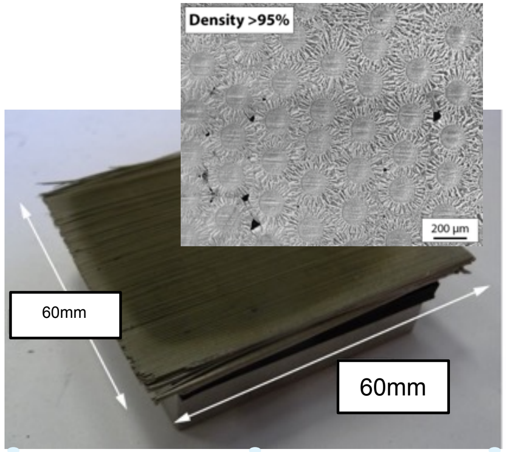
xposure in Modelplasma / Linear

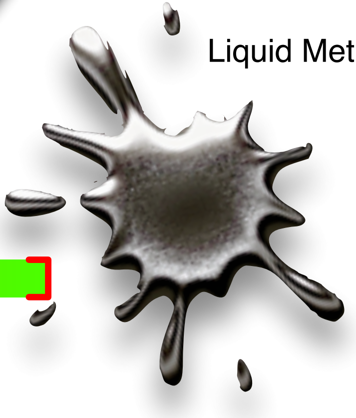
exposure

DEMO

Industrialisation







3. Materials

DEMO

Fusion Electricity

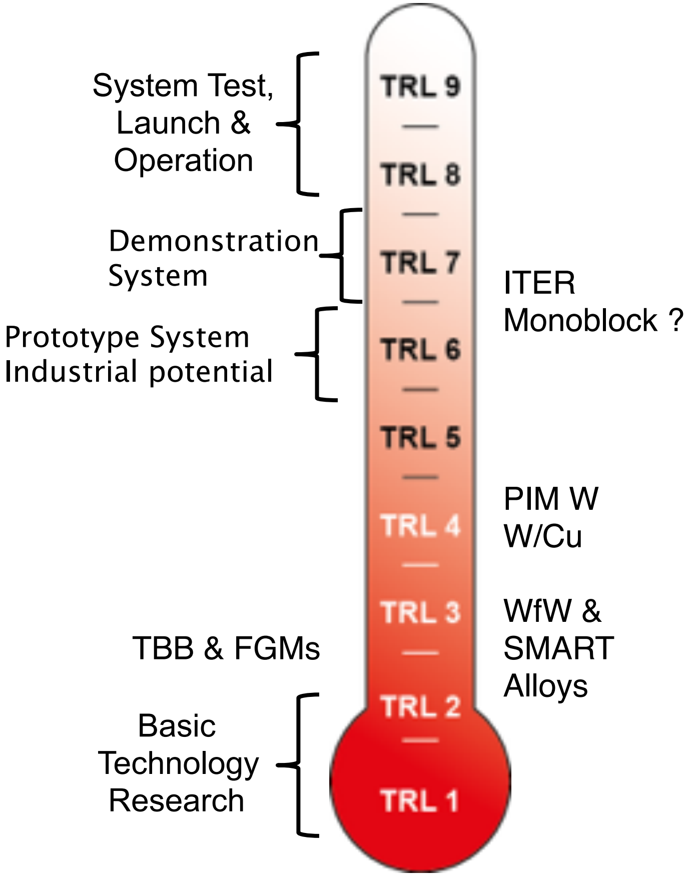
6. DEMO

Component Design and Engineering Design | Construction | Operation

2010 2020 2030 2040 2050

The next Steps

- **The aim is a component - HHF/ PWI testable <5 years (TRL 5-6)**
- **Test Samples are needed on short timescales to test PWI - & Exhaust relevant parameters**
- *How do we integrate our efforts between the component relevant materials?*
- *We consider forbidden‘ materials such as Cu, Al, Er e.g. Y ?!*
- ***We need to understand neutron effects on materials***
- PWI on reactor components
- **Test in linear devices & tokamaks**



System Test, Launch & Operation

Demonstration System

Prototype System Industrial potential

TBB & FGMs

Basic Technology Research

ITER Monoblock ?

