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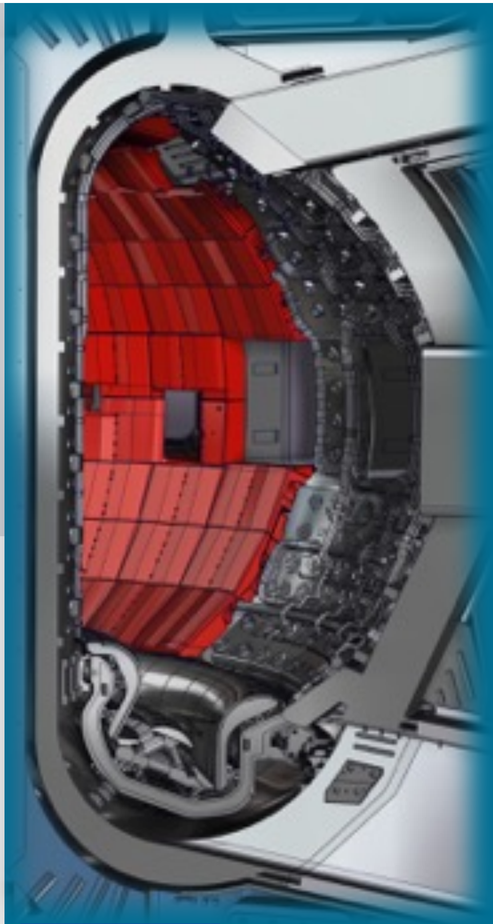
Materials for DEMO and Reactor Applications

Boundary Condition and New Concepts



J.W.Coenen[1*], S.Antusch[4], M.Aumann[1], W.Biel[1,3], J.Du[1], J.Engels[1], S.Heuer[1], A.Houben[1], T.Hoeschen[2], B.Jasper[1], F.Koch[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] and Ch.Linsmeier[1]

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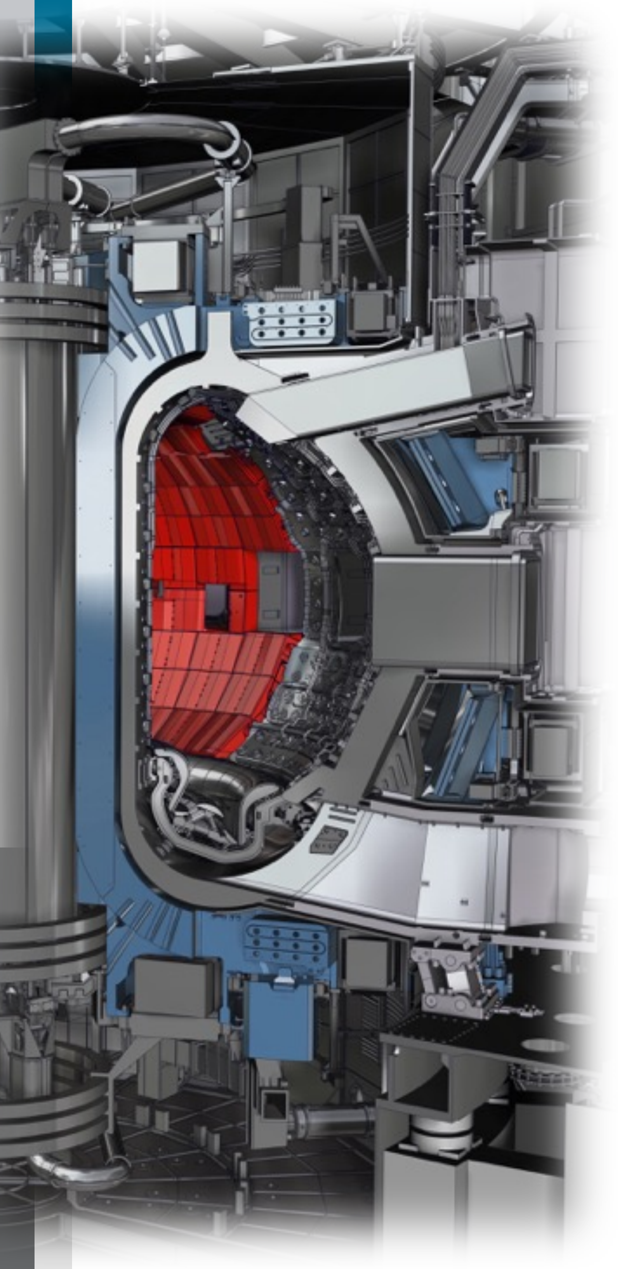
Overview

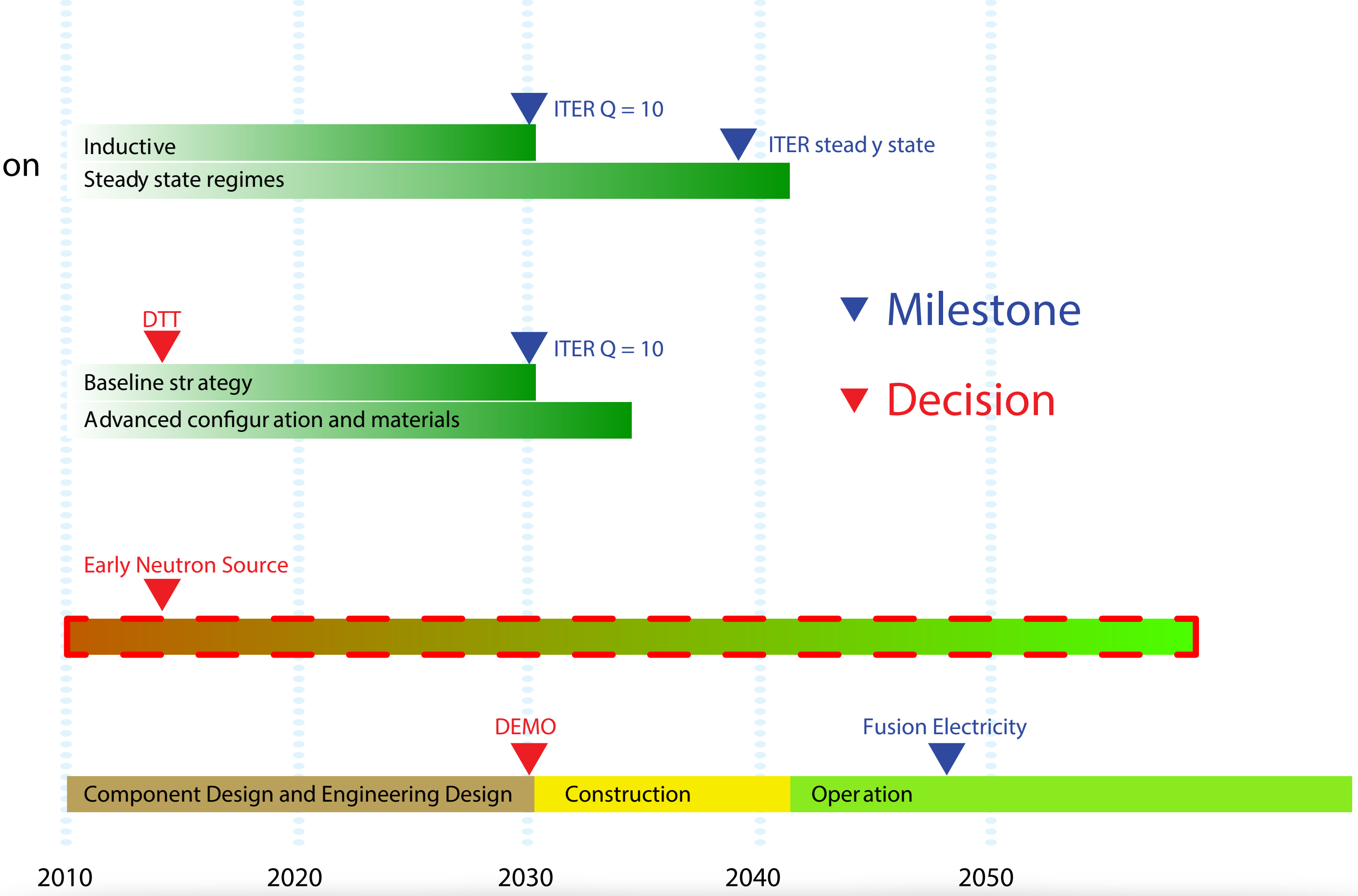


- Boundary Conditions
- Todays Options and Issues
- New Materials & PFCs
- Building a Component
- Conclusions & Outlook

also see A.Moeslang Wednesday

Roadmap

Fusion Electricity - EFDA November 2012



1. Plasma operation

ITER Q = 10

ITER stead y state

Inductive

Steady state regimes

2. Heat exhaust

DTT

ITER Q = 10

Baseline str ategy

Advanced configur ation and materials

3. Materials

Early Neutron Source

6. DEMO

DEMO

Fusion Electricity

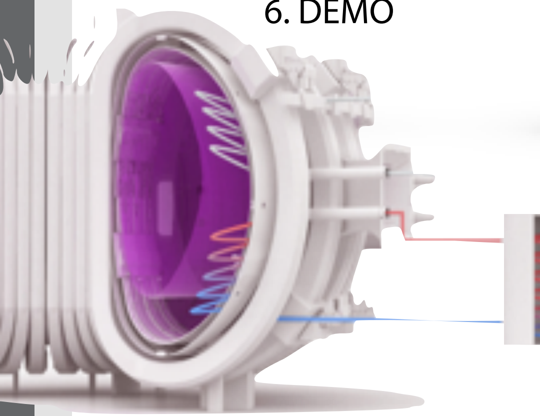
Component Design and Engineering Design

Construction

Oper ation

▼ Milestone

🔻 Decision



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

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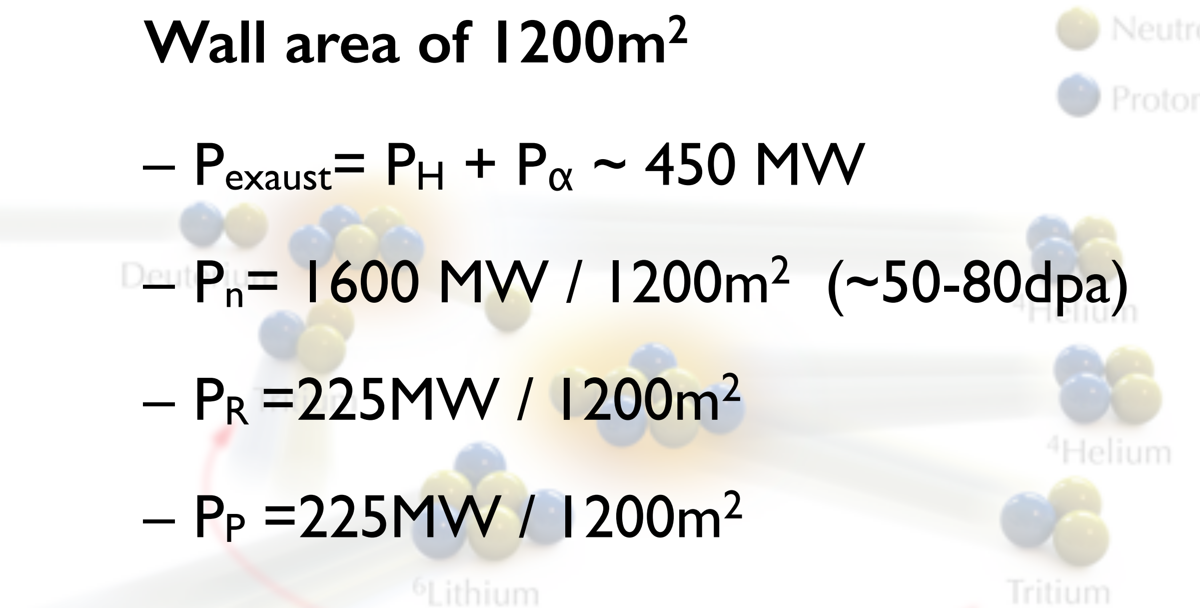
Boundary Conditions

A Fusion Reactor

Lets assume Fusion Power 2GW and a Wall area of 1200m^2

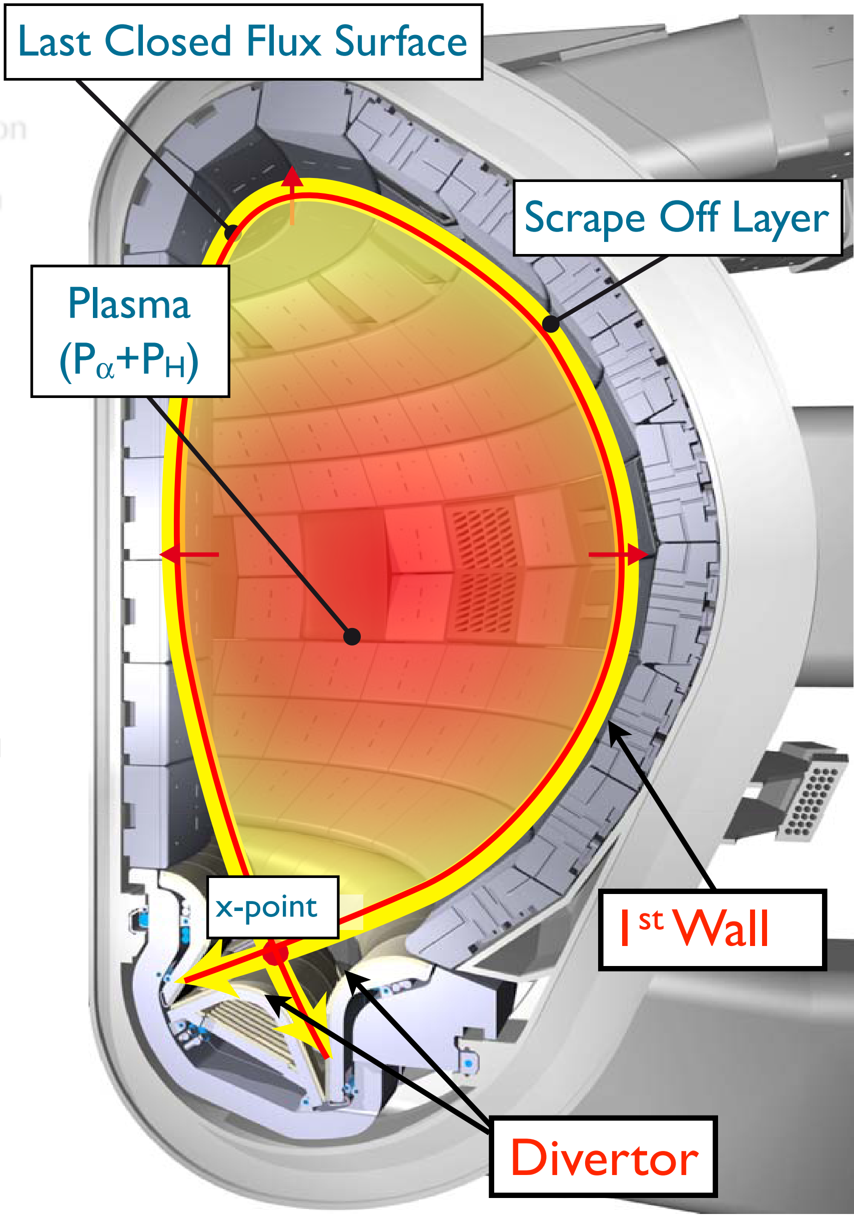


- $P_{exaust} = P_H + P_\alpha \sim 450$ MW
- $P_n = 1600$ MW / 1200m^2 (~50-80dpa)
- $P_R = 225$MW / 1200m^2
- $P_P = 225$MW / 1200m^2

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.

1st Wall & Divertor

PFCs & PFCs with some structural loads

Structural see A.Moeslang

New Materials

Power Exhaust (Energy Production)

The blanket exhausts the power and hence must operated at elevated temperatures to allow for efficient energy conversion

Choose Material with suitable operational window and sufficient exhaust capability

Mitigate material degradation due to neutrons & Reduce radioactive waste

Select materials that allow high temperature operation, mitigate effect of operational degradation such as embrittlement and neutron effects

Tritium self-sufficiency / Safety

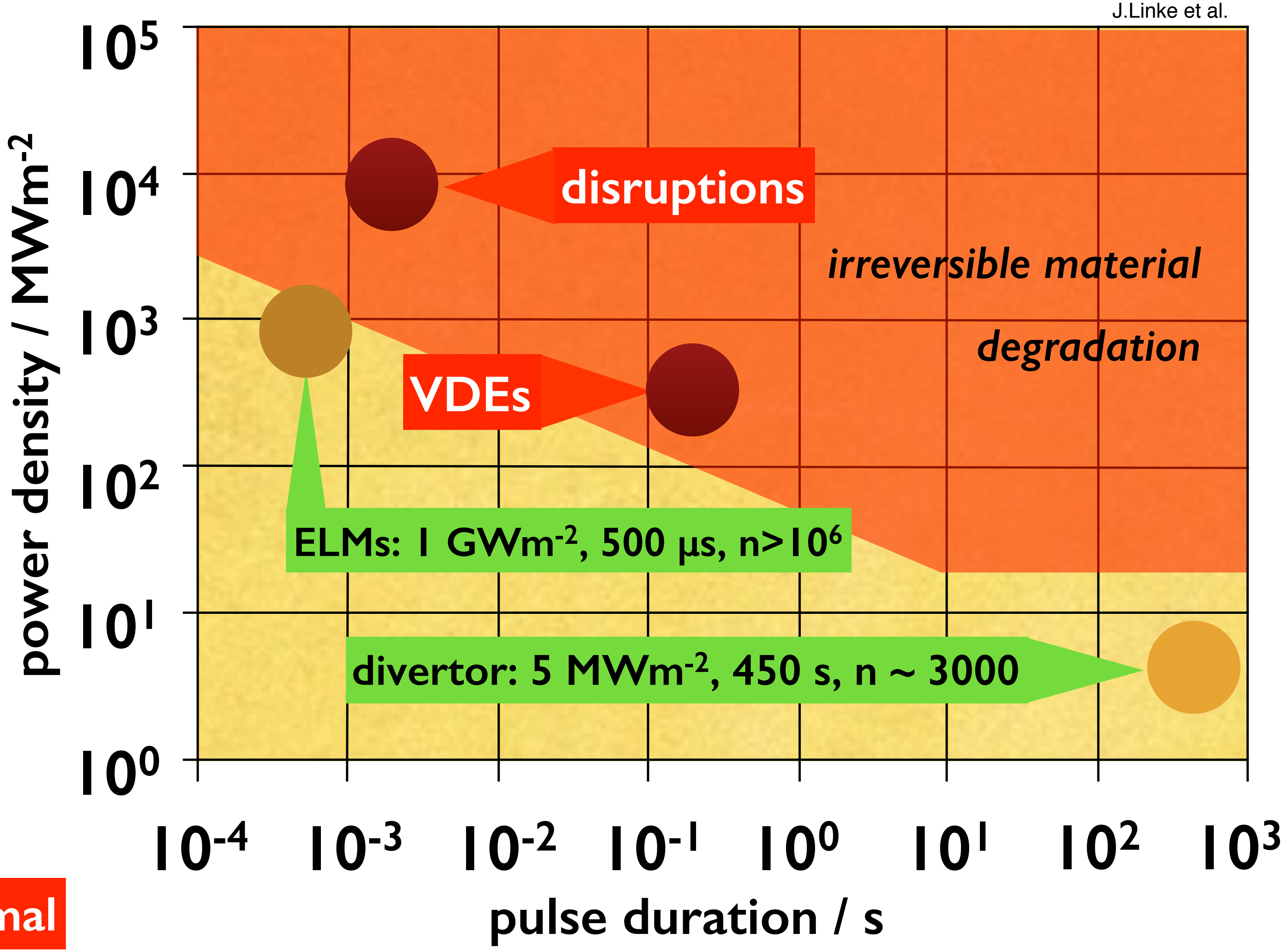
22 kg/year of T required for a 2GW plasma operated at 20% availability, ~85% of in-vessel surface must be covered by breeding blanket

Loss of tritium without ability to recover needs to be minimized

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.

Wall loads on W

J.Linke et al.



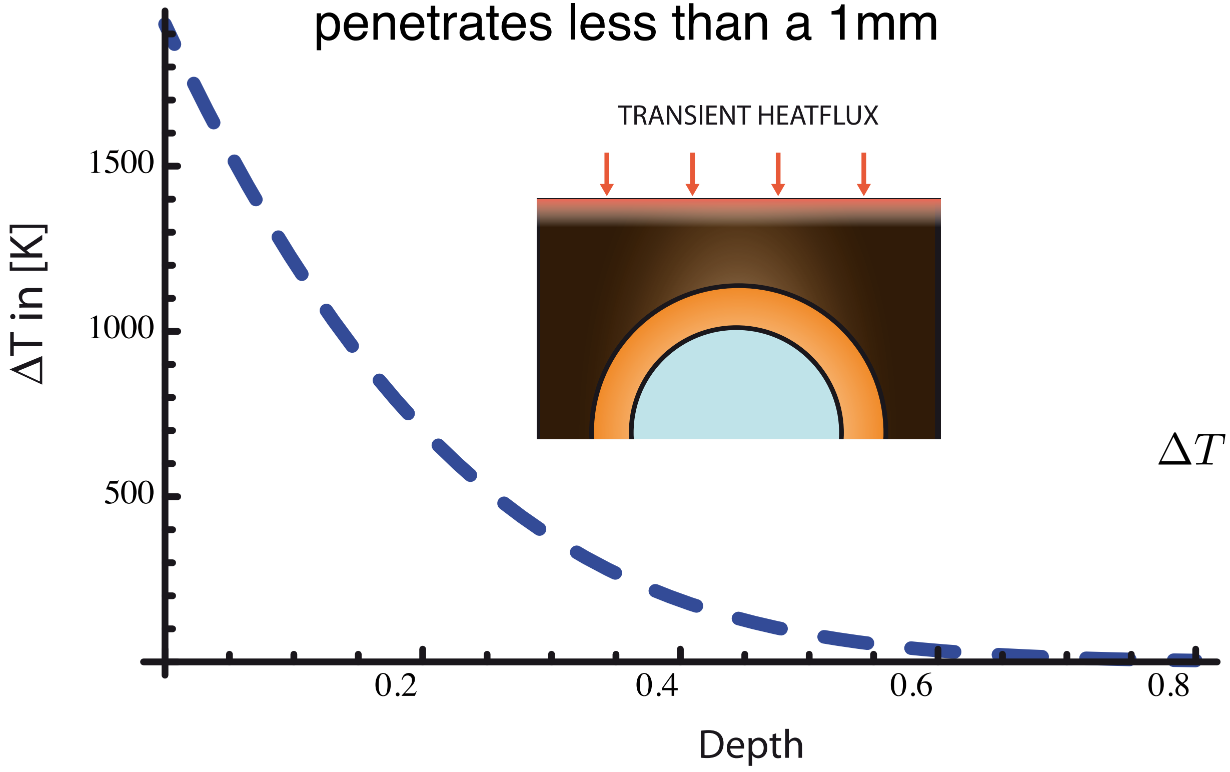
off-normal

normal

In a reactor 'normal' operation becomes challenging

Transient Heat loads

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



Heat Penetration Coeff.

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

κ = Heat capacity
ρ = density
c = heat conduction

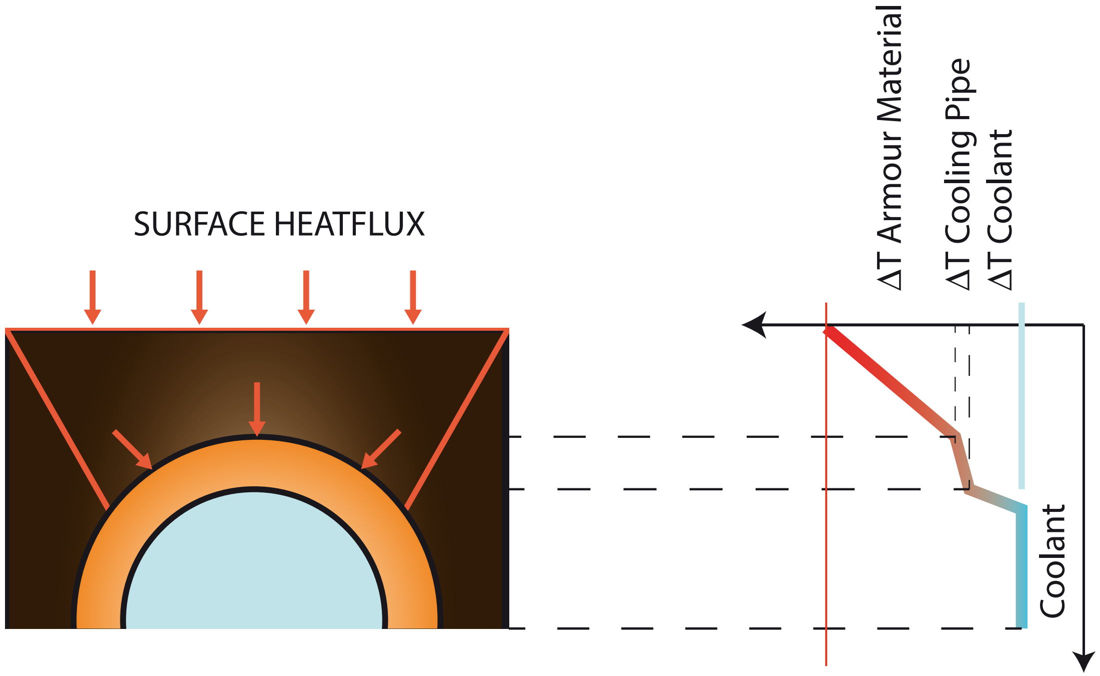
$$d = \frac{c^2}{b}$$

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

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

Choose a crack resilient material if transients can not be avoided

Steady State Loads



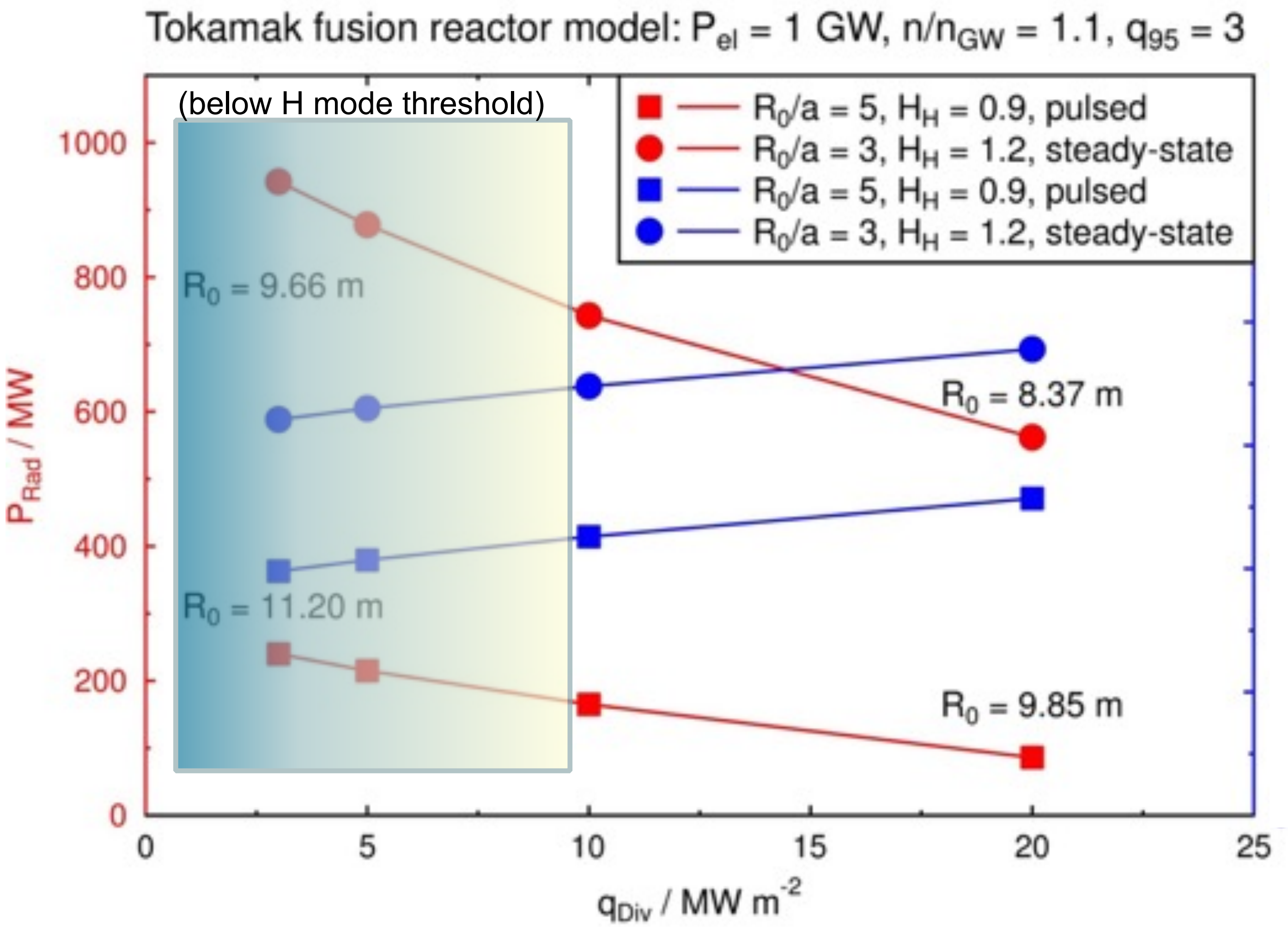
Tungsten	κ~178
Copper	κ~390
Steel	κ~20

$$T_{surf} = T_{cool} + \frac{q * d_2}{\kappa_2} + \frac{q * d_1}{\kappa_1}$$

$$q = \frac{T_{sur} - T_{cool}}{d_1/\kappa_1 + d_2/\kappa_2}$$

- 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 (lifetime vs. erosion & damage)</u>**

Divertor Heat Loads

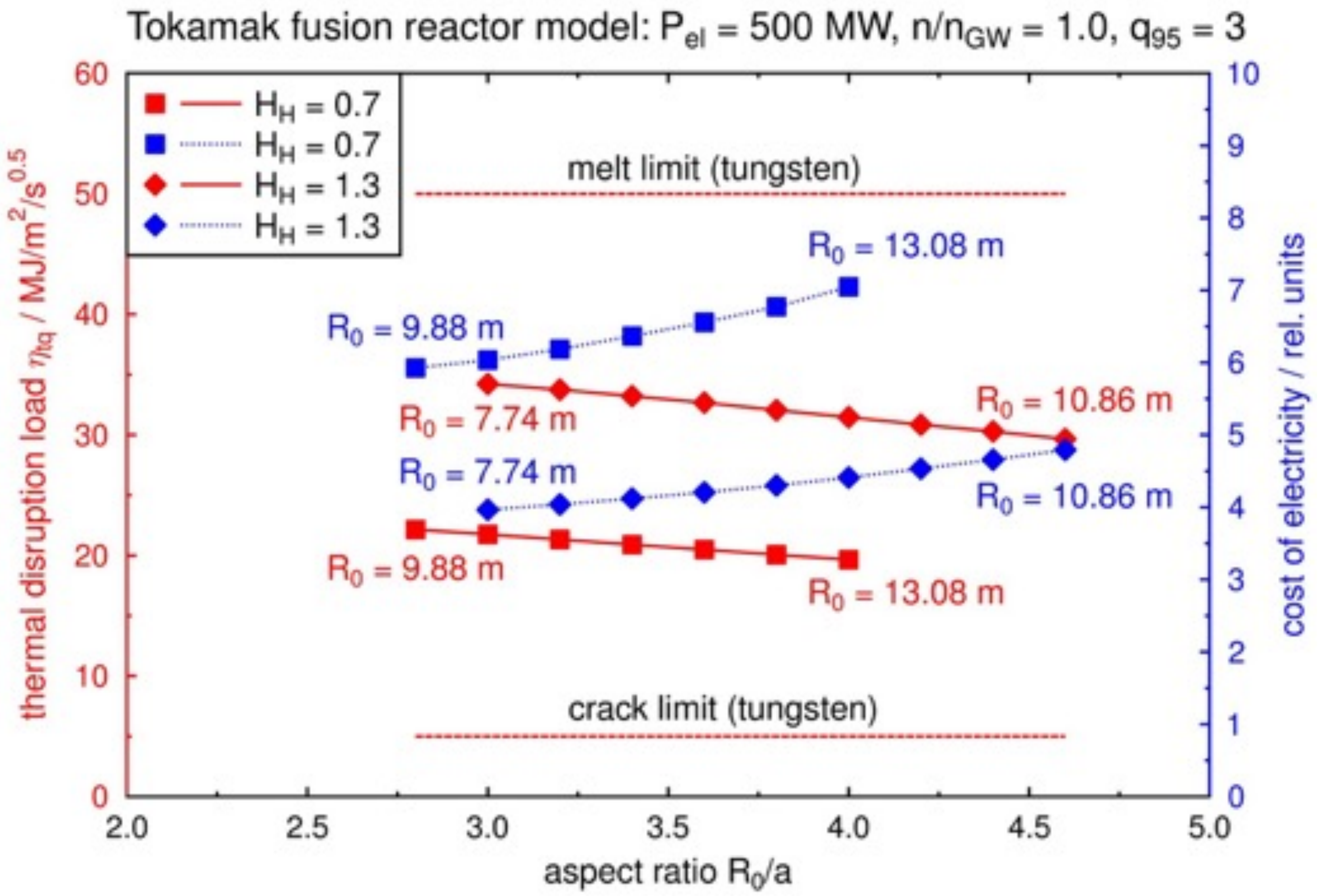


High performance plasma operation is associated with extreme local wall loads or with global plasma radiation fractions which are difficult to control;
+ conflict with H mode threshold

Steady state operation without ELMs	DEMO I divertor/FW	DEMO II divertor/FW
Power load, MW/m²	5 / 0.5-1	8.9 / 1-5

DEMO Design Summary, EFDA_D_2L2F7V v1.0, 2012S.

Disruptions



- Assumptions: 50% of W_{th} radiated during thermal quench; inhomogeneity tor.+pol. factor 2 each

➡ Thermal disruption loads are always much above the crack limit.

➡ Variation of the torus geometry (aspect ratio) provides only moderate reduction of loads.

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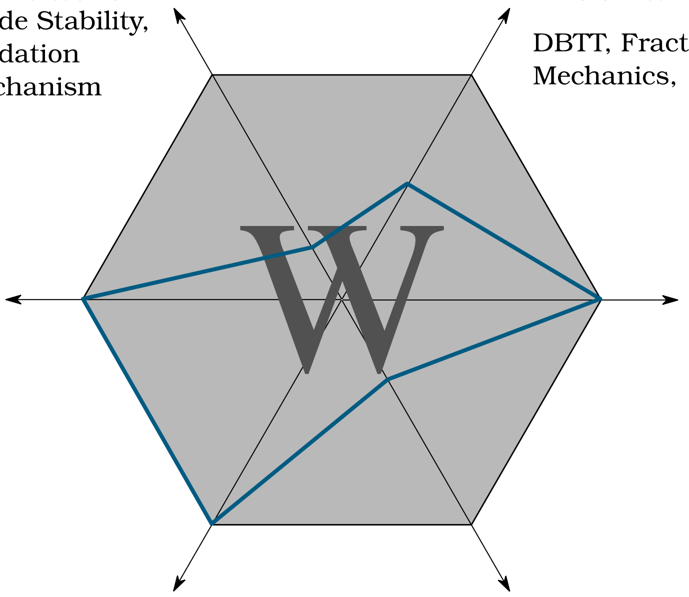
Todays Options & Issues

Status



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

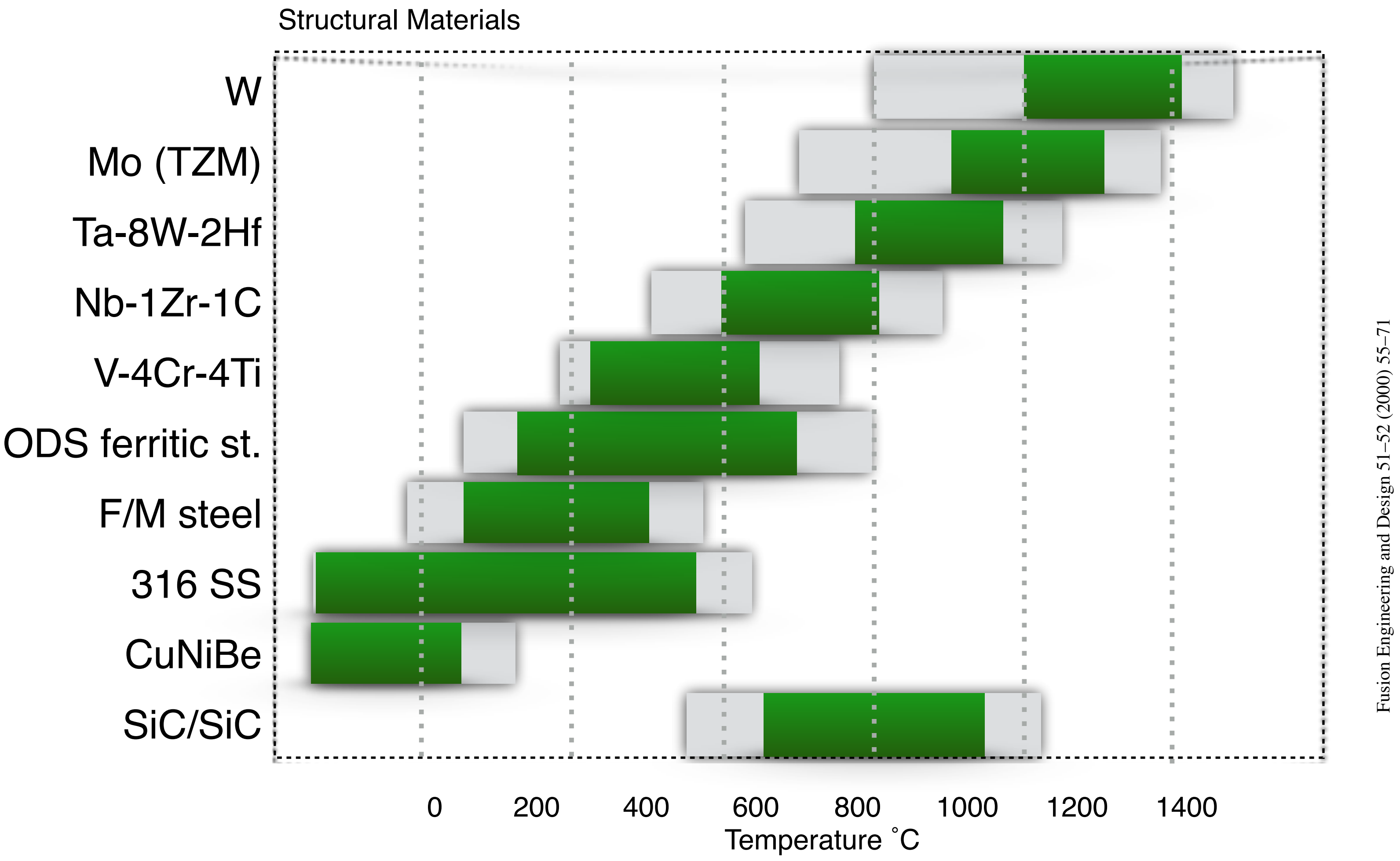
Operating Temp.

- **The lower operating temperature limit in all alloys is mainly determined by radiation embrittlement (decrease in fracture toughness), most pronounced for irradiation temperatures below ~ 0.3 T_{melt}, where T_{melt} is the melting temperature.**

- **The upper operating temperature limit is determined by one of four factors, all of which become more pronounced with increasing exposure time:**

  1. Thermal creep (grain boundary sliding or matrix diffusional creep);
  2. High temperature He embrittlement of grain boundaries;
  3. Cavity swelling.(particularly important for Cu alloys)
  4. Coolant compatibility: corrosion issues.

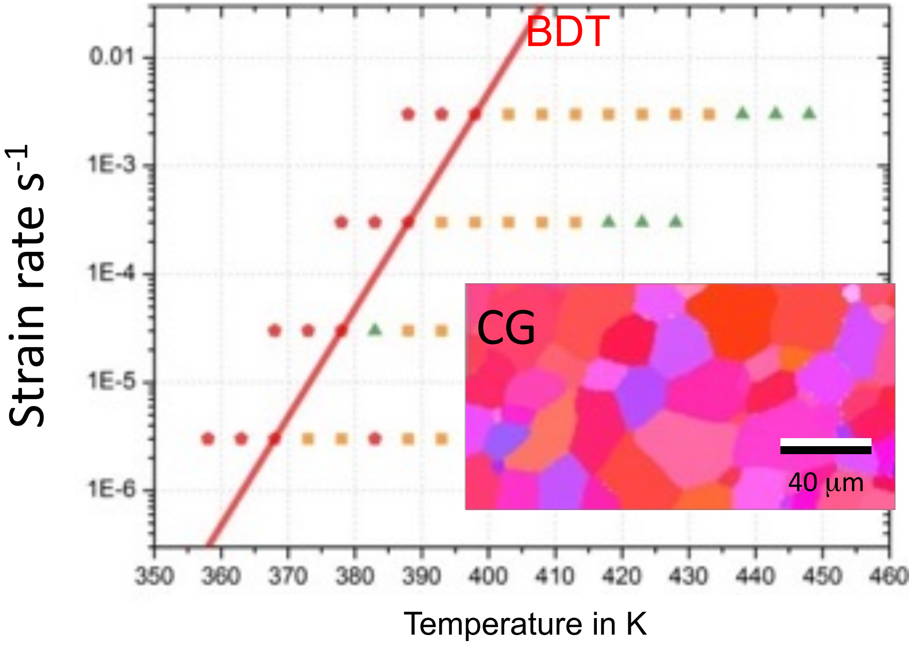
Operational Window



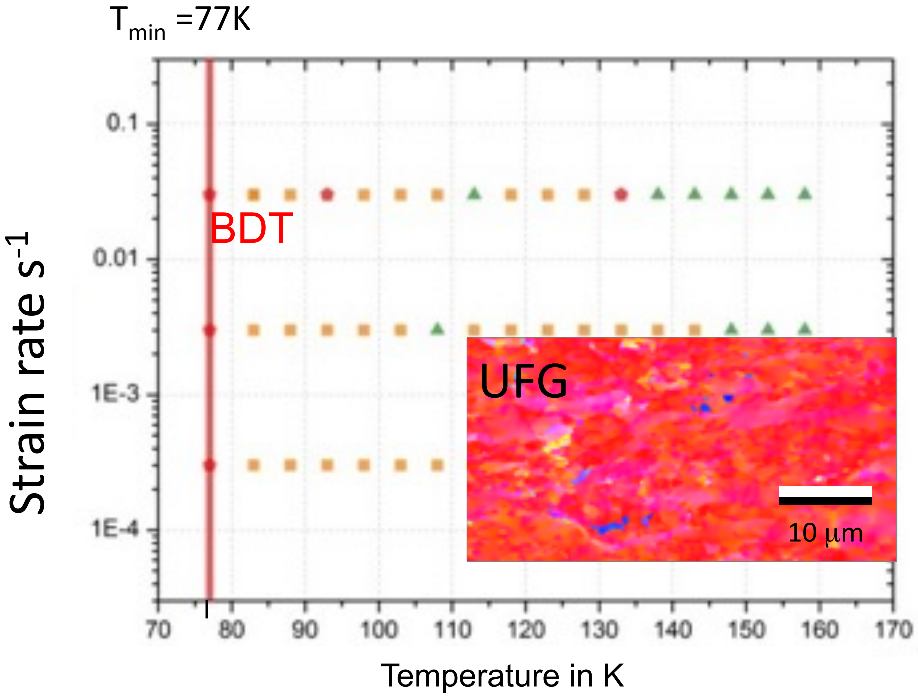
Fusion Engineering and Design 51–52 (2000) 55–71

Paradoxes of W

- Cold rolled (UFG/NC) W foil has exceptional properties in terms of…
  - … ductility, *Q. Wei, L.J. Kecskes (2008)* 10.4028/www.scientific.net/MSF.579.75
  - … toughness, and *P. Pippan (2014)* 10.1098/rsta.2014.0366
  - … brittle-to-ductile transition. *A.A.N. Németh (2015)* doi:10.1016/j.ijrmhm.2014.11.005



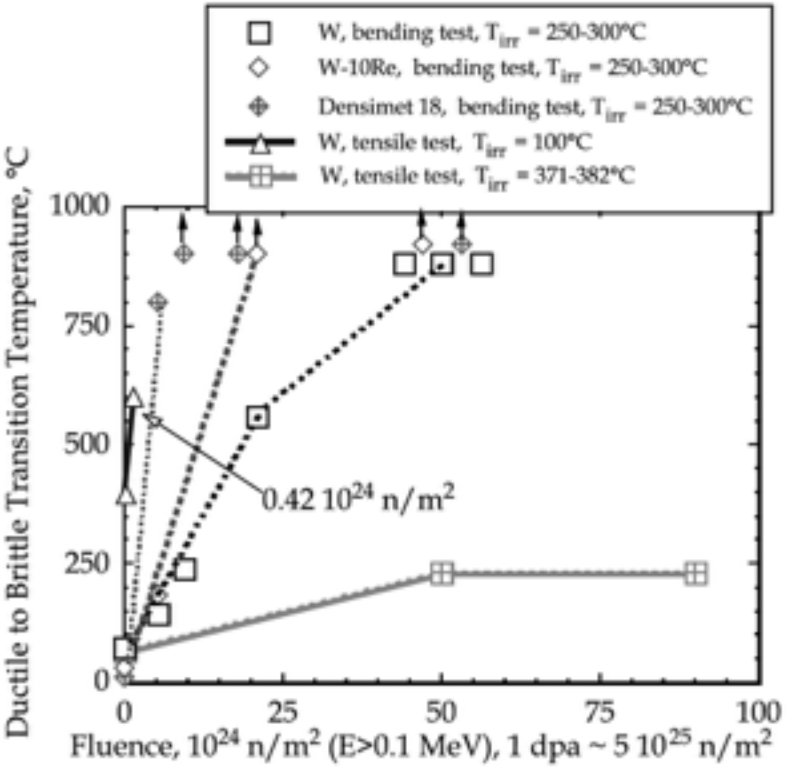
→ BDT controlled by **screw** disl. glide