PIM W W/Cu

WfW & SMART Alloys

Technology Readiness Level (TRL)

starting 2016

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Add Ons

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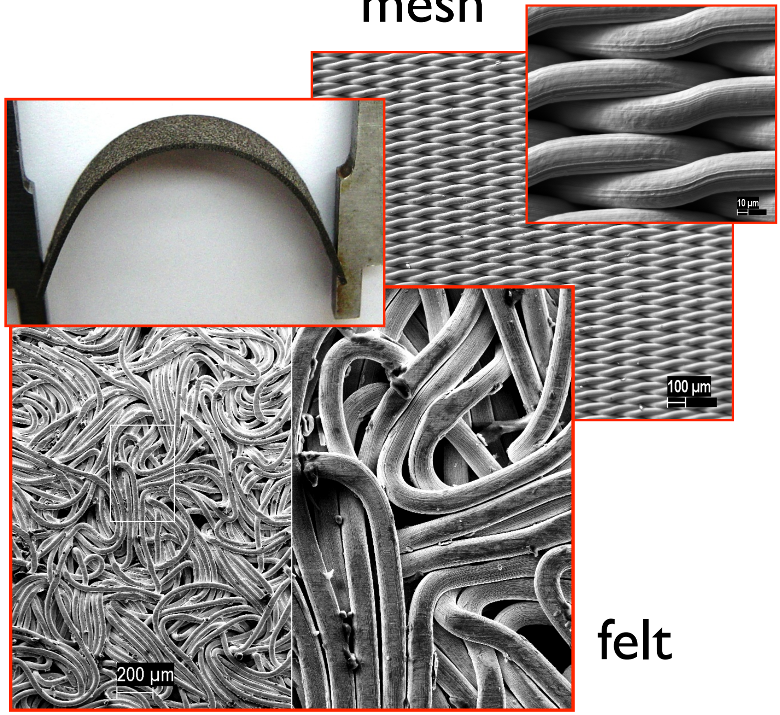
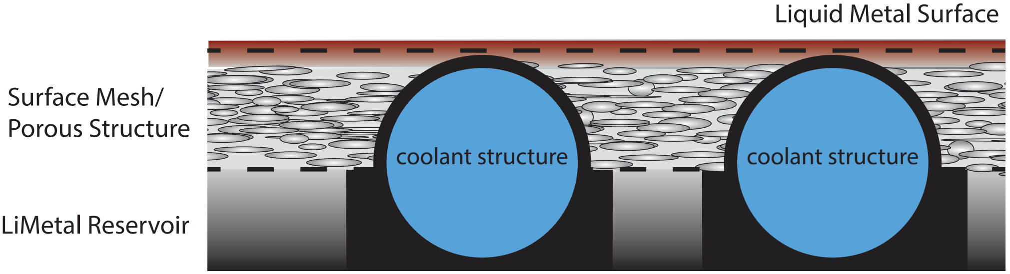
Liquid Metals

mesh



felt

Make the PFCs tolerant to erosion especially during transient events (Material replenishment)