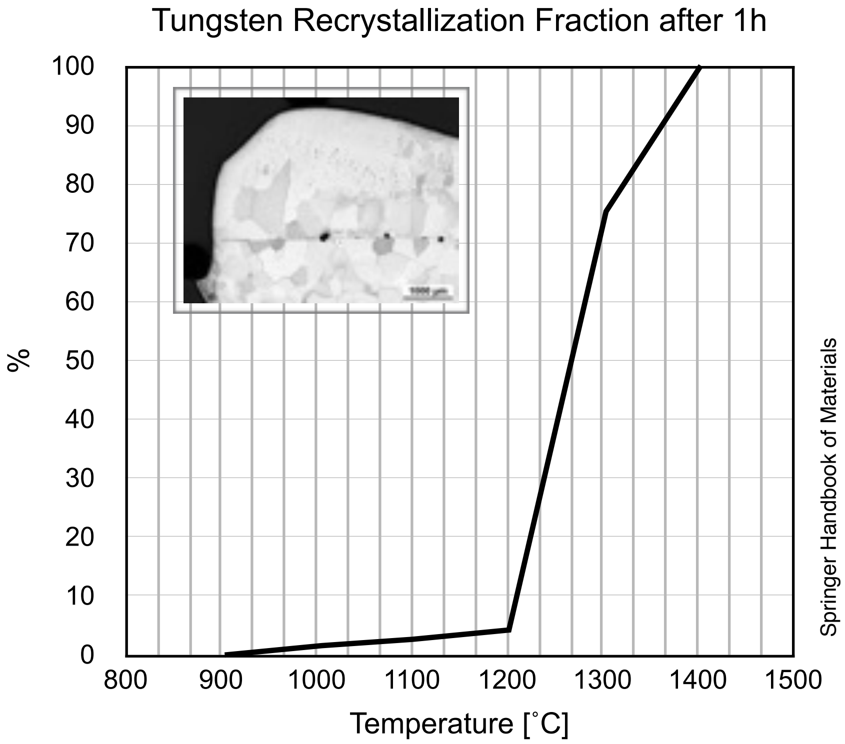
doi:10.1016/j.ijrmhm.2014.11.005

→ BDT controlled by **edge** disl. glide

Embrittlement



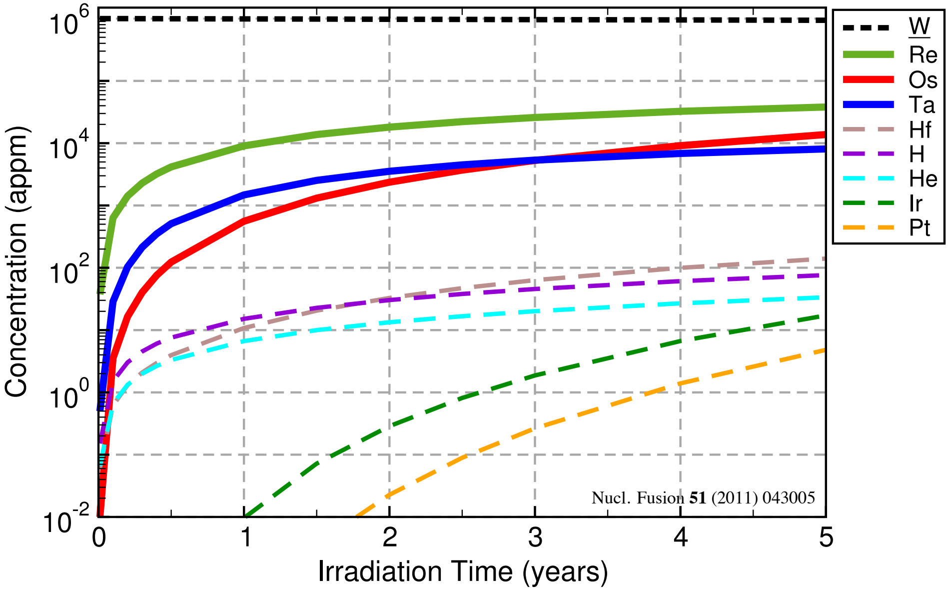
Bolt et al. Journal of Nuclear Materials, 2002, Part 1, 43 - 52



Springer Handbook of Materials

Materials operate 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

Transmutation

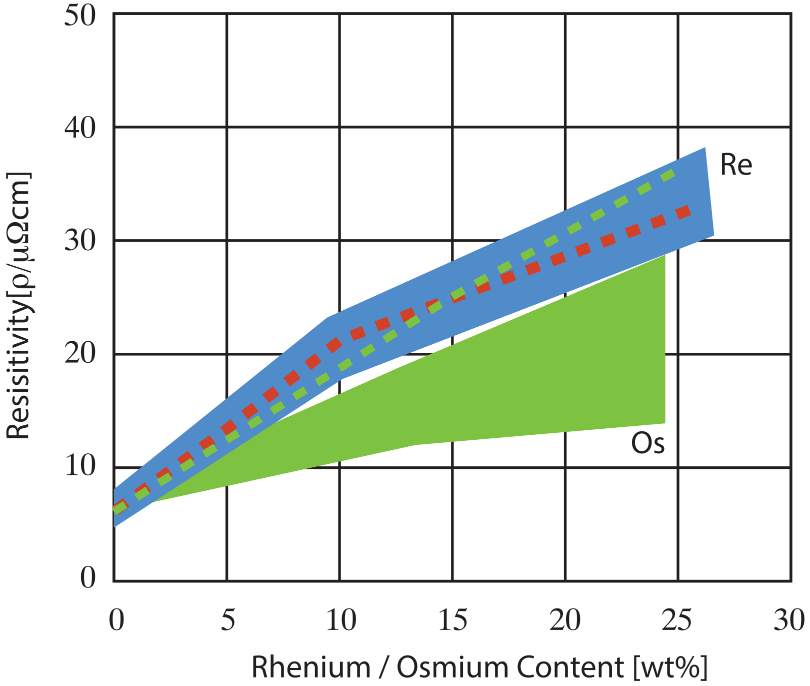


Nucl. Fusion **51** (2011) 043005

	5 years
W	94 %
Re	3.8 %
Os	1.38
He	<0.01
H	<0.01

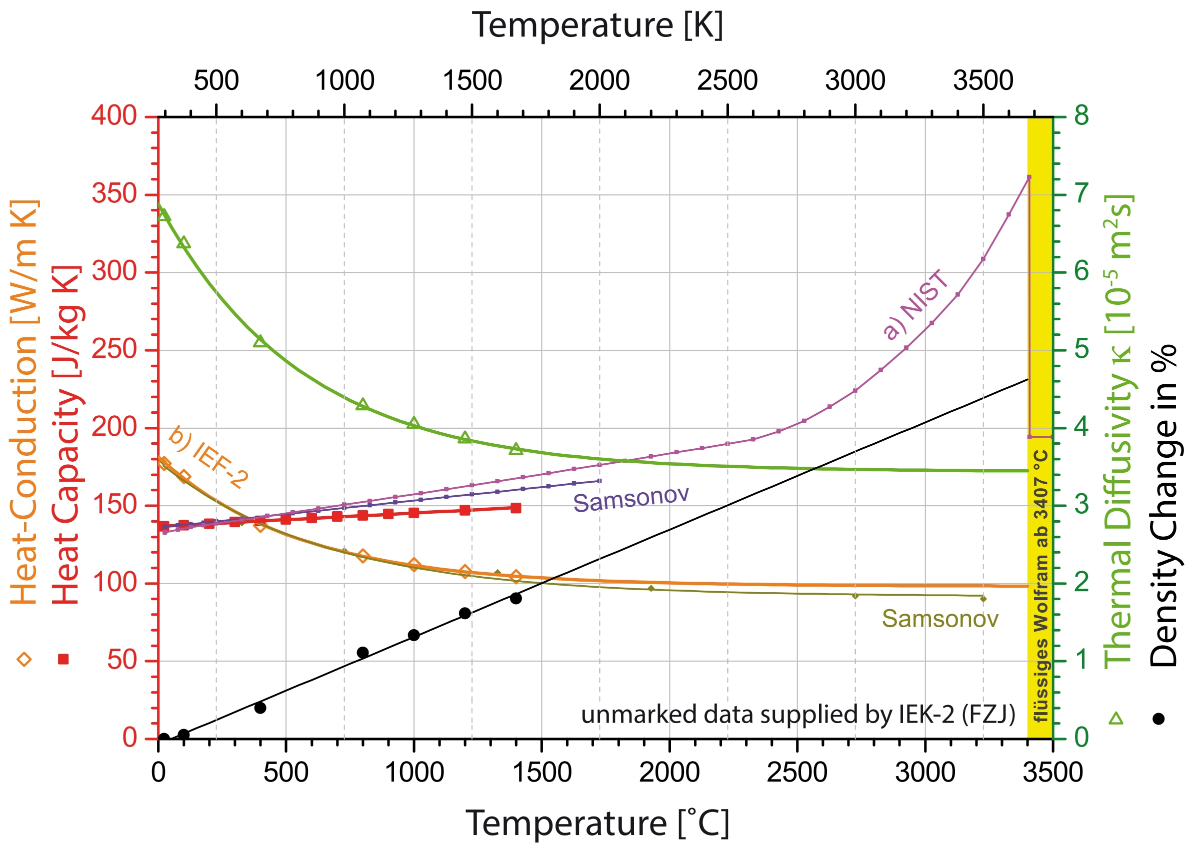
Material changes and transmutation can alter material properties and limits - test predefined „alloys“

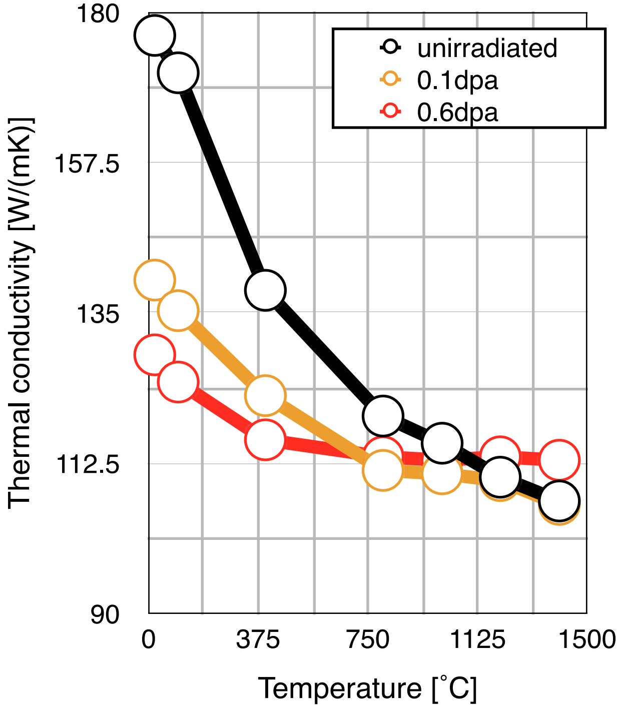
T. Tanno 2009



Thermal conductivity of the initially pure tungsten **decreases to 60%** of its initial value if rhenium content approaches 5%.

Thermal Properties





J.Linke TRANSACTIONS OF FUSION SCIENCE AND TECHNOLOGY VOL. 53 FEB. 2008

Heat Conductivity W/(m K)	
Copper	~390
Tungsten	~173
Molybdenum	~138
StainlessSteel	~17

Heat Capacity J/kg K	
Copper	~385
Tungsten	~134
Molybdenum	~250
StainlessSteel	~466

Thermal Expansion μm / mK	
Copper	~16.5
Tungsten	~4.5
Molybdenum	~4.8
StainlessSteel	~12

(at RT)

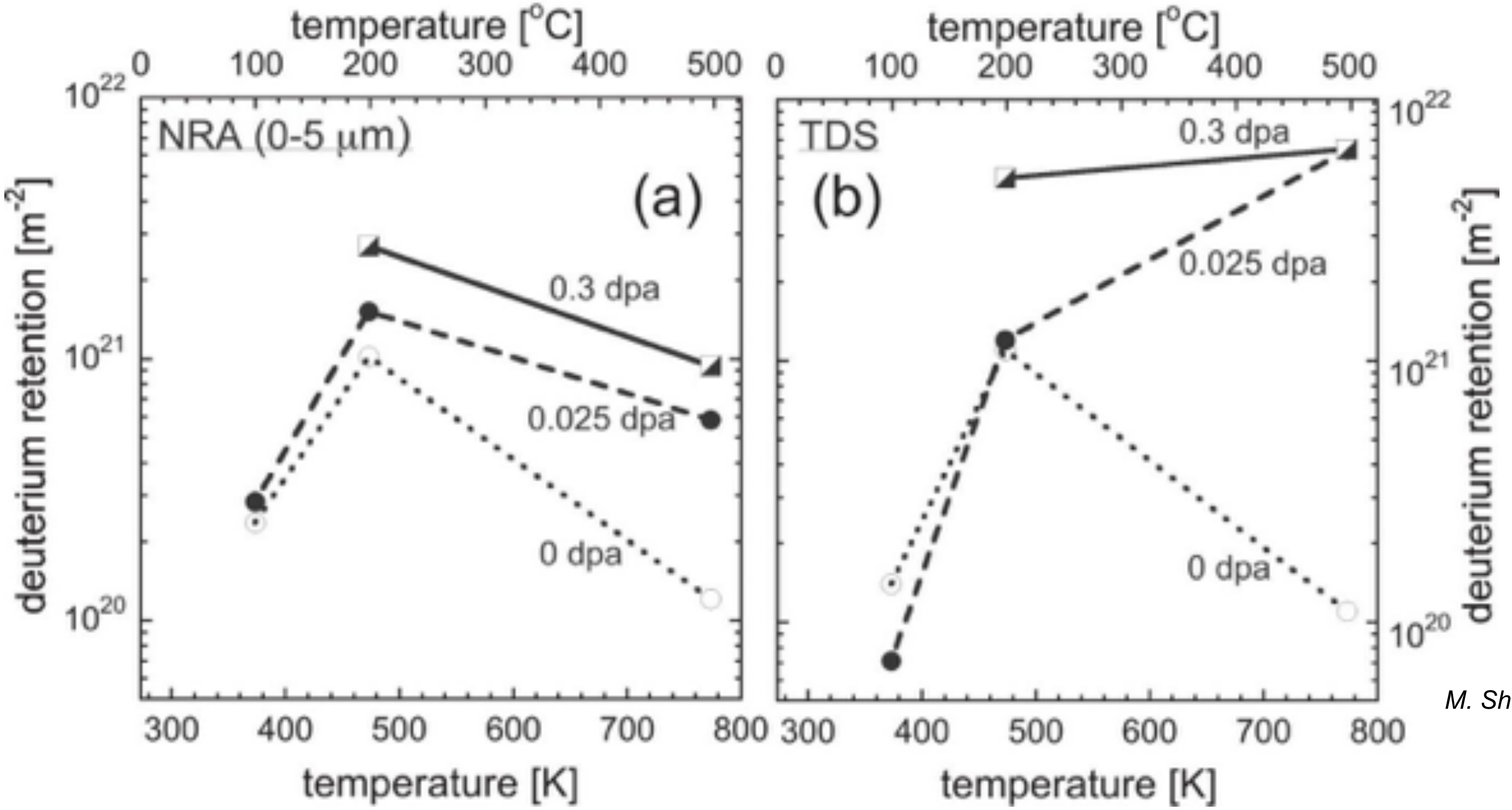
Retention

High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory 50 – 70 ˚C (>0.1 MeV)

- 4.4 × 10^{24}m^{-2} 33 h **0.025 dpa**
- 4.8 × 10^{24}m^{-2} 391 h **0.3 dpa**

Tritium Plasma Experiment, Idaho National Laboratory 100, 200 and 500 ˚C

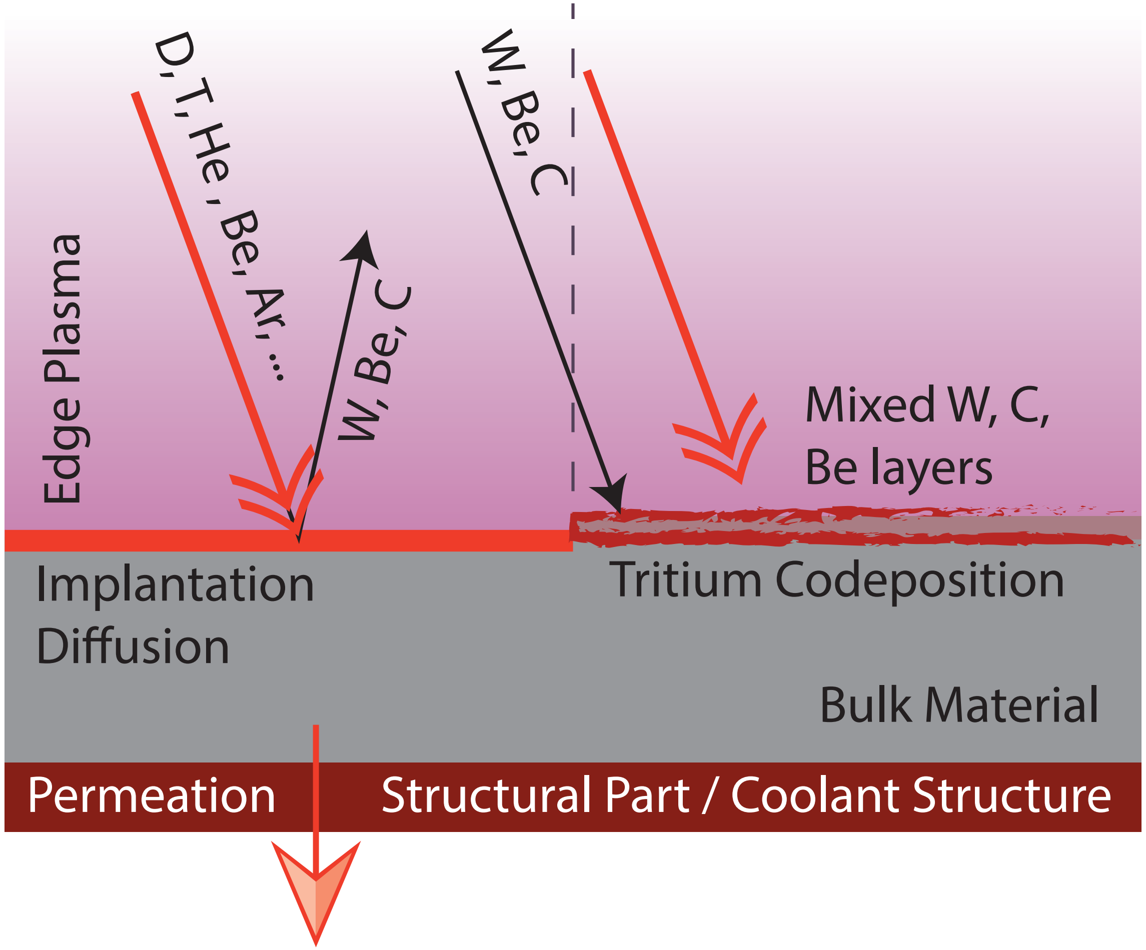
- 1 × 10^{26}m^{-2} (~100 eV)



M. Shimada et al 2015

Permeation

An issue for fuel retention and TBR



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

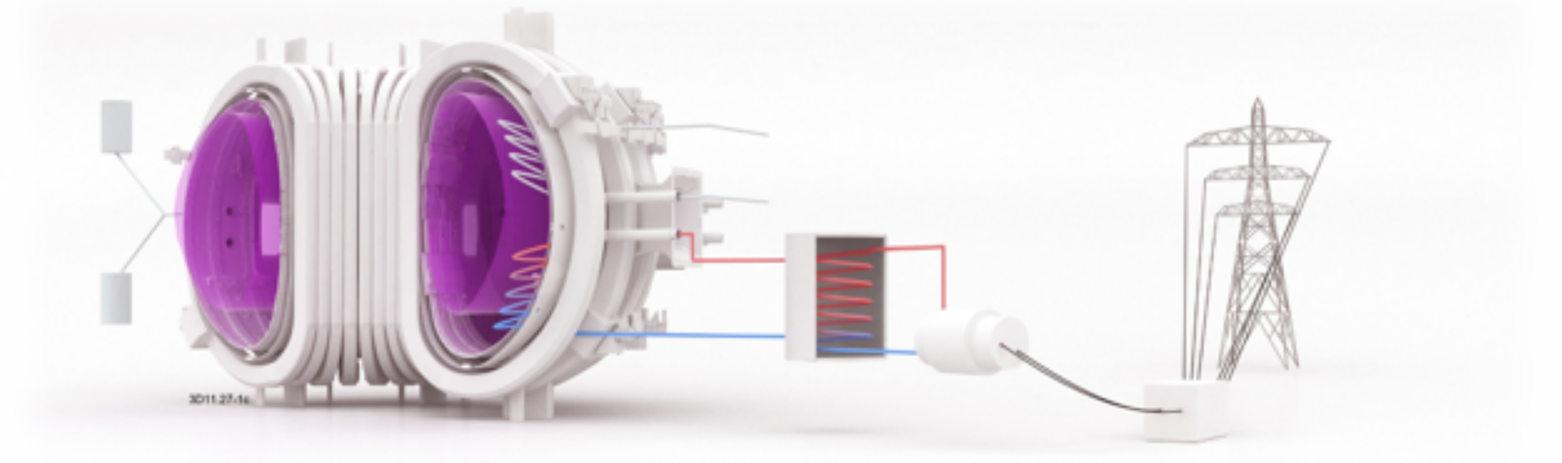
From the Material

Temperature Window
500°-1000°C

Neutron Exposure
e.g. Limits after 5 year exposure
Activation / Transmutation

Fuel Diffusion, Permeation
H-Embrittlement, Activation, TBR

Safety Issues & Licensing



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New Materials and PFCs

Close to the limit

We are faced with a multilayer approach incl. Armor, Fuel Barriers, Cooling Structures & Breeding elements and hence we have to consider:

- **A multitude of interacting materials** **<u>incl. new materials / material concepts</u>**
- **A generally new components concepts to circumvent classical definitions of limits**
  - Damage resilient materials
  - A much better definition what can be tolerate
  - Define lifetime with more parameters than erosion and cracking for PFCs

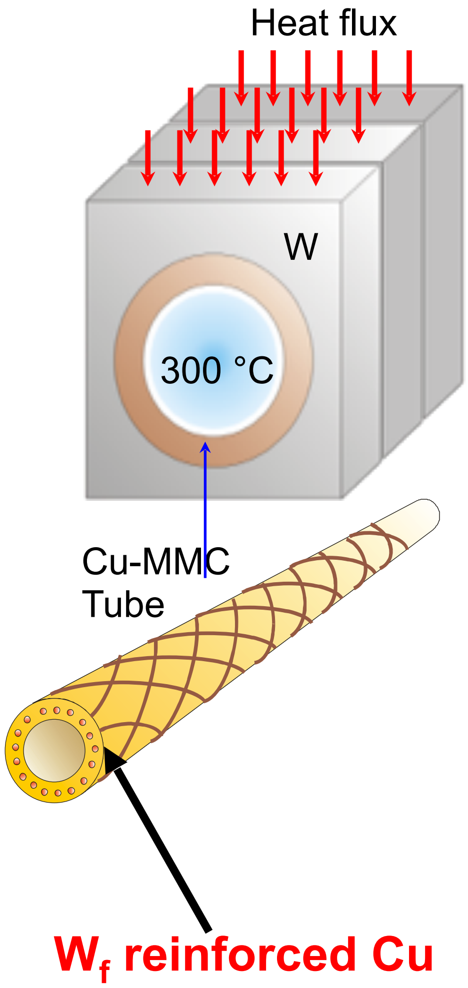
General Ideas

- Composite approaches to enhance material parameters and mitigate damage modes by utilizing mixed properties
- Self-healing or damage tolerant materials
- Smart materials / alloys which adapt to the operational scenario (Steady State / Transient / System Failure)
- Consider typical issues as benefits : *erosion -> leads to surface enrichment of alloying elements*
- **Study integrated components PFC -> Coolant -> Structural**

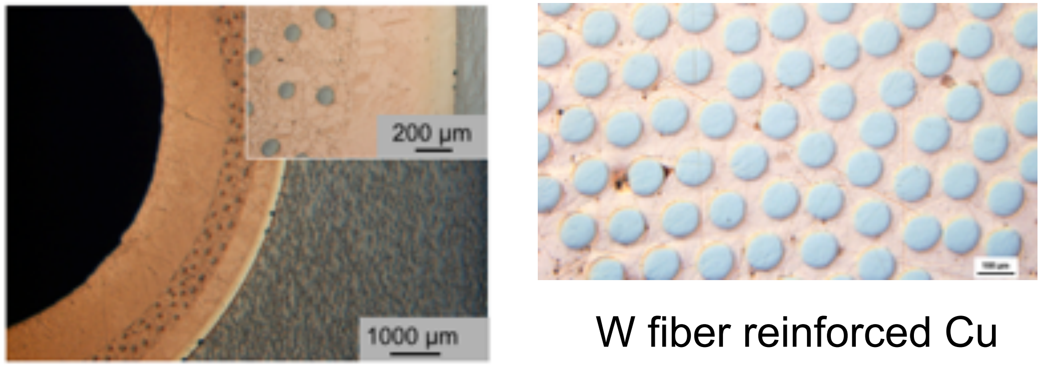
Divertor Components

Composites W/Cu

Improve thermal behavior in particular strength and expansion matching



Herrmann, You , Soebel



W fiber reinforced Cu

Fibers remained stably embedded up to 10.5 MW/m^2

Advanced Concept W/Cu FGM

The yield strength is superior to that of a W/Cu composite owing to the hardening effect of Cu1CrZr alloy.