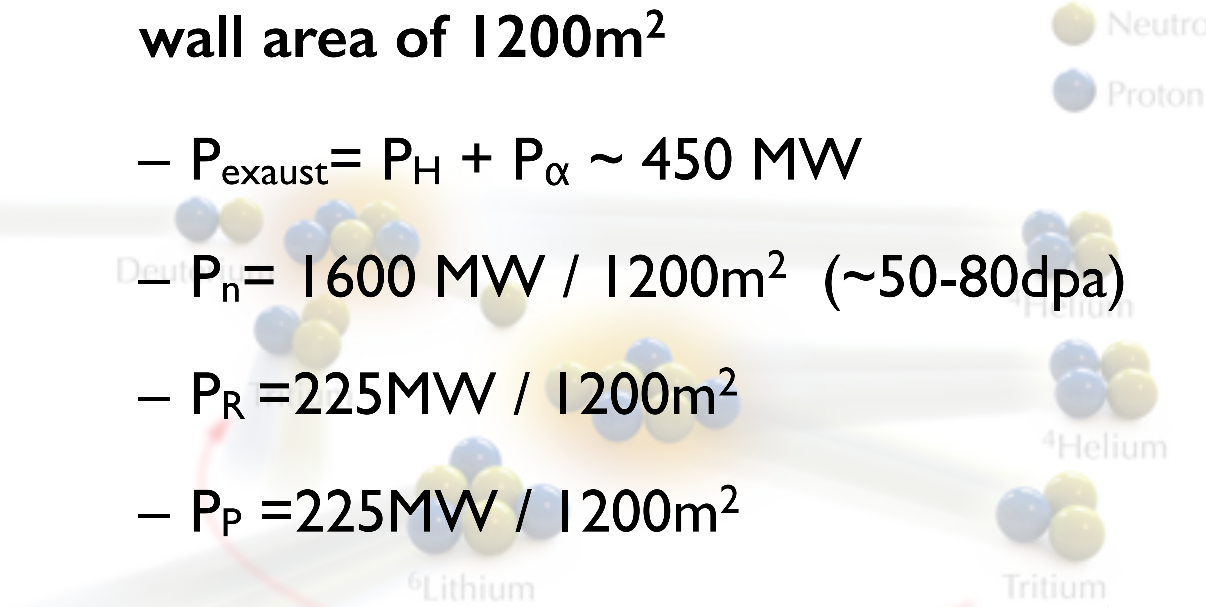


stabilize the liquid surface and replenish the liquid metal by capillary action

Liquid Divertors consist of largely the same materials as conventional ones and have hence the same issues for conventional heat exhaust and neutron /thermal embrittlement damage

Also here we do need new ideas

A Fusion Reactor



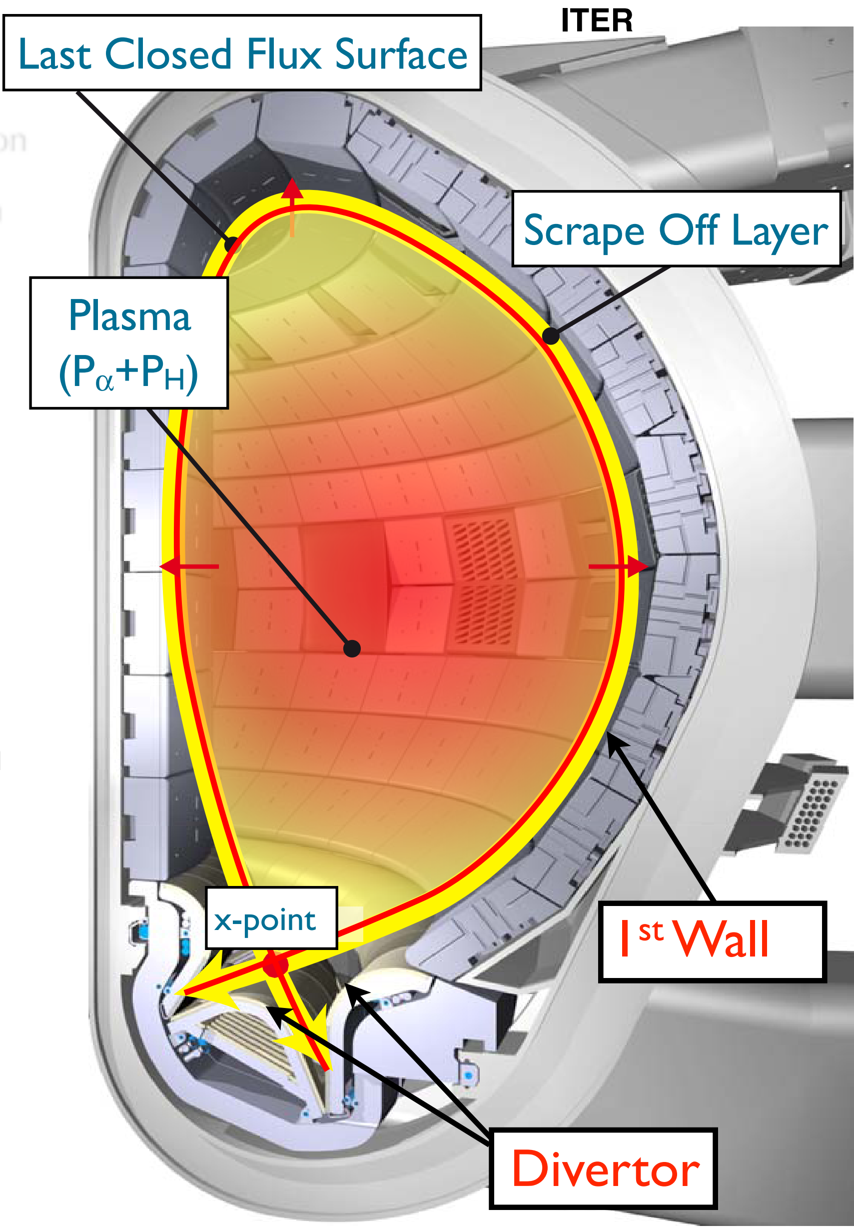
Lets assume fusion power 2GW and a wall area of 1200m^2