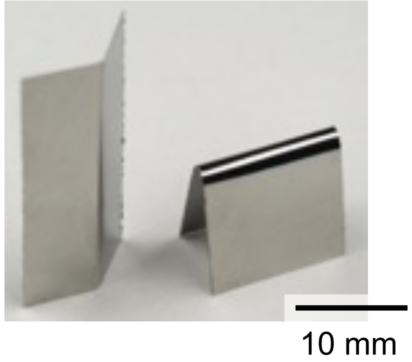
J-H . You et. al - IPP

W Laminates

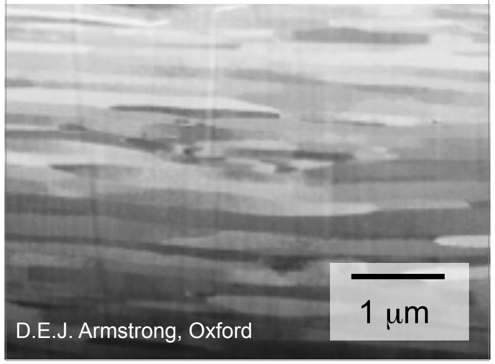
Can the ductility and the toughness of a UFG W foil be transferred to the bulk?

→ W-foil laminate materials

W-foil

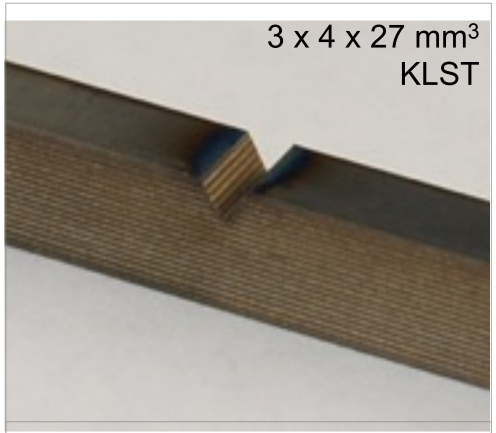


- Metal physics

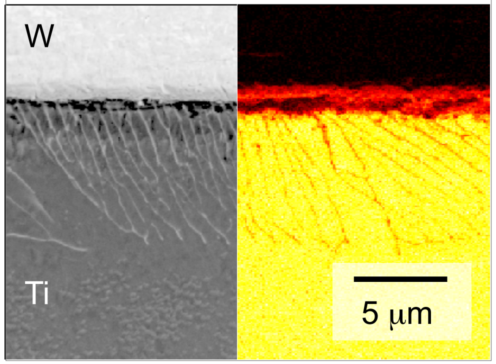


D.E.J. Armstrong, Oxford

W laminate plate

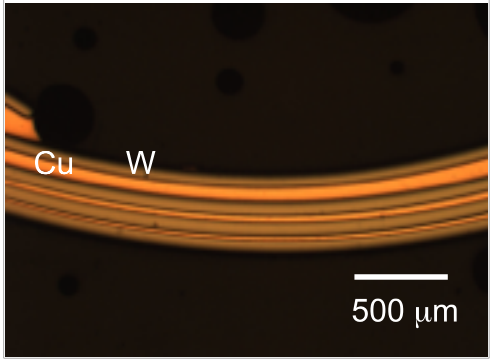


- Bonding and ageing

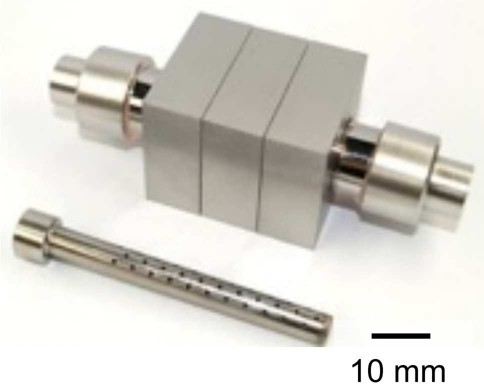


W laminate pipe

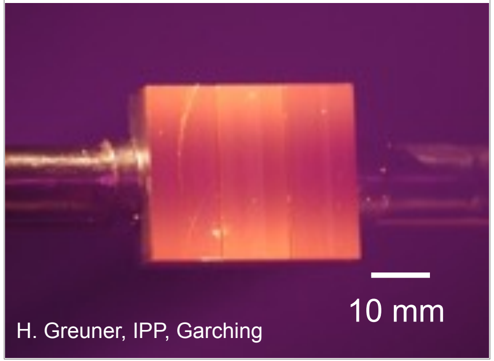
- Joining technology



Applications



- Fabrication and testing



H. Greuner, IPP, Garching

Jens Reiser KIT

W_f/W Composits

Fibre

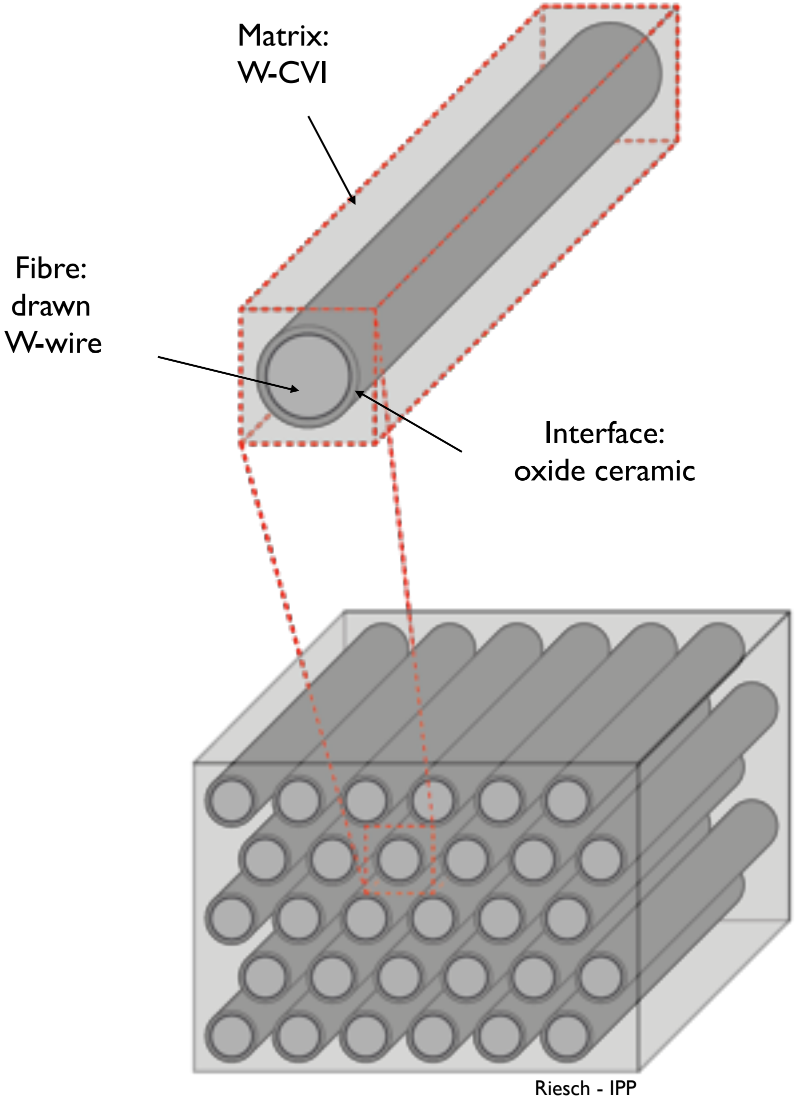
- Drawn tungsten wire (d = 150 µm) regular arrangement (100 µm)
- potentially K-doped

Interface

- Optimized adhesion + stability e.g. reactive magnetron sputtering
- Candidates ErOx, YtOx, ZrOx …

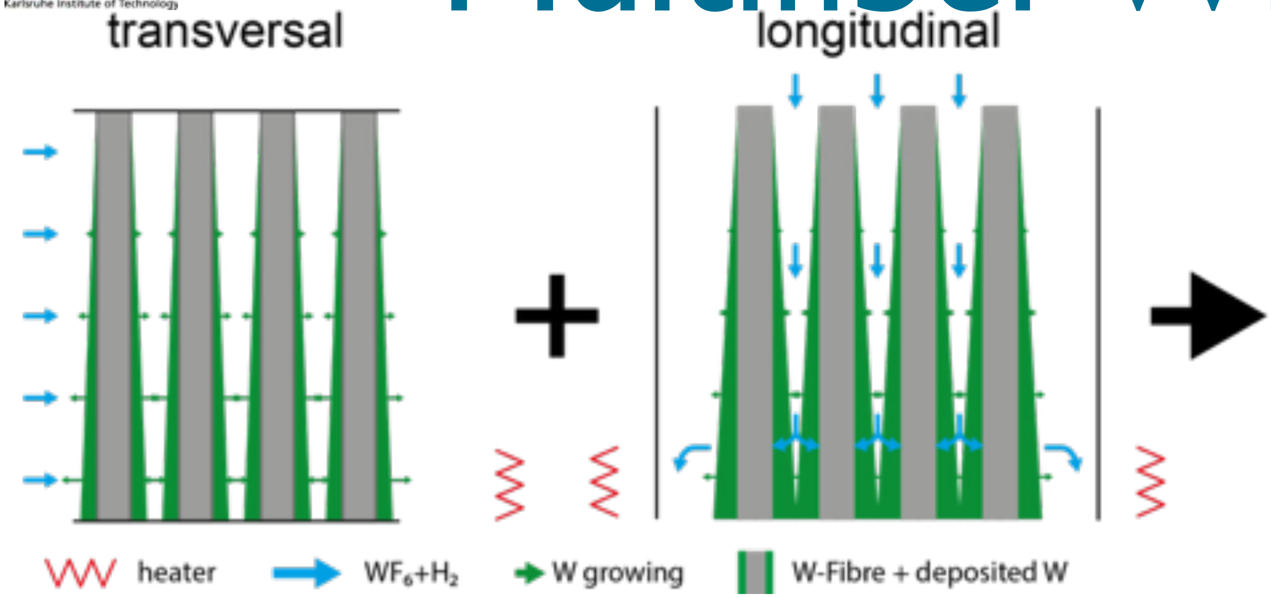
Matrix

- Common manufacturing techniques? (CVI , PM)

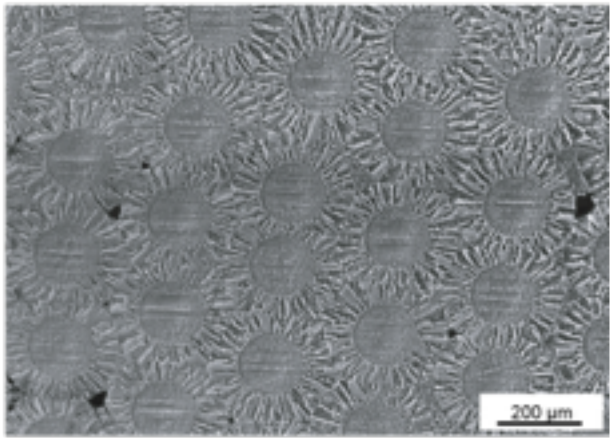


Talk by J.Riesch

Multifiber Wf/W



Density >95%

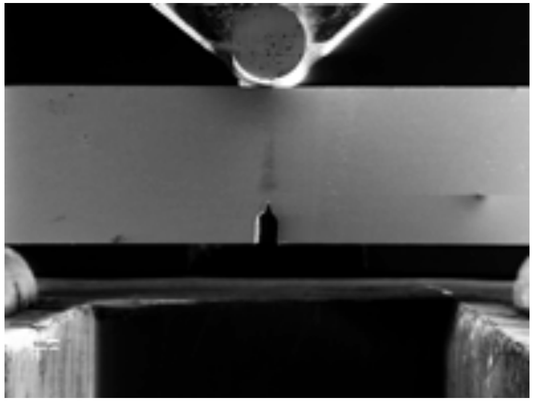


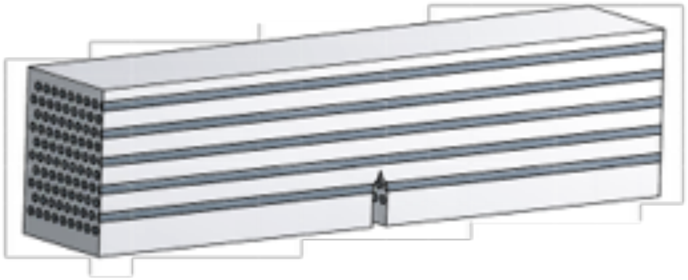
Multi-fibre Composite

→ W-CVI

→ 10 layers x 9 fibres

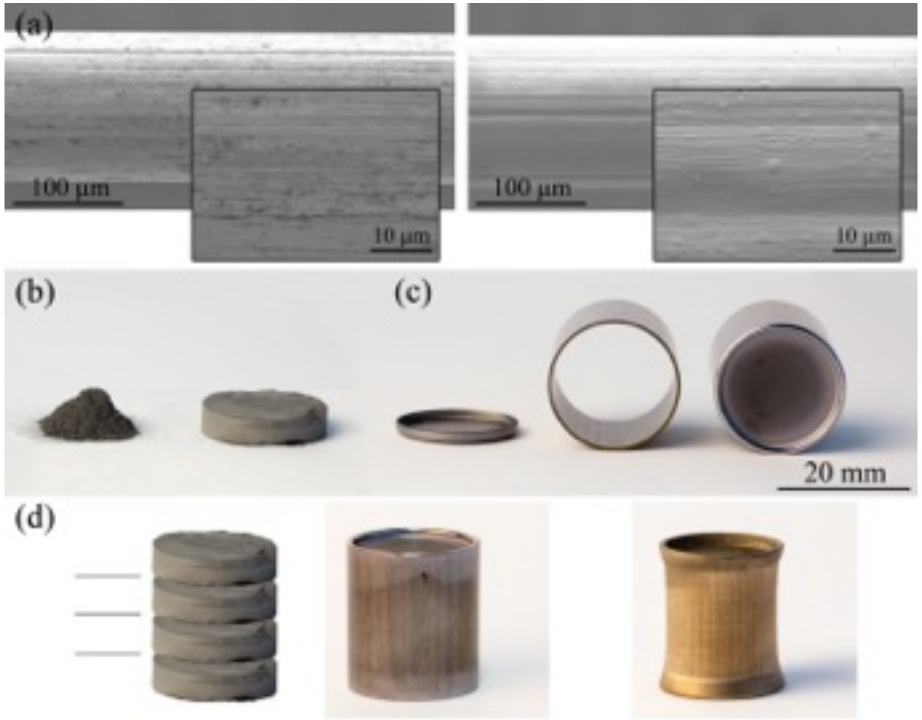
→ 2.2 mm x 3 mm



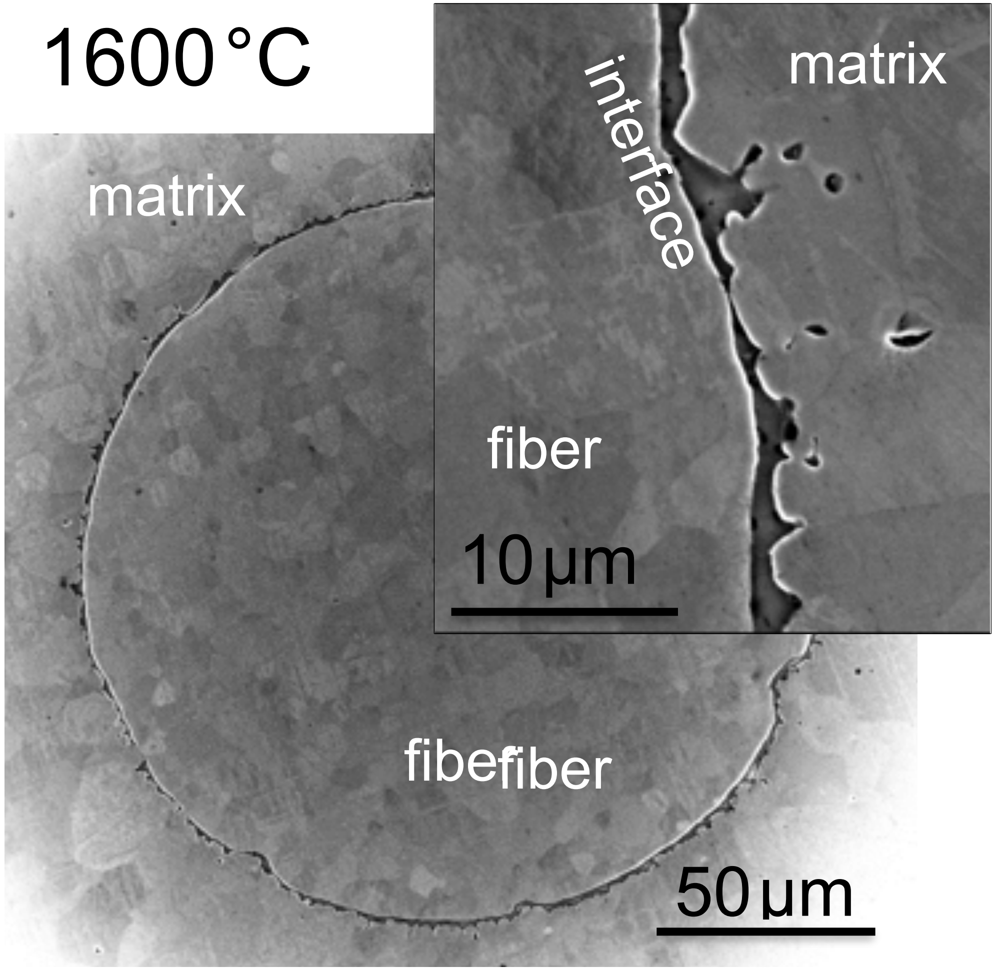


Mechanical toughening mechanism

HIP W_f/W Samples



1600 °C



Single Fiber Composite

Tungsten PIM

Powder Injection Molding

Mass production of components

- Mass production of near-net-shape parts
- Create new materials / Investigation of properties
- Brittle to ductile transition for pure PIM W at 200 °C (low strain rates)
- No porosities or cracks, high density (better than 99 % T.D.)
- No recrystallization – possible grain growth at very high temperatures only
- Fully anisotropic material properties
- High thermal shock resistance

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

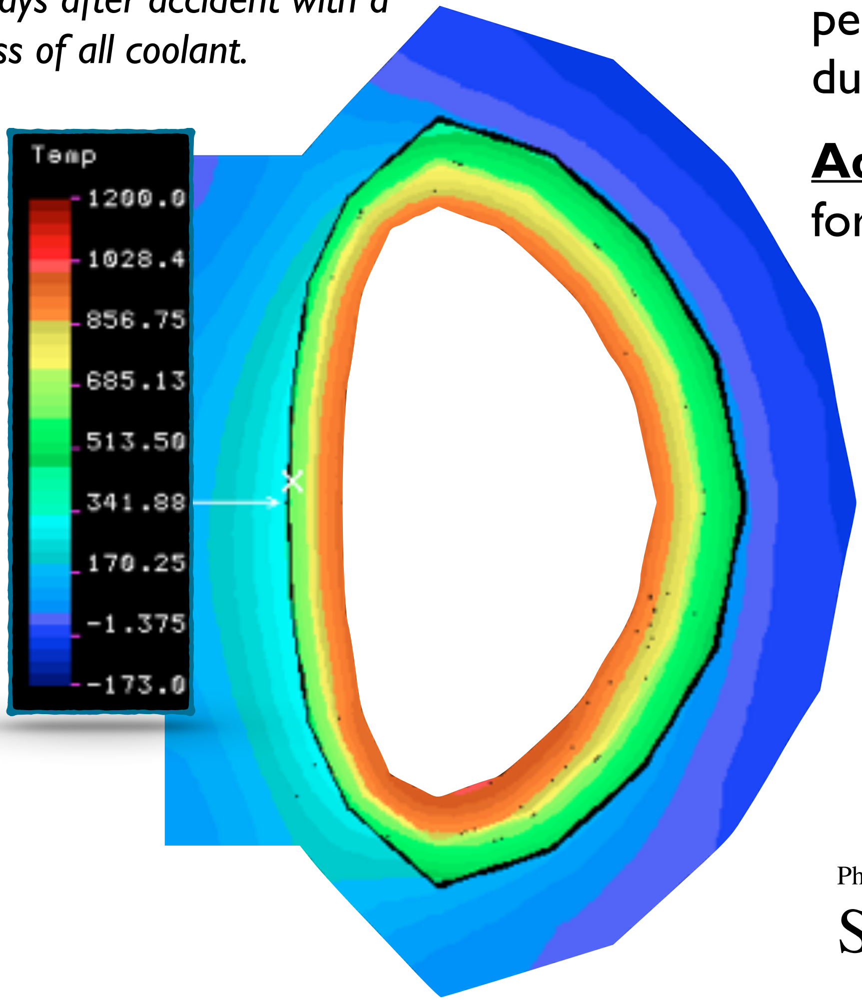
steffen.antusch@kit.edu

New alloys

Self Passivating Alloys

LOCA Scenario

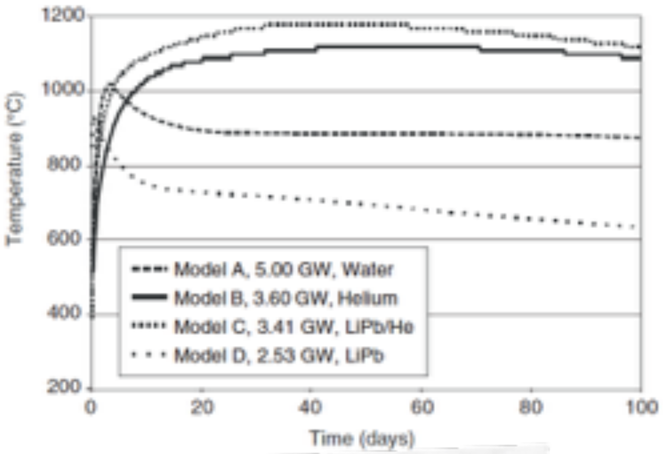
Temperature profile in PPCS Model A, 10 days after accident with a total loss of all coolant.