- P_{exaust}= P_H + P_α ~ 450 MW
- P_n= 1600 MW / 1200m^2 (~50-80dpa)
- P_R =225MW / 1200m^2
- P_P =225MW / 1200m^2

This means an average of 1.5MW/m^2 on the 1st Wall (1.3MW/m^2 vol. neutrons)

Typically 10-20 MW/m^2 on the divertor

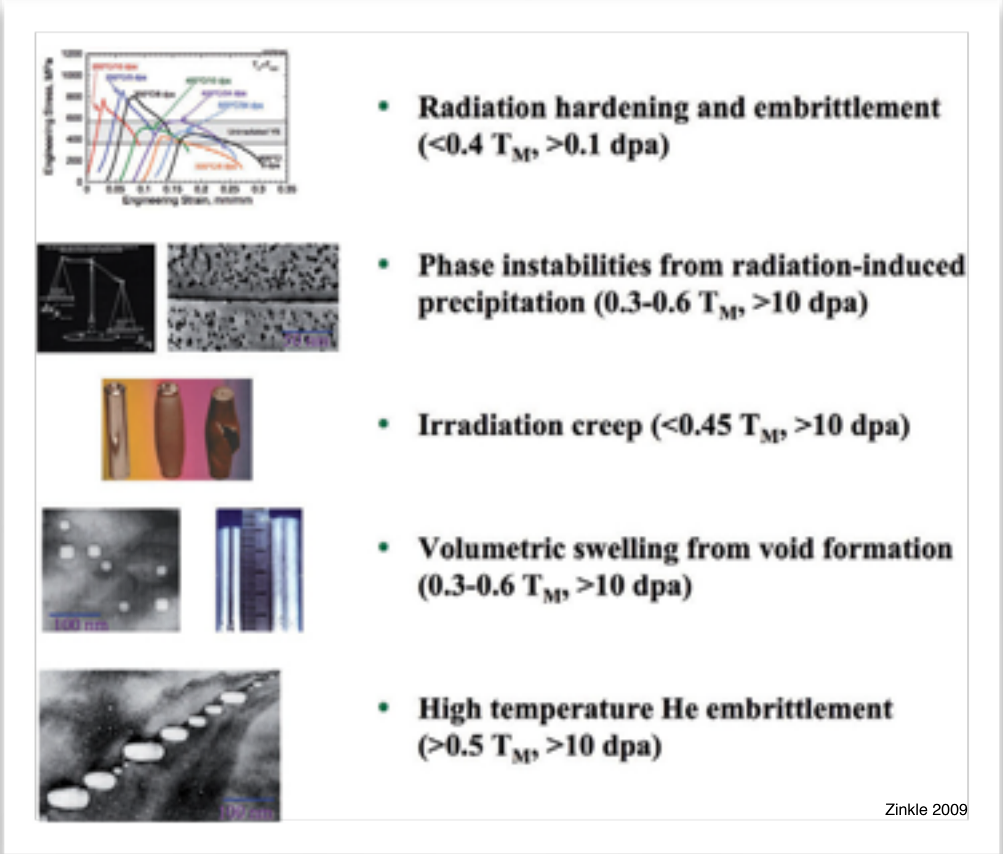
Not yet considered transients



C. Bachmann et al., Initial DEMO Tokamak Design Configuration Studies, SOFT2014 ,
G. Federici et al., Overview of EU DEMO Design and R&D Activities, in press on Fus. Eng. Design 2014.