Final Report of the European Fusion Power Plant Conceptual Study, EFDA(05)-27/4.10, 2004
Maisonnier D et al 2005 A conceptual study of commercial fusion power plants Final Report of the European Fusion

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)



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

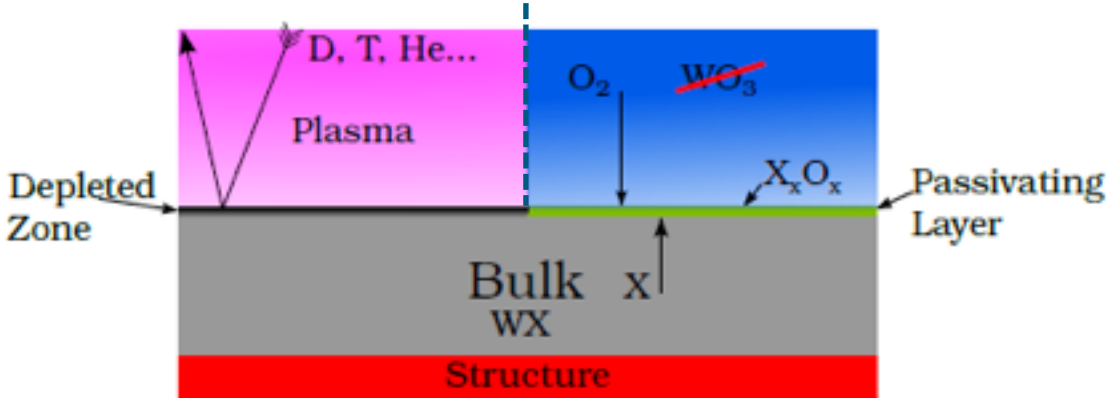
SMART Alloys

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

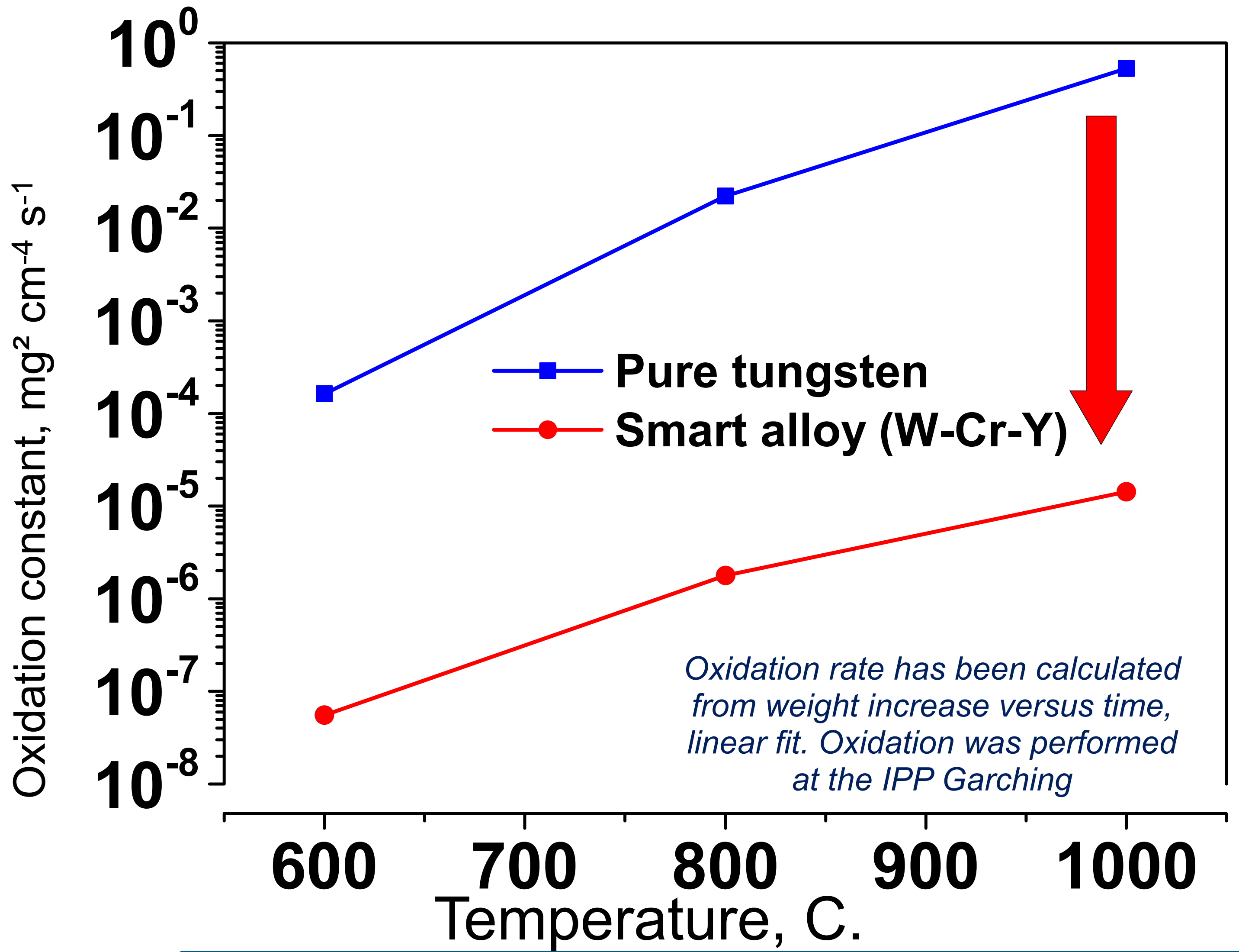
- ❖Tungsten-rich plasma-exposed surface due to preferential sputtering of alloying elements by plasma ions

Accidental conditions (>1000^{o}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

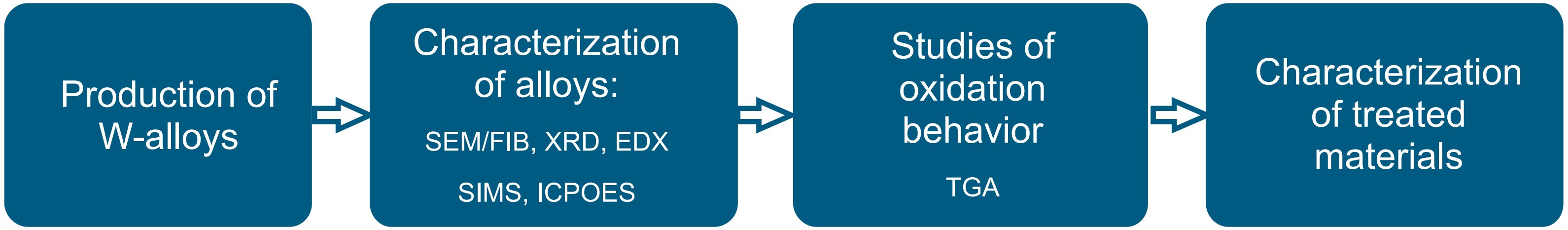
K_p (smart alloy W-Cr-Y) = $1.4*10^{-5}$

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

Manufacturing

Magnetron sputtering:
production of thin films

- Oxide formation, oxidation rates and phases
- Integrity of alloy
- Elemental composition incl. bulk materials



Production of W-alloys ⇨ Characterization of alloys: SEM/FIB, XRD, EDX SIMS, ICPOES ⇨ Studies of oxidation behavior TGA ⇨ Characterization of treated materials

Industry

Industry: production of bulk samples e.g. by HIPing

CEIT , Spain

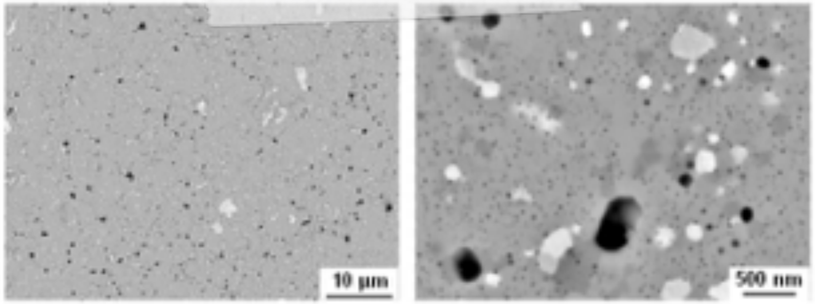


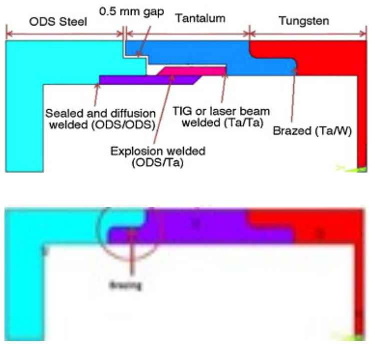
Figure 6. BSE-SEM images of a WCr10Si10 sample after HIP at 1350 °C.

P López-Ruiz et al , Phys. Scr. T145 (2011) 014018 (5pp)

Mitglied der Helmholtz-Gemeinschaft

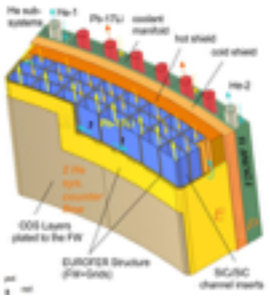
Functionally Graded Materials

W/steel-FGMs

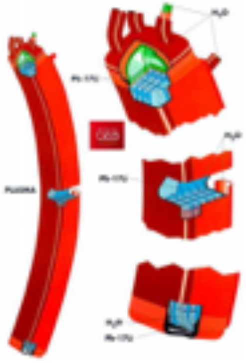


D. Navaei et al., Fusion Engineering and Design 2013

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

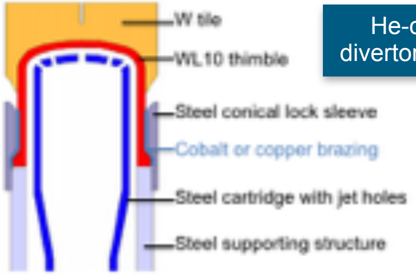


DCLL TBM (Dual-coolant lithium lead)

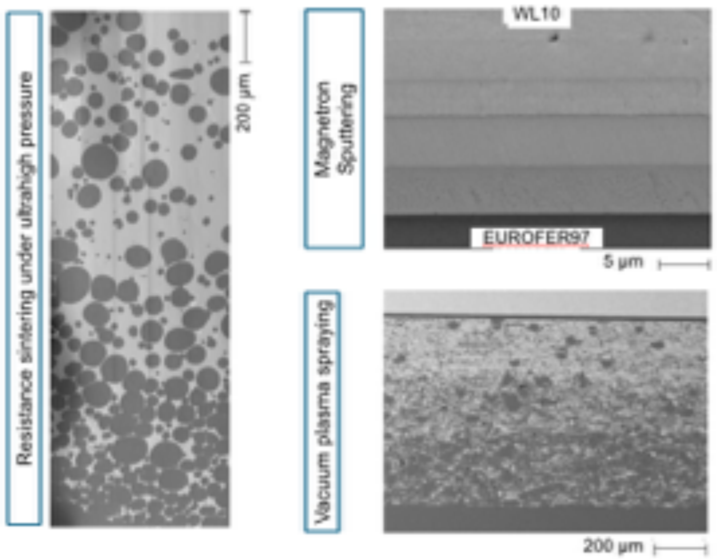


WCLL TBM (Water-cooled lithium lead)

He-cooled divertor concept



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



T. Weber et al., J. Nucl. Mat. 436 (2013)

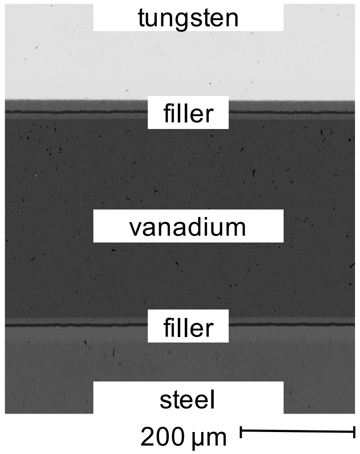
Problem - Thermal induced stresses

- tungsten: $\alpha = 4.4\cdot10^{-6}$/K
- steel: $\alpha = 12.0\cdot10^{-6}$/K

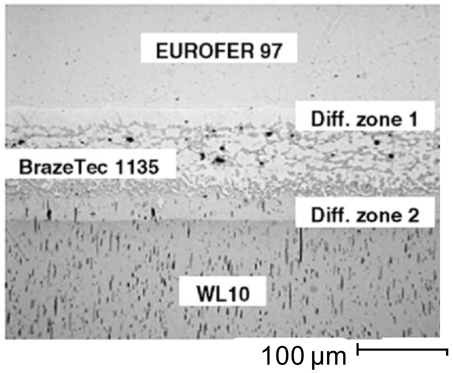
➡ FGM present a solution ✓

Avail. W/Steel Joints

Brazing with fillers

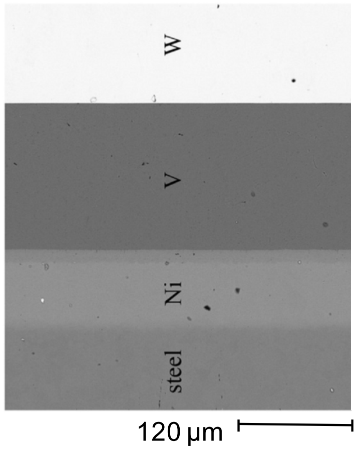


Y. Ma et al., Mat. Sc. Forum (2014)

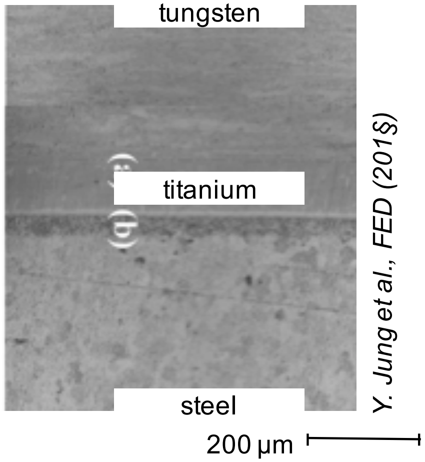


J. Aktaa et al., JNM (2007)

Diffusion bonding with Ni, V or Ti



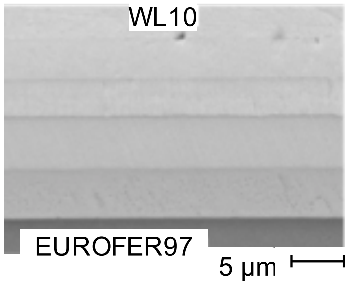
W. Liu et al., Mat. Charac. (2013)
W. Basuki et al., JNM (2013)



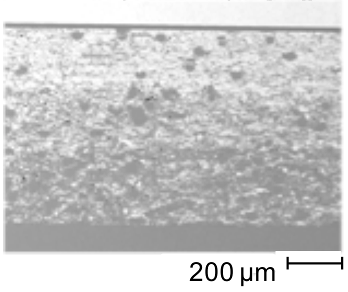
Y. Jung et al., FED (2015)
Z. Zhong et al., Gre. E.& T. (2009)

Functionally graded interlayers

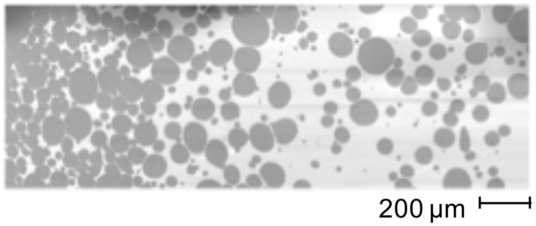
Magnetron sputtering



Vacuum plasma spraying



Resistance sintering under ultrahigh pressure

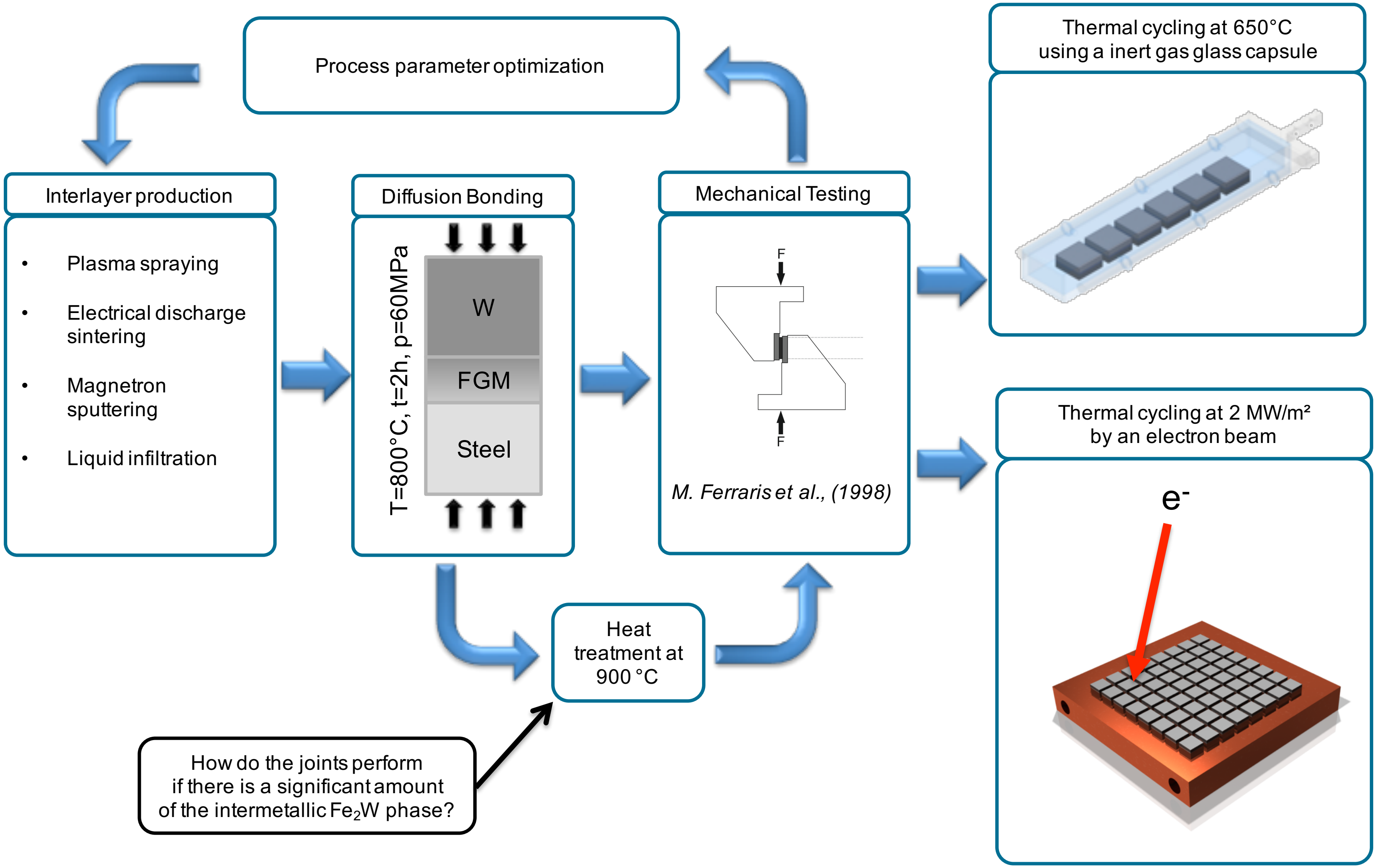


T. Weber et al., JNM, (2013)

The question is now, which thermal fatigue performance do they have?

And how do they compare and are FGMs really a solution?

Optimization & Benchmarking


Process parameter optimization

Interlayer production

- Plasma spraying
- Electrical discharge sintering
- Magnetron sputtering
- Liquid infiltration

Diffusion Bonding

Mechanical Testing

M. Ferraris et al., (1998)

Heat treatment at 900 °C

How do the joints perform if there is a significant amount of the intermetallic Fe_2W phase?

Thermal cycling at 650°C using a inert gas glass capsule

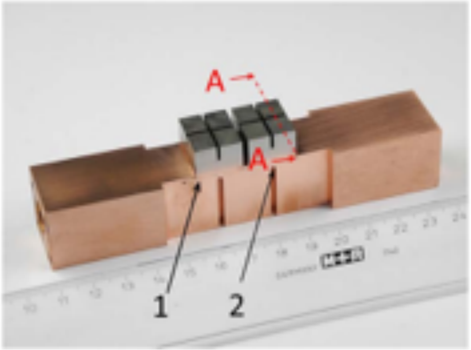
Thermal cycling at 2 MW/m² by an electron beam

Th. Weber IEK-2

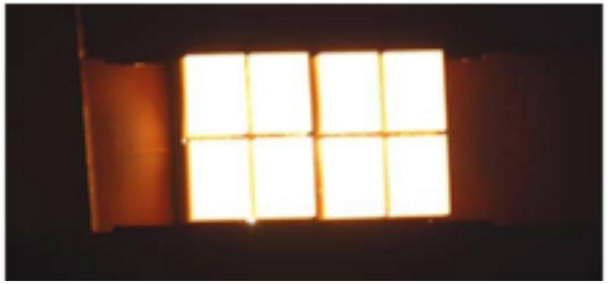
W/Cu FGMs

Melt infiltration

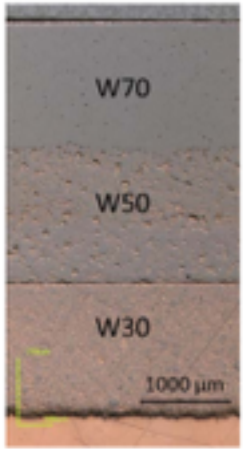
- HHF testing of W/CuCrZr multilayer composites performed in 2014:
- Fabrication of tri-layer-graded W/CuCrZr composites
- 3 mock-ups were manufactured and successfully tested up to 20 MW/m^2



Mock-up with W/CuCrZr multilayer composite



During HHF test (15 MW/m^2 pulse)



Cross section of the composite after test (20 MW/m^2)

J.-H. You, A. Brendel Journal of Nuclear Materials 438 (2013) 1–6
&SOFT 2014

Mitglied der Helmholtz-Gemeinschaft

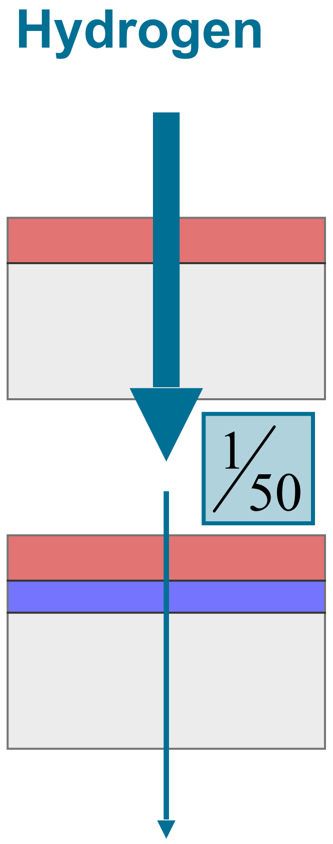
Tritium Management

Permeation Barriers

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

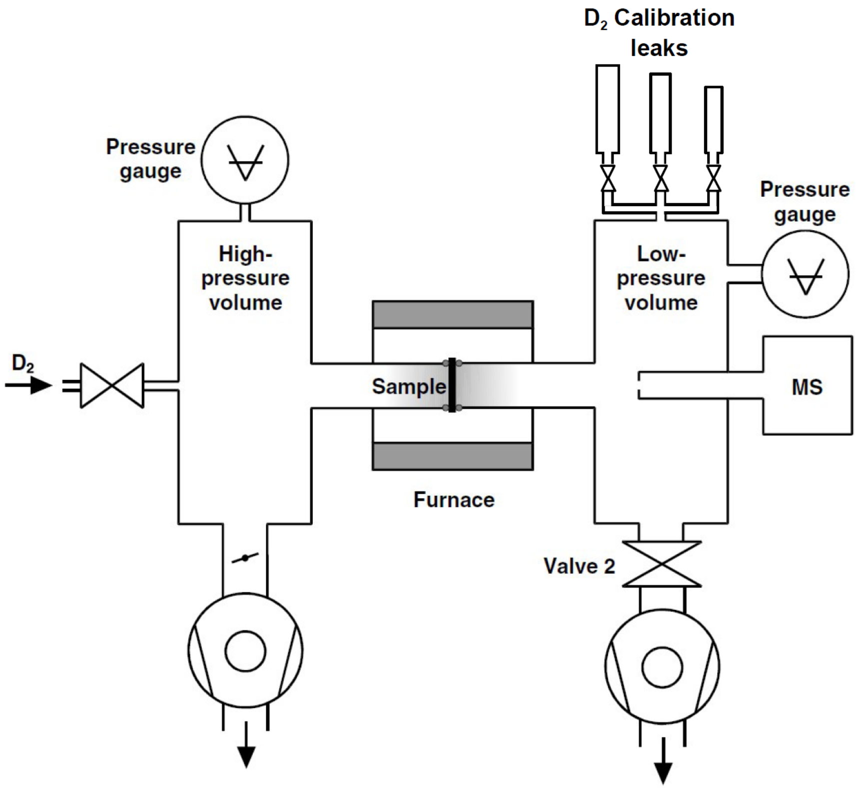
⇒ **Reduction of permeation by a factor 50…100 necessary**

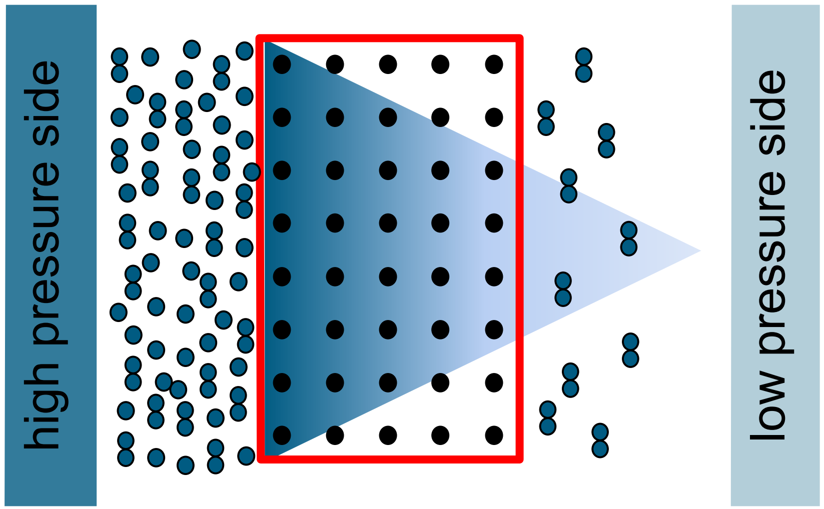


Integration of T-Barriers into components is required for a viable DEMO PFU

Gas Driven Permeation

Levchuk *et al.*, *J. Nucl. Mater.* **328** (2004)



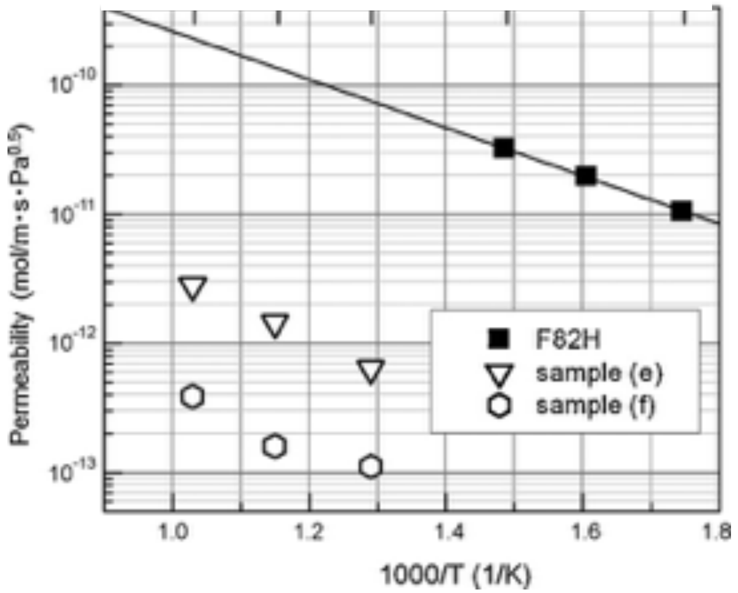


Features:

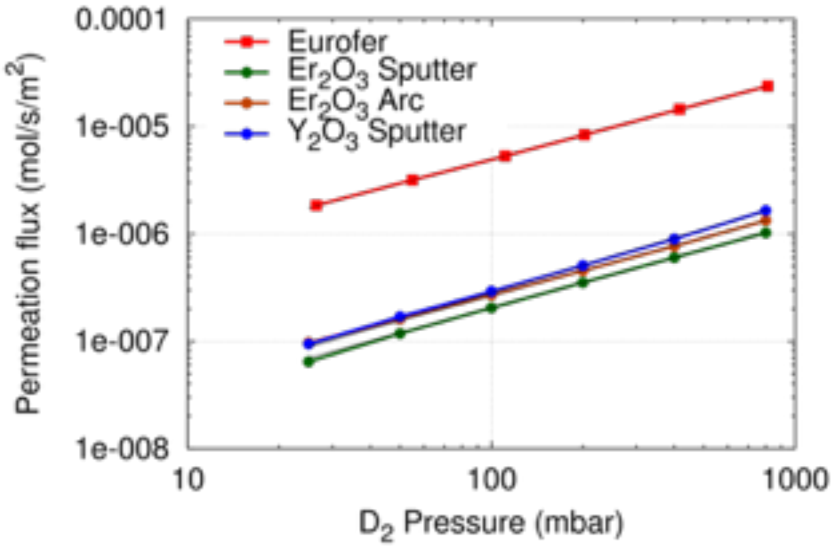
- → base pressure: ~10^{-9} mbar
- → heatable sample holder up to 600°C
- → D_2 pressure and temperature dependent measurements
- → calibration of mass spectrometer signal by D_2 calibration leaks

Experimental Data

Er_2O_3 by metal-organic decomposition



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



- Several Approaches are used for applying coatings especially to steel components (Breeding Blankets): Arc deposition, chemical routes, Magnetron Sputtering etc.
- Hydrogen permeation is drastically reduced by applying erbia, alumina or yttria

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

- Erbia and Alumina may cause issues with activation

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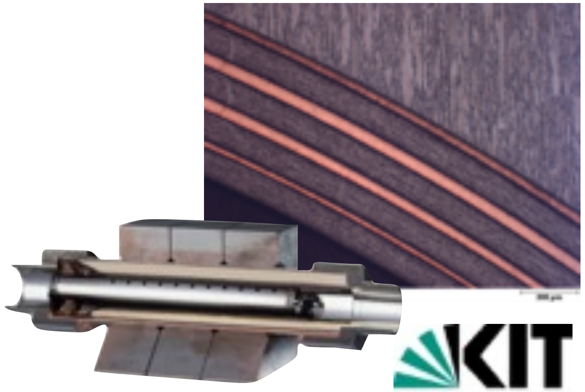
Building a component

Combined approach

DEMO I Div.

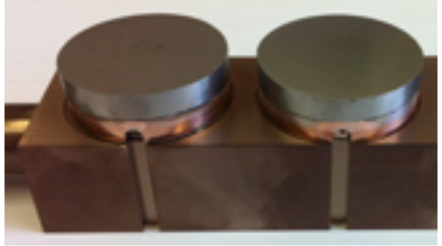
W/Cu laminate
Brazing



Cu felt thermal break
Brazing

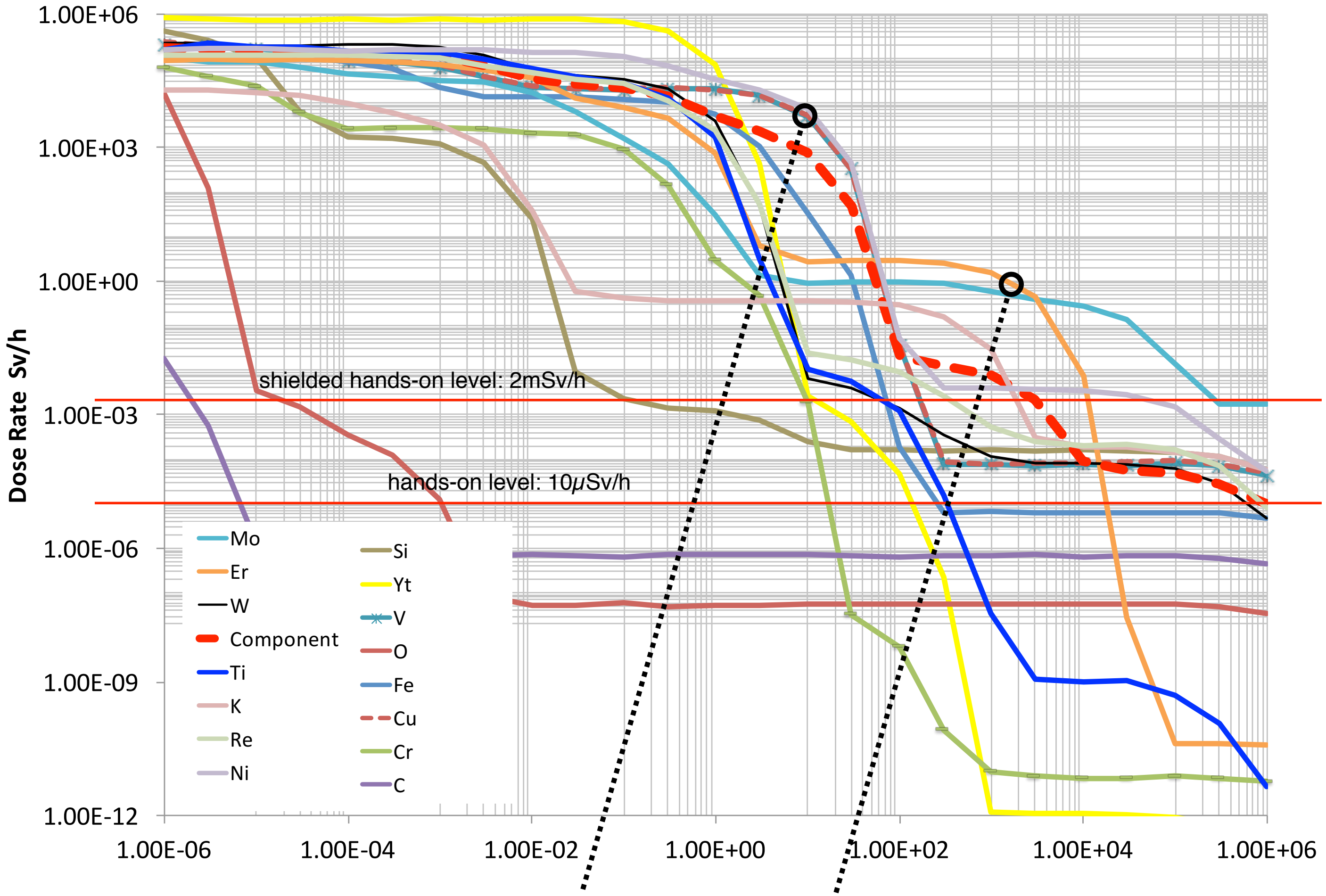
Tom Barrett

W/Cu FGM
Spark plasma sintering



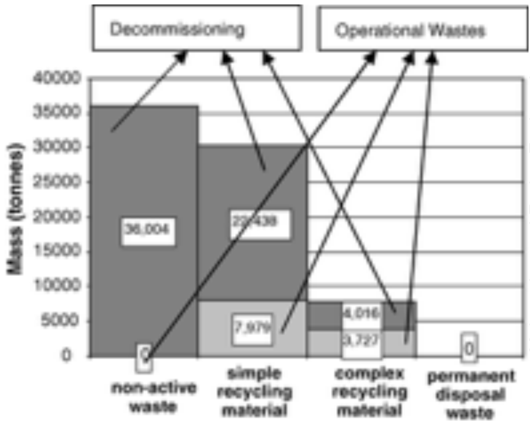
Material supplied .J.H You WPDIV , IPP
Material supplied .Reiser KIT

Activation



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



Maisonnier et al Fusion Engineering and Design 81 (2006) 1123

Conclusion & Outlook

For a Fusion Reactor

- Lifetime of PFCs and Joints due to erosion / creep / fatigue / embrittlement
- Thermal properties of composites / 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)
- Maintainability - Recycling of used materials / components e.g. minimize e.g. activation
- Large scale production of advanced materials / components

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 next Steps

- **The aim is a component - HHF/ PWI testable <5 years**
  - **Test Samples are needed on short timescales to test PWI - & Exhaust relevant parameters, e.g. sputtering, heat conduction)**
  - *How do we integrate our efforts between the component relevant materials?*
  - *We consider also ‚forbidden' materials such as Cu, Al, Er e.g. Y*
  - *We need neutron effects on components & materials*

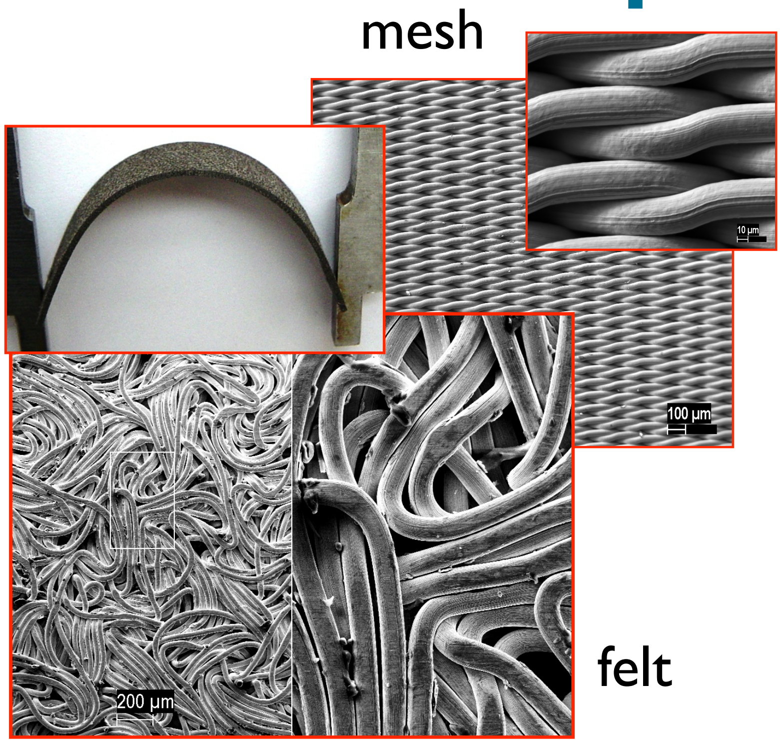
  - **PWI on reactor components**
  - **Test in tokamaks e.g. AUG div. manipulator / JET / WEST**

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.