Neutrons

Radiation effects

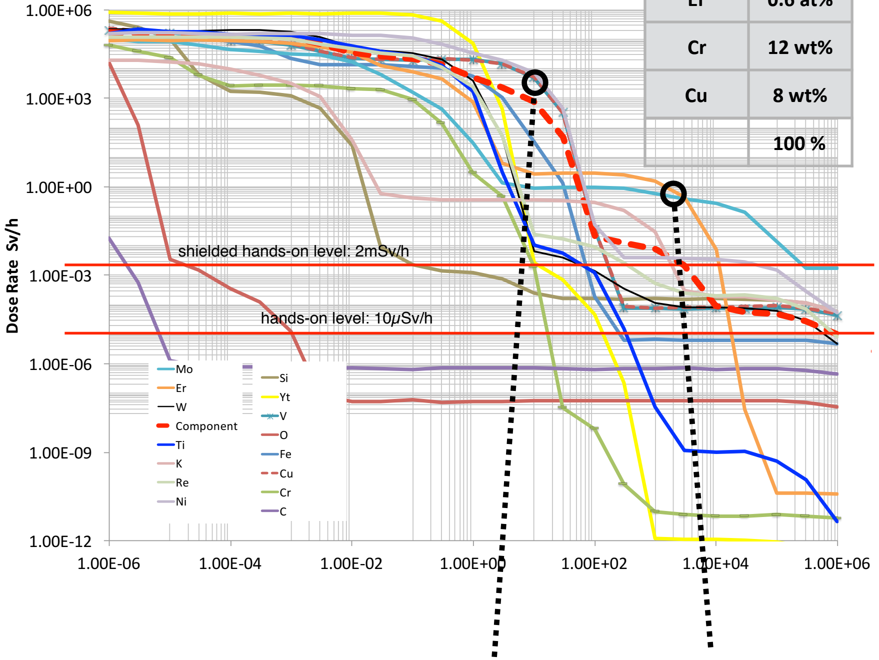


- **Radiation hardening and embrittlement ($<0.4\ T_M$, >0.1 dpa)**
- **Phase instabilities from radiation-induced precipitation (0.3-$0.6\ T_M$, >10 dpa)**
- **Irradiation creep ($<0.45\ T_M$, >10 dpa)**
- **Volumetric swelling from void formation (0.3-$0.6\ T_M$, >10 dpa)**
- **High temperature He embrittlement ($>0.5\ T_M$, >10 dpa)**

Zinkle 2009

Materials operating as PFCs in a fusion device will most certainly not retain their desired and design properties. Embrittlement will occur due to Neutron irradiation and elevated temperatures

Component	
w	79 at%
Er	0.6 at%
Cr	12 wt%
Cu	8 wt%
	100 %

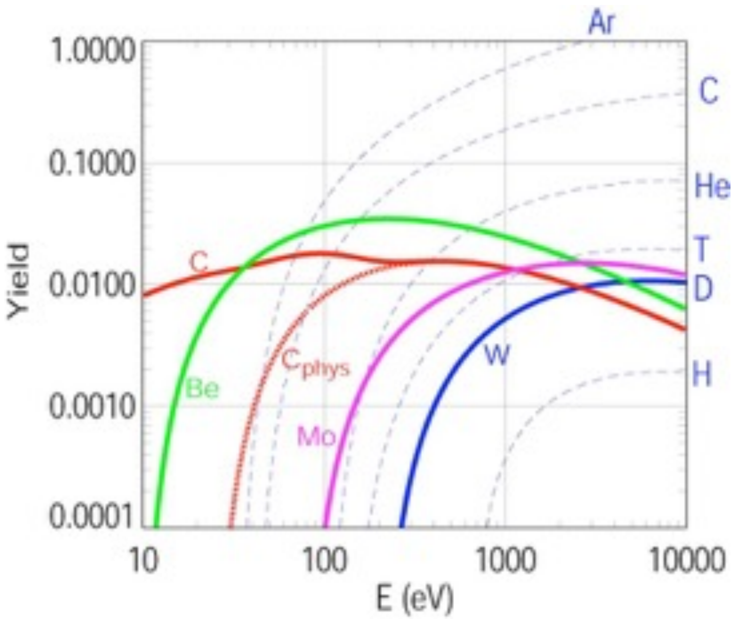


Already adding Cu, and Er at reasonable amounts will make activation an issue for recycling - not yet even considering swelling and high temp. operation