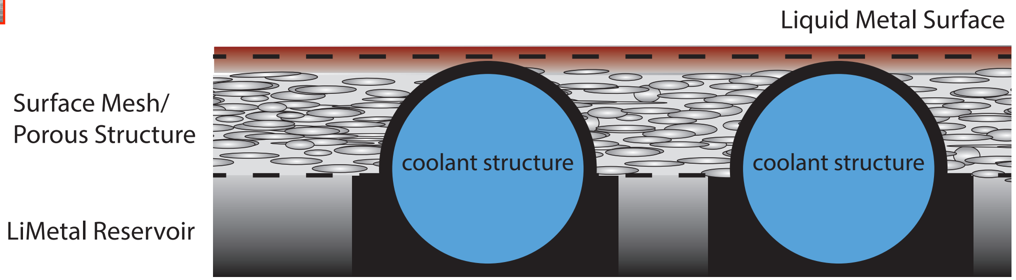
Add Ons

`

Liquid Metals



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

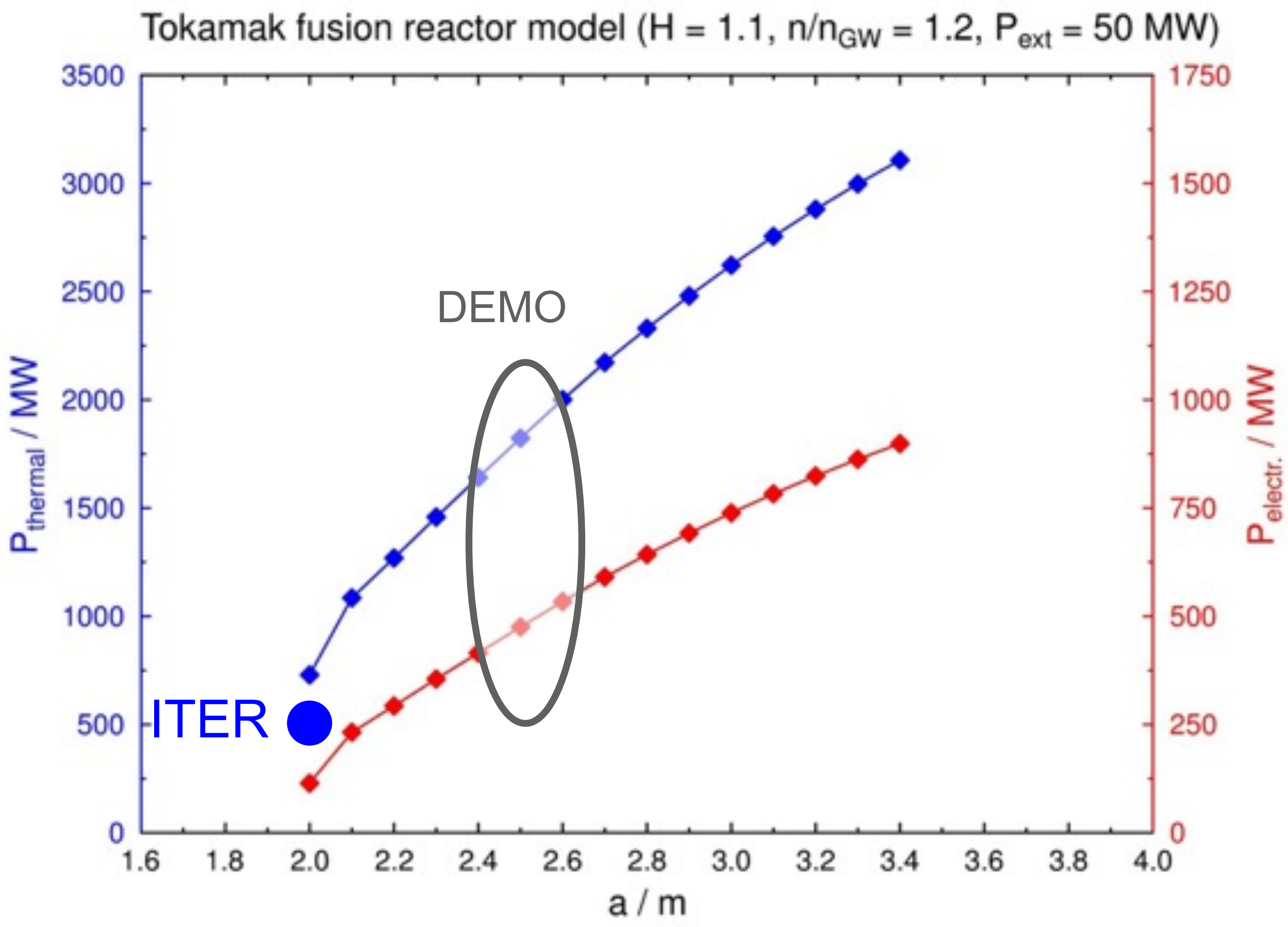


stabilize the liquid surface and replenish the liquid metal by capillary action

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

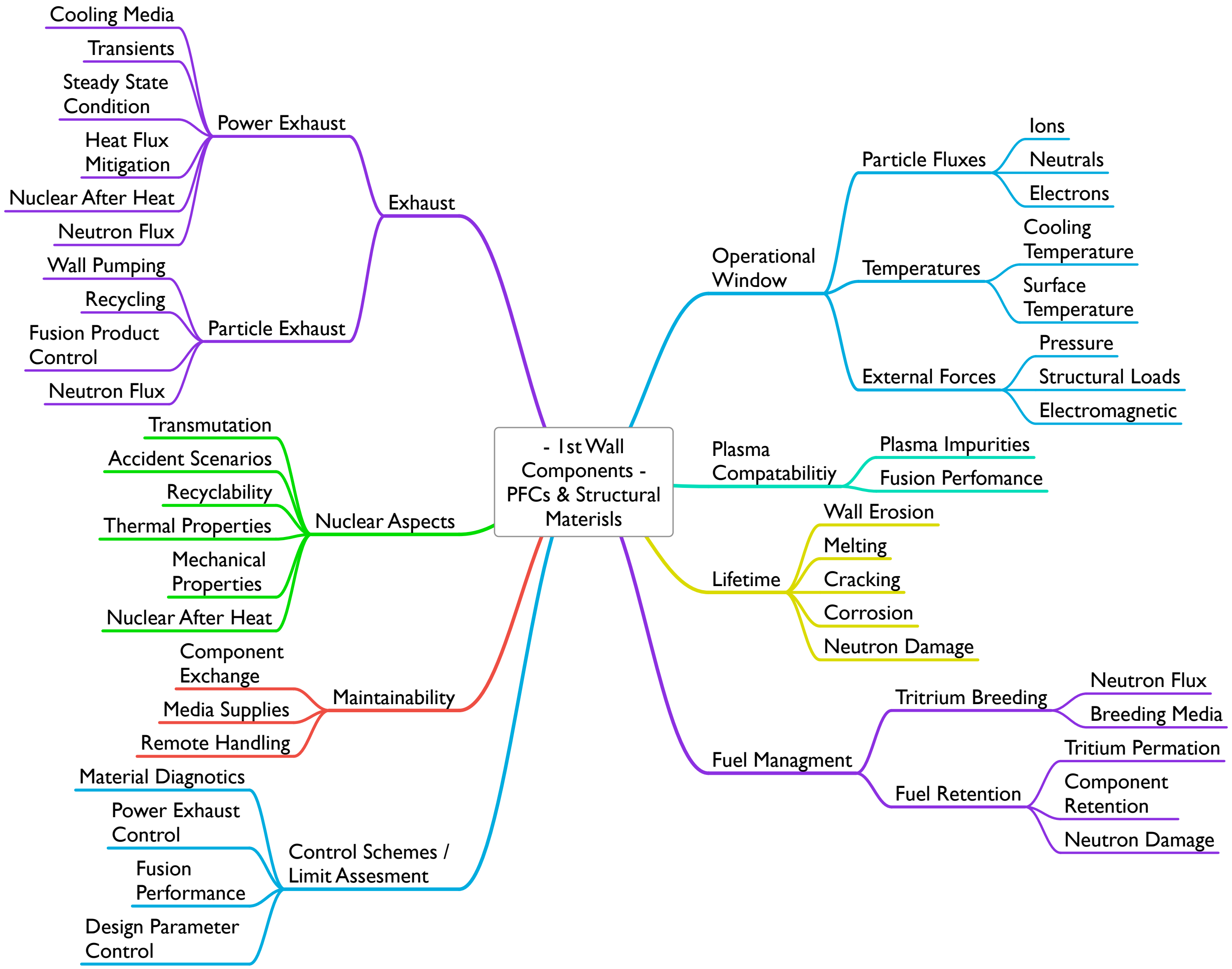
Also here we do need new ideas

Minimum Size



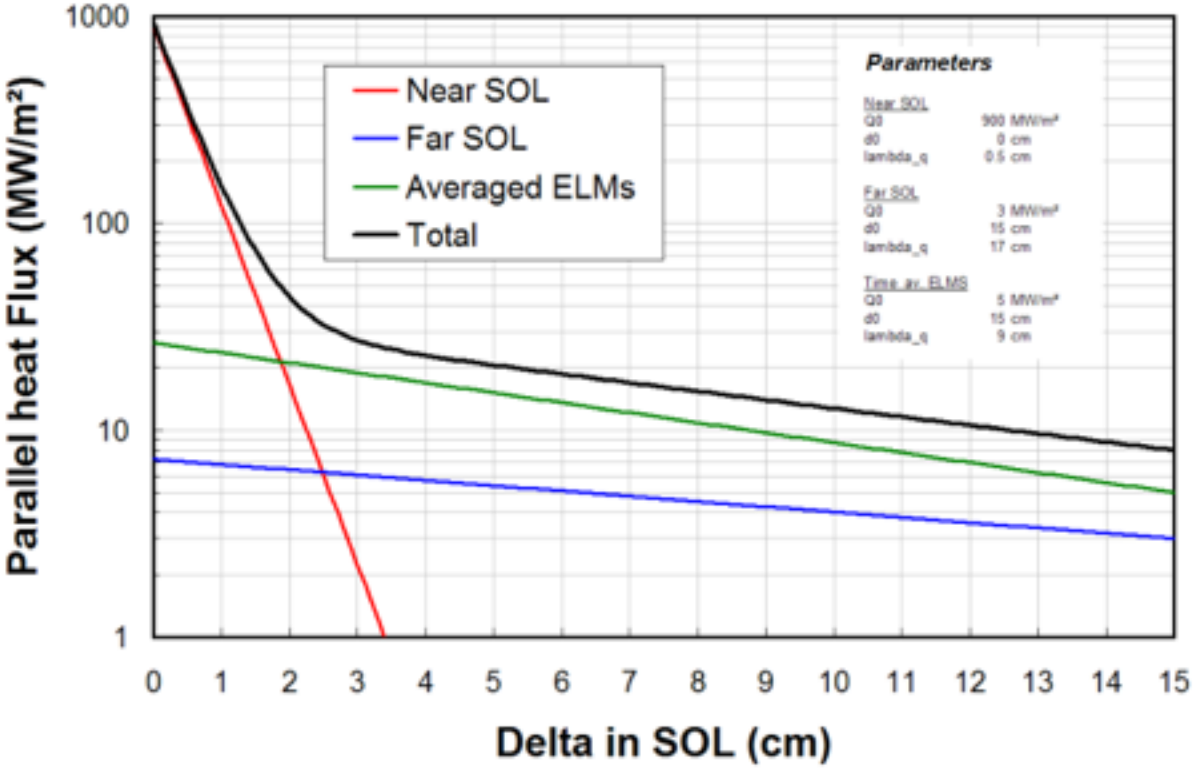
Economic electricity production (500 MW_{el}) in a tokamak requires a plasma diameter of 5-6 m

Materials



- 1st Wall Components - PFCs & Structural Materisls
  - Exhaust
    - Power Exhaust
      - Cooling Media
      - Transients
      - Steady State Condition
      - Heat Flux Mitigation
      - Nuclear After Heat
      - Neutron Flux
    - Particle Exhaust
      - Wall Pumping
      - Recycling
      - Fusion Product Control
      - Neutron Flux
  - Nuclear Aspects
    - Transmutation
    - Accident Scenarios
    - Recyclability
    - Thermal Properties
    - Mechanical Properties
    - Nuclear After Heat
  - Maintainability
    - Component Exchange
    - Media Supplies
    - Remote Handling
  - Control Schemes / Limit Assesment
    - Material Diagnotics
    - Power Exhaust Control
    - Fusion Performance
    - Design Parameter Control
  - Operational Window
    - Particle Fluxes
      - Ions
      - Neutrals
      - Electrons
    - Temperatures
      - Cooling Temperature
      - Surface Temperature
    - External Forces
      - Pressure
      - Structural Loads
      - Electromagnetic
  - Plasma Compatabilitiy
    - Plasma Impurities
    - Fusion Perfomance
  - Lifetime
    - Wall Erosion
    - Melting
    - Cracking
    - Corrosion
    - Neutron Damage
  - Fuel Managment
    - Tritrium Breeding
      - Neutron Flux
      - Breeding Media
    - Fuel Retention
      - Tritium Permation
      - Component Retention
      - Neutron Damage

Blanket Specifications



- The plasma SOL wets the FW with variable intensity during the different phases of the plasma discharge.
- The plasma contact with the wall is mainly toroidal, which means that only one or two rows of FW panels have a high load for a given situation

R. Mitteau et al., The combined effects of magnetic asymmetry, assembly and manufacturing tolerances on the plasma heat load to the ITER first wall, PSI 2014.
Boccaccini - EFPW , 1-3 December 2014 - Split

ELMs

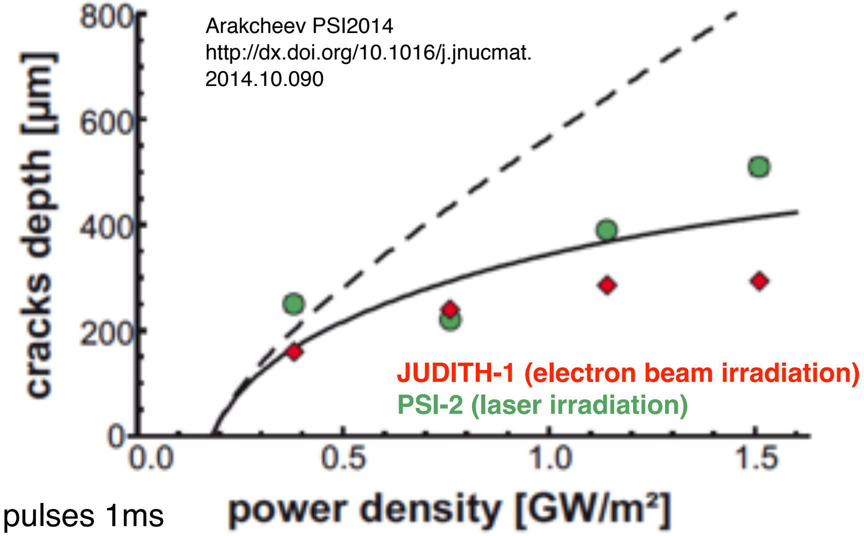
KIT-SR-7661 (2015)

	JET[1]	ITER[2]	DEMO1 divertor / FW unmitigated ELMS [3]	DEMO1 divertor mitigated ELMs
Energy loss per ELM[MJ]	0.00045	20	80-100/ 10-15	3
Frequency	10	2	0.8/0.8	26
Deposition time [ms]	0.1	1	1.2 / 0.6	1.2
deposition area [m^2]	0.43	0.68	2.75/90	2.75/90
Peak energy deposition [MJ/m^2]	0.01	0.5	15-20 / 0.2	0.6

[1] ITER Physics Basis, Chapter 9: ITER contributions for Demo plasma development.
[2] D. Maisonnier, D. Campbell, I. Cook, L. Di Pace, L. Giancarli, J. Hayward.,
"Power plant conceptual studies in Europe", Nucl.Fusion 47 (2007) 1524
[3] DEMO Design Summary, EFDA_D_2L2F7V v1.0

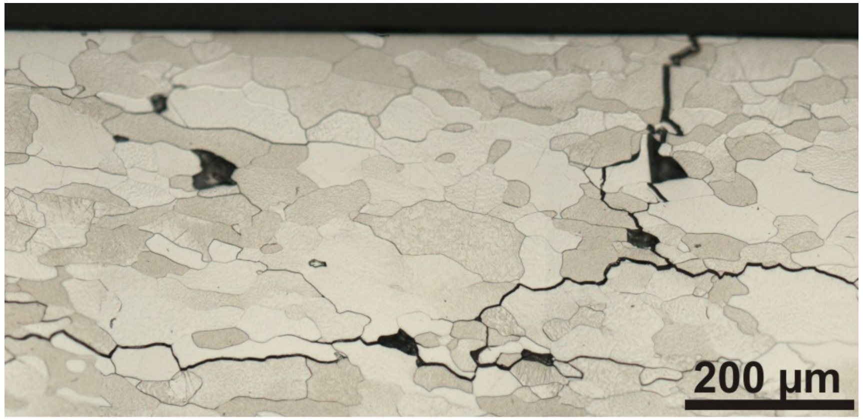
Melting for DEMO is difficult to avoid during transients

Example Cracking



Arakcheev PSI2014
http://dx.doi.org/10.1016/j.jnucmat.2014.10.090

100 pulses 1ms



Develop an understanding on damage modes of the 1st Wall and Divertor

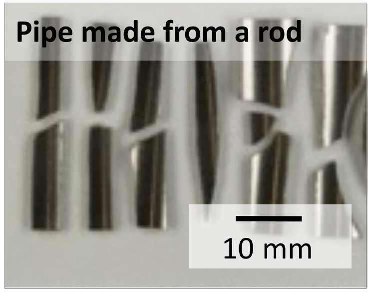
- Heat Load Limits are insufficient
- Develop Criteria for safe operation of cracked materials
- **Does no damage mean safe operation??**

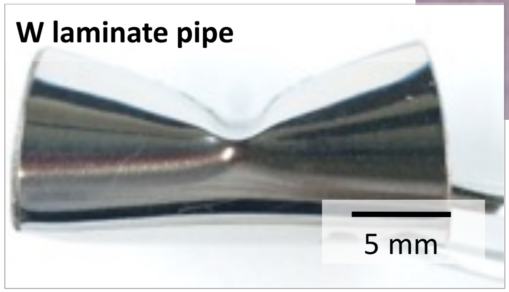
W laminate pipes

- Characterized by
  - Charpy impact tests
  - Burst test
  - HHF tests

Burst test, RT, 1000 bar (in cooperation with PLANSEE SE, T. Huber, A. Zabernig)

Charpy impact test at 300°C



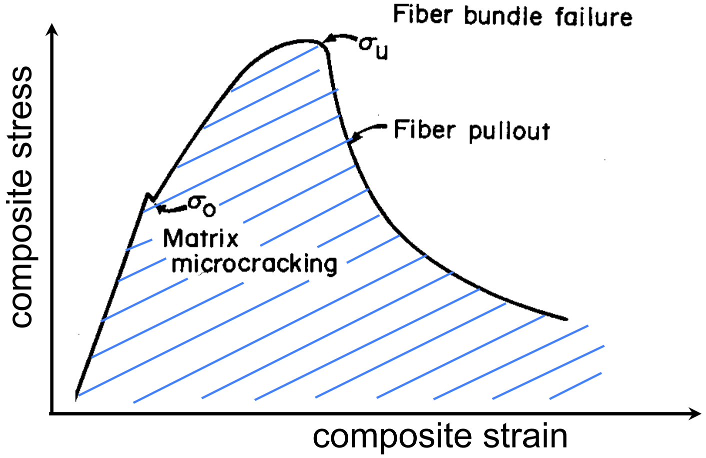


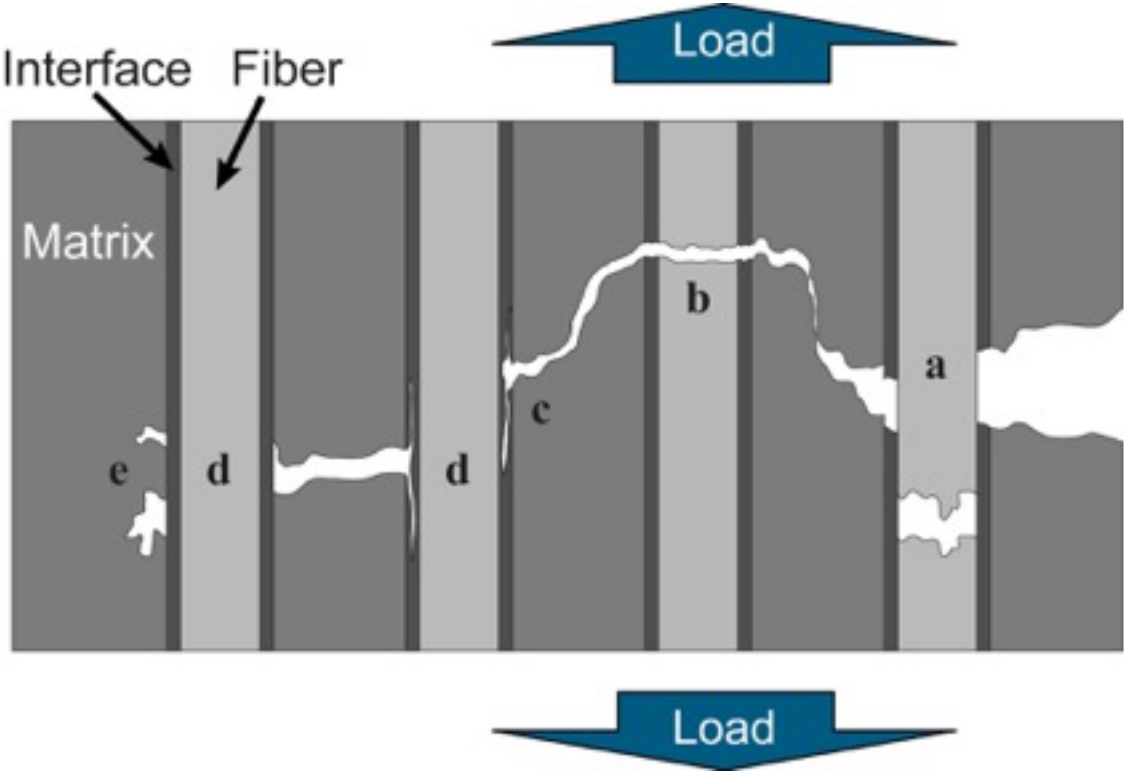
Material supplied J.Reiser

Composites

→ We will have cracks!

- A tungsten composite could be the solution!





Energy dissipation mechanisms:

a – pull-out of fibers
b – pull-out of matrix elements
c – crack deflection at interface
d – crack bridging by fiber
e – crack meandering at interface

Manufacturing Routes

Chemical Vapor Infiltration (CVI)

- + Low production temperatures
- + low residual stresses
- + Matrix attaches well to fiber/ interface
- – Long production times (days)
- – higher porosity
- ○ In-house at Wilma (W infiltration machine)

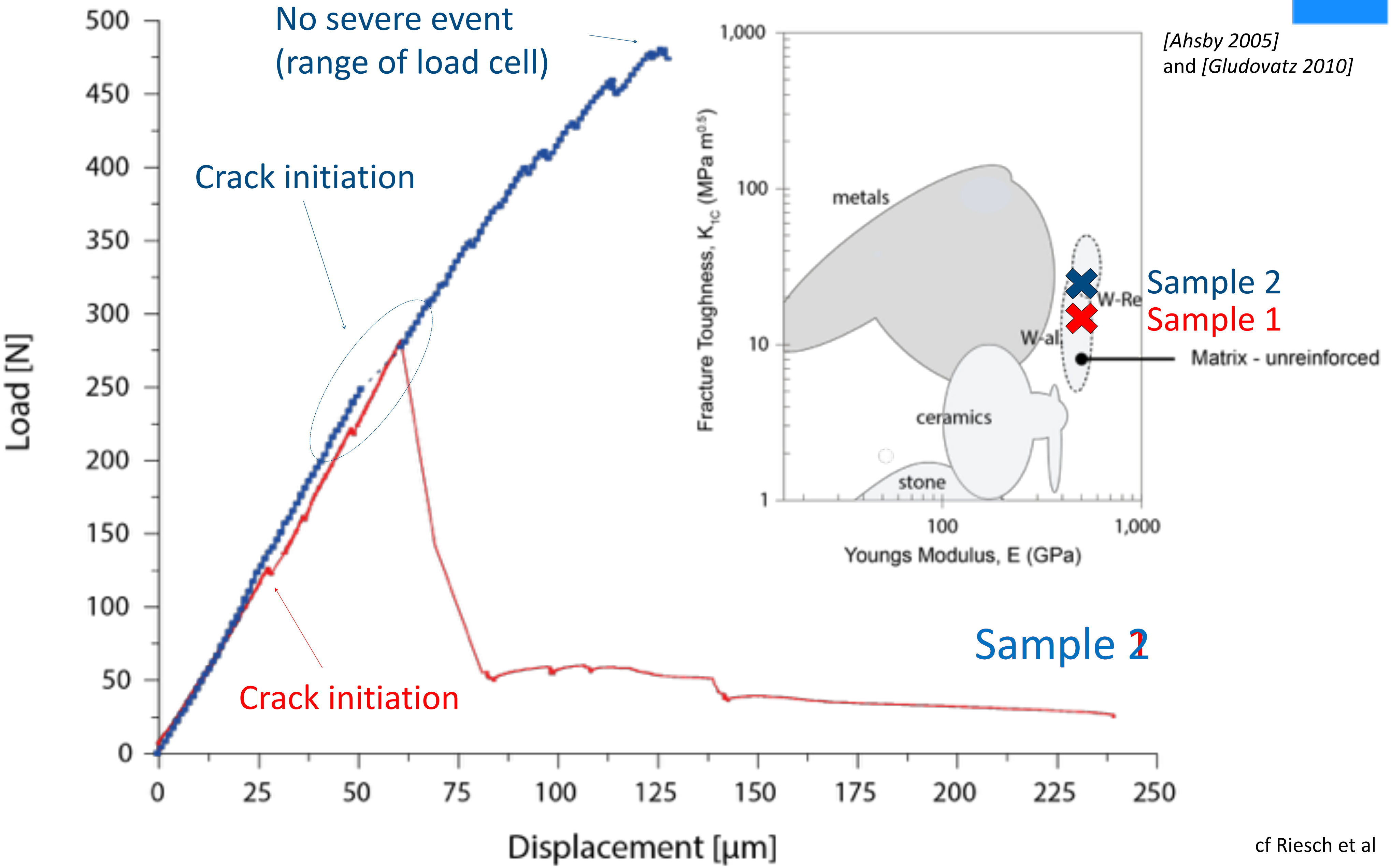
Hot Isostatic Pressing (HIP)

- + Faster than CVI (1 - 4 h)
- + Possibly easier implementation of W-alloys
- + Standard for Industrial W Production
- ▪ Indentations of Matrix in Interface
- – High production temperatures and pressures (up to 1900 °C / 250 MPa)
- • Resulting residual stresses and
- • Mechanical properties?
- ○ Easily accessible

Production route is crucial for mechanical properties of the resulting composite

cf. Talk by J.Riesch

Improved Toughness



No severe event
(range of load cell)

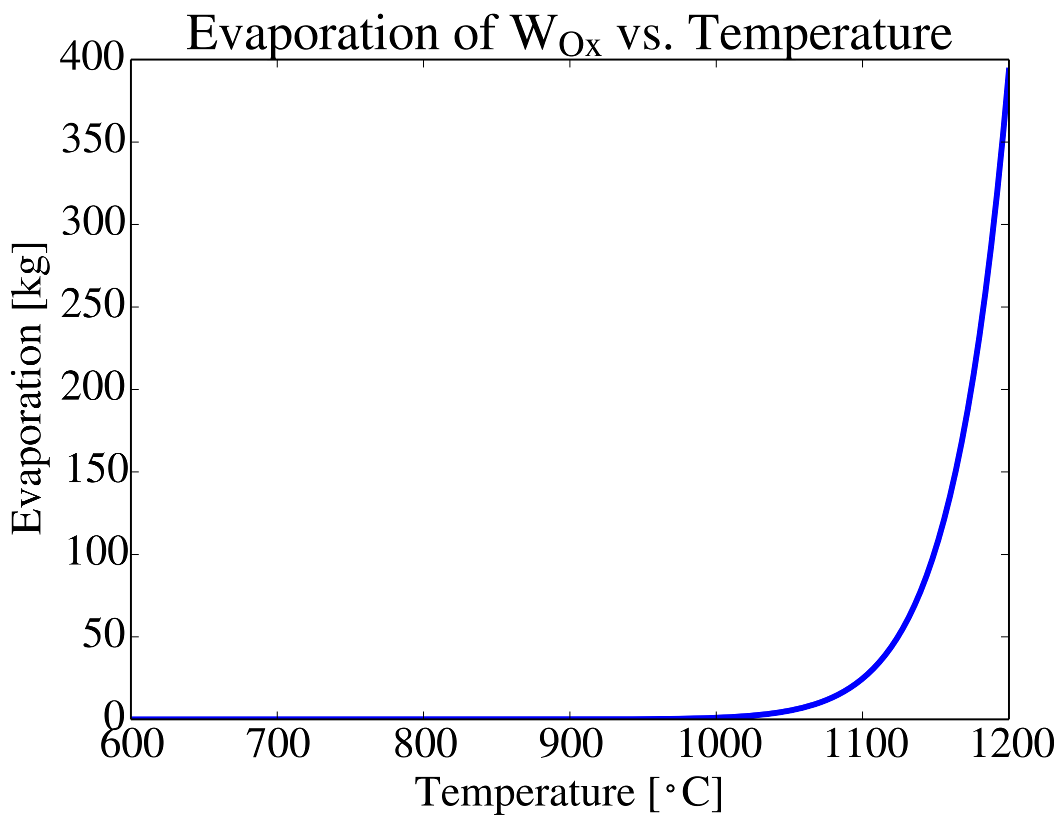
Crack initiation

Crack initiation

[Ahsby 2005]
and *[Gludovatz 2010]*

cf Riesch et al

Evaporation



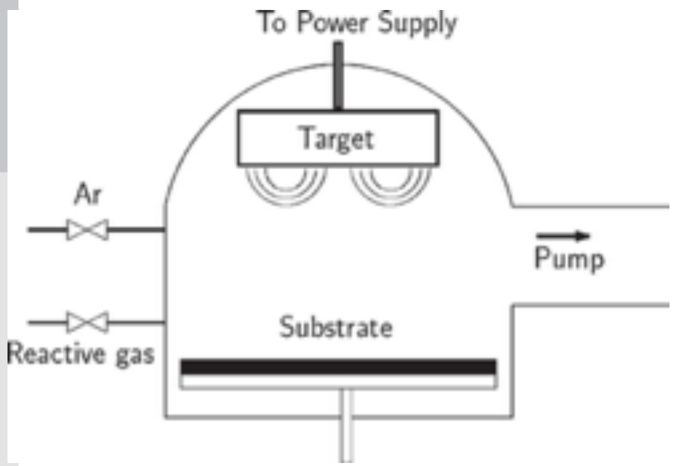
The rate determining process is the evaporation,WOx

This leads to an evaporation mass loss of about 400 kg/h on 1200 m^2 and at 1200 C.