PWI in a nutshell

Materials in Fusion Devices

Components Lifetime



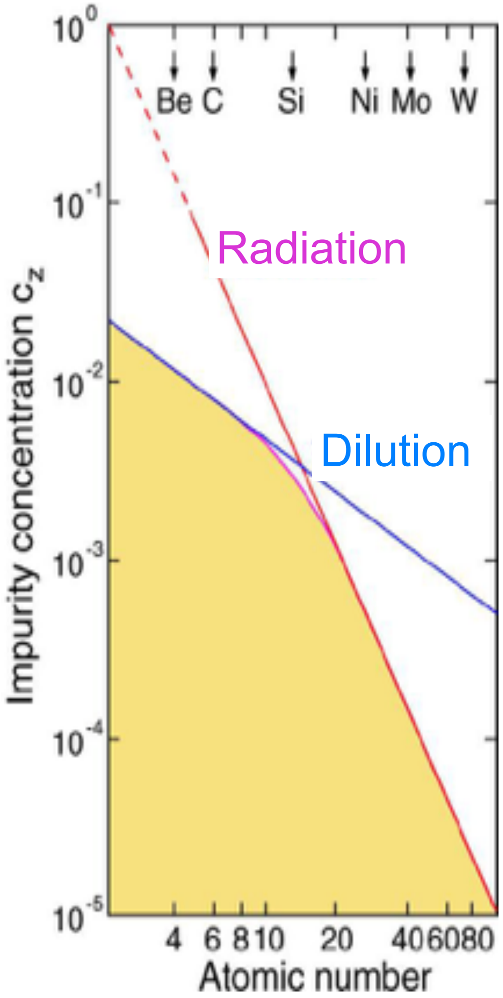
Low-Z: strong wall erosion

High-Z: low sputtering / mainly by impurities

Metals: potential melting

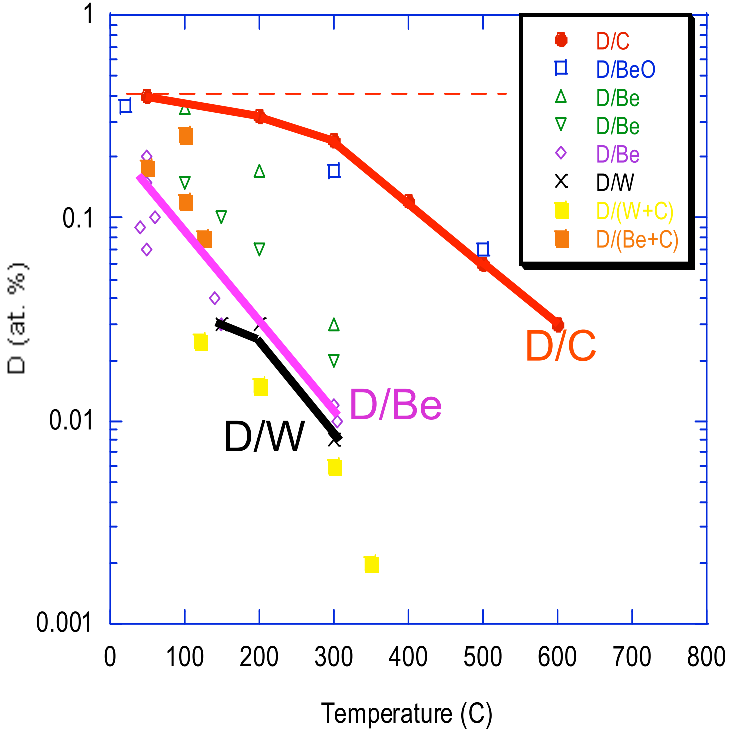
+ neutron hardness

Plasma Performance



Maximum allowed concentration for W:

Fuel Retention



Co-deposition dominates long term retention in C

Metals: low retention

EFDA Task Force
Plasma-Wall-Interactions