Idea: Passivate the material

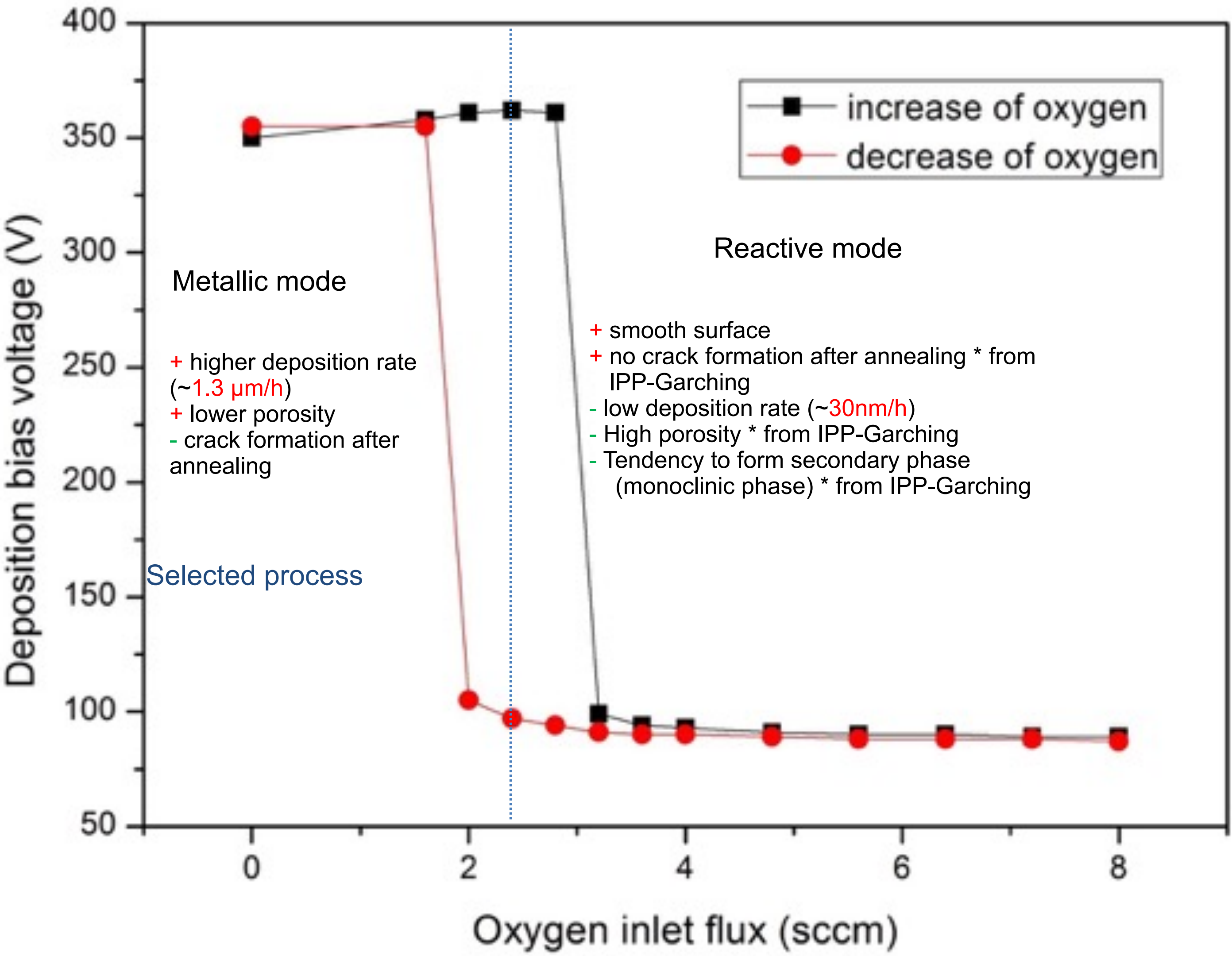
Surface composition automatically adjusts itself to the environment

Y_2O_3 Magntron



-Depla D, Mahieu S: Reactive sputter deposition: Springer; 2008.

Deposition bias voltage vs. Oxygen flux at 350W RF power supply



Metallic mode

\+ higher deposition rate (~1.3 µm/h)
\+ lower porosity
\- crack formation after annealing

Selected process

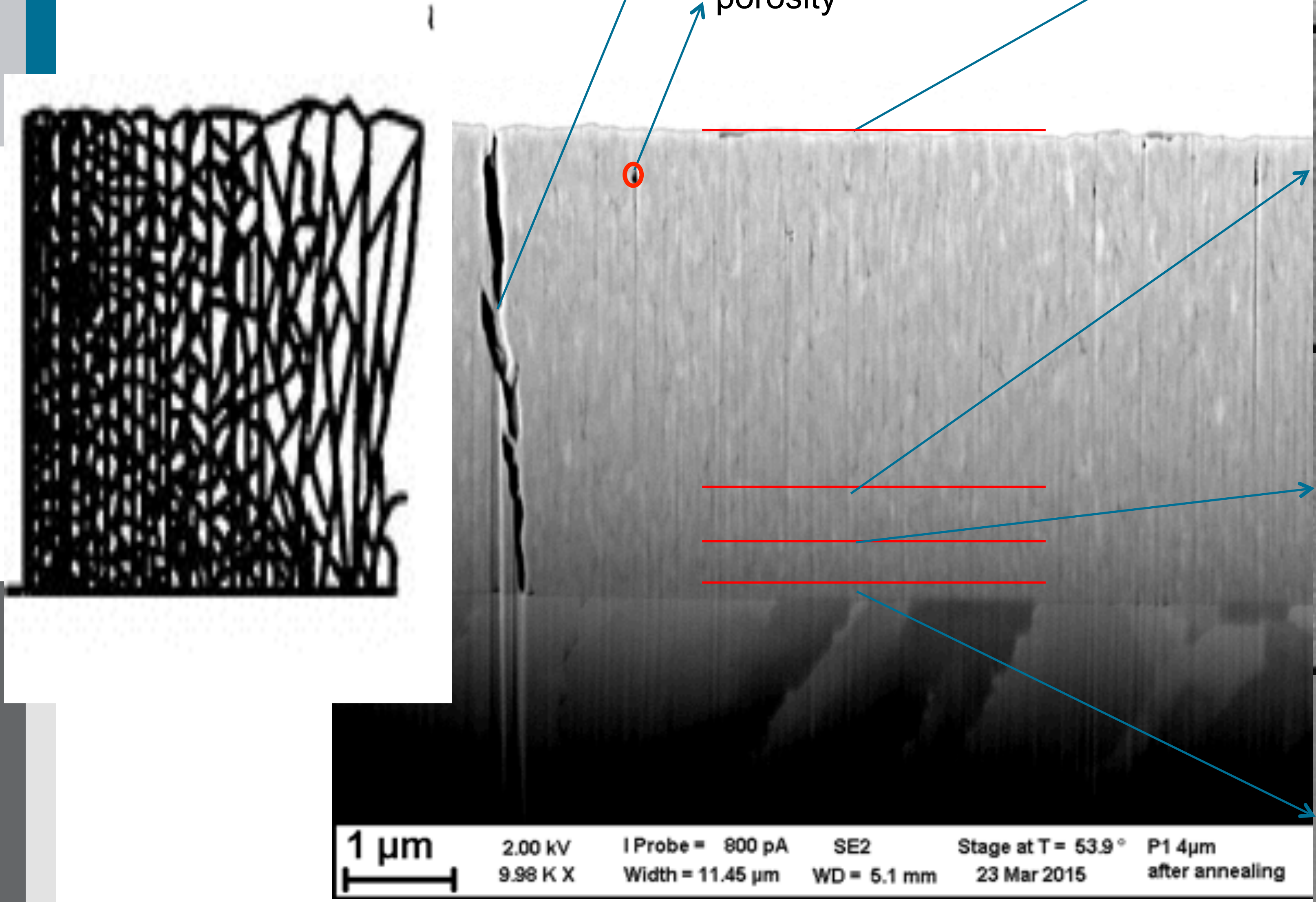
Reactive mode

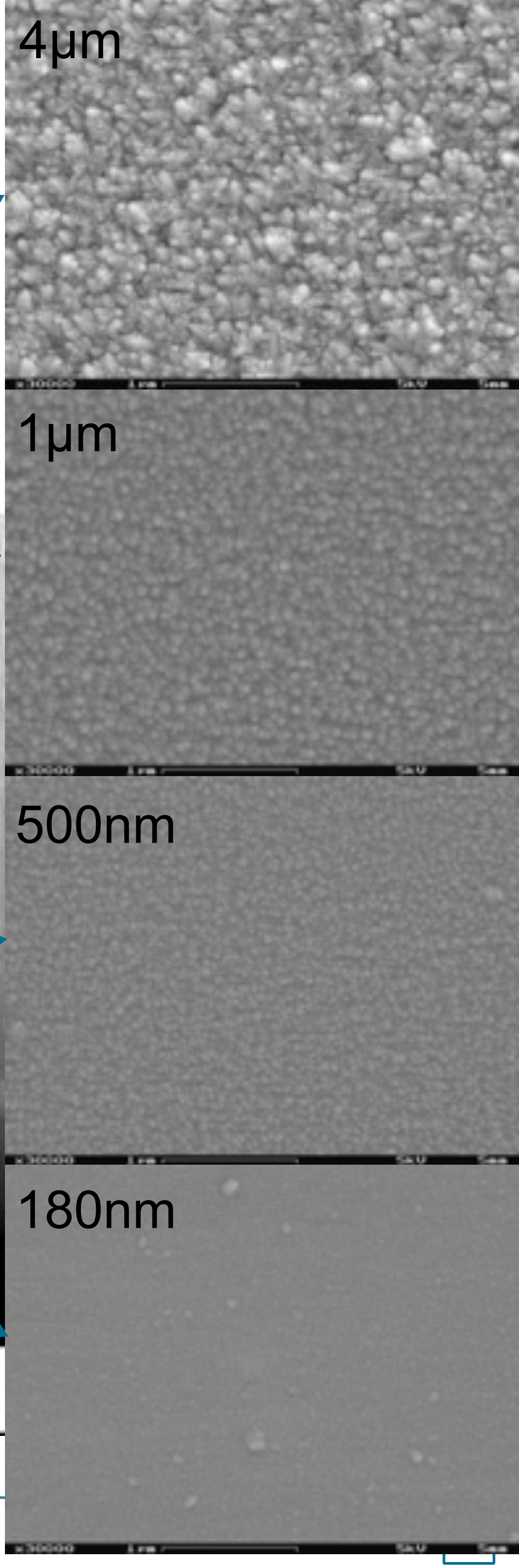
\+ smooth surface
\+ no crack formation after annealing * from IPP-Garching
\- low deposition rate (~30nm/h)
\- High porosity * from IPP-Garching
\- Tendency to form secondary phase (monoclinic phase) * from IPP-Garching

Film Structur

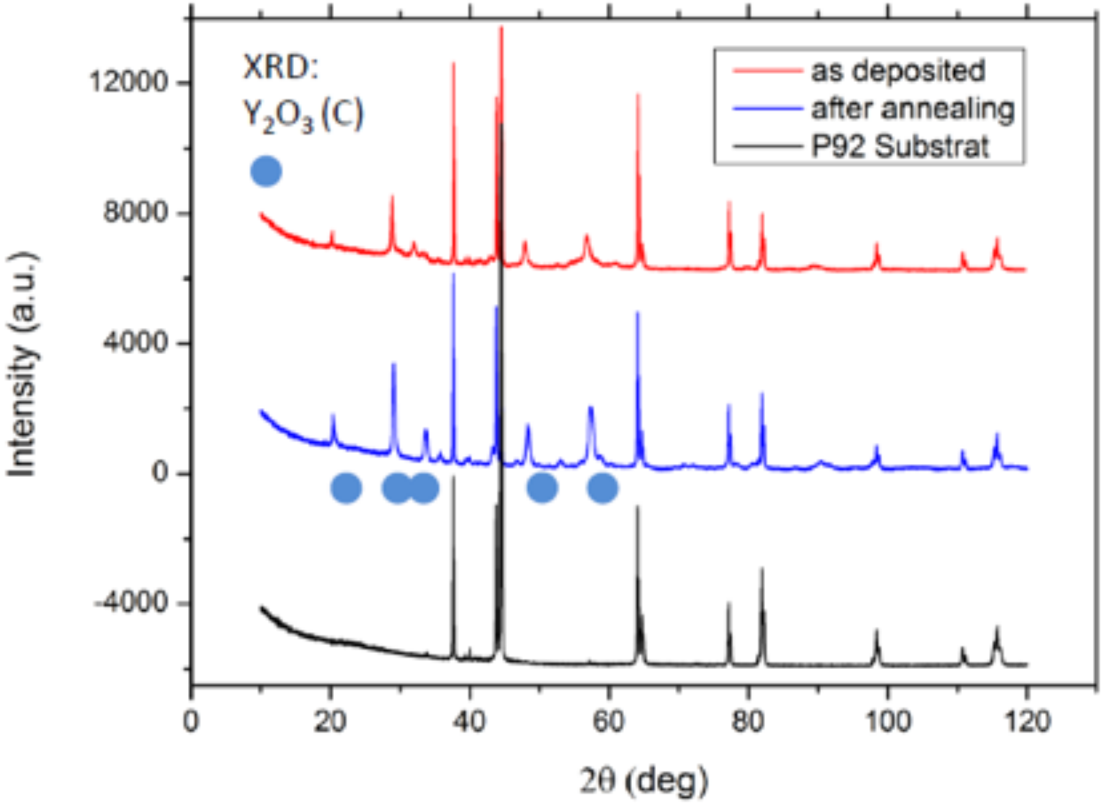
Cracks after annealing

porosity





Crystalline Structure



- Y_2O_3 cubic phase was formed
  (almost no other impurity phase can be seen)
- Grain growth and recrystallization happened after annealing
  (Y_2O_3 intensity peak get higher and steeper)

The next Steps

- **The aim is a a component - HHF/ PWI testable <5 years**
  - Test Samples Perm / SMART / Wf/W are needed on short timescales (PWI - Concept relevant parameters, e.g. sputtering)
  - How do we integrate our efforts between the component relevant materials / topics ?
  - DEMO Divertor / 1st Wall Component CD ?
  - Do we consider ‚forbidden' materials
  - Neutron effects on components & Materials are crucial
  - PWI in reactor components

New Solution

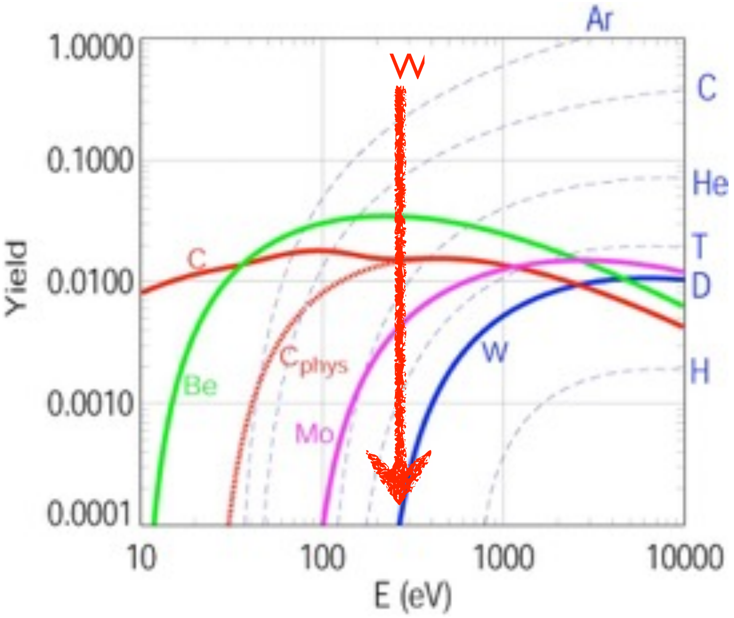
- FGM Weber / KIT
- KIT Divertor
- J.Reiser
- Gonzales / Koch
- Monica Ferraris
- Hinoki
- Anne / Shizuoka
- Liquids
- Bachmann EFDA / KIT

Recent progress in research on tungsten materials for nuclear fusion applications in Europe - Journal of Nuclear Materials 432 (2013) 482–500

Materials in Fusion

Materials in Fusion Devices

Components Lifetime



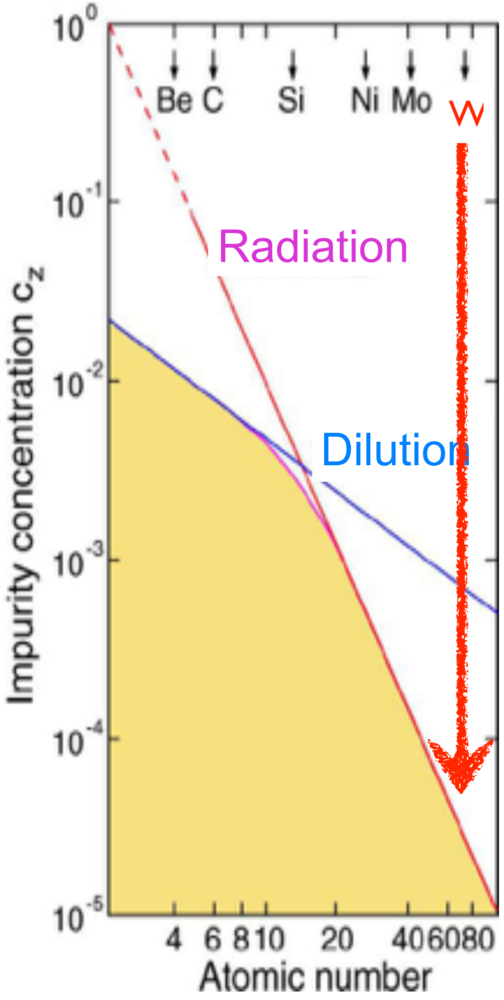
Low-Z: strong wall erosion

High-Z: low sputtering / mainly by impurities

Metals: potential melting

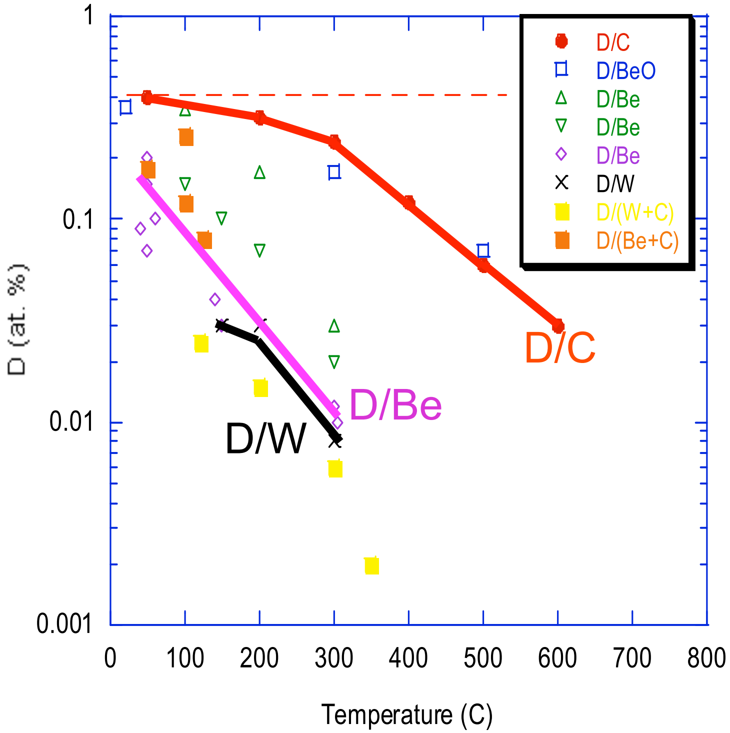
+ neutron hardness

Plasma Performance



Maximum allowed concentration for W:

Fuel Retention

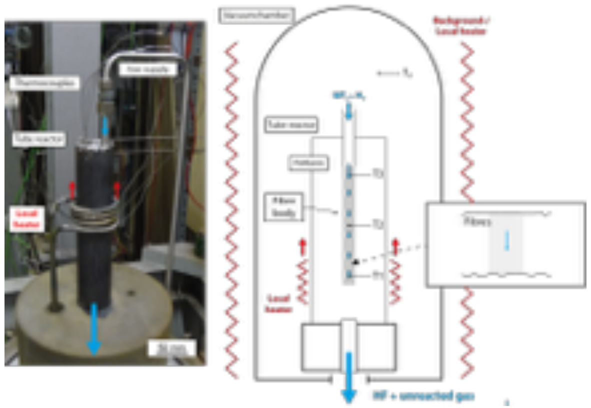


Co-deposition dominates long term retention in C

Metals: low retention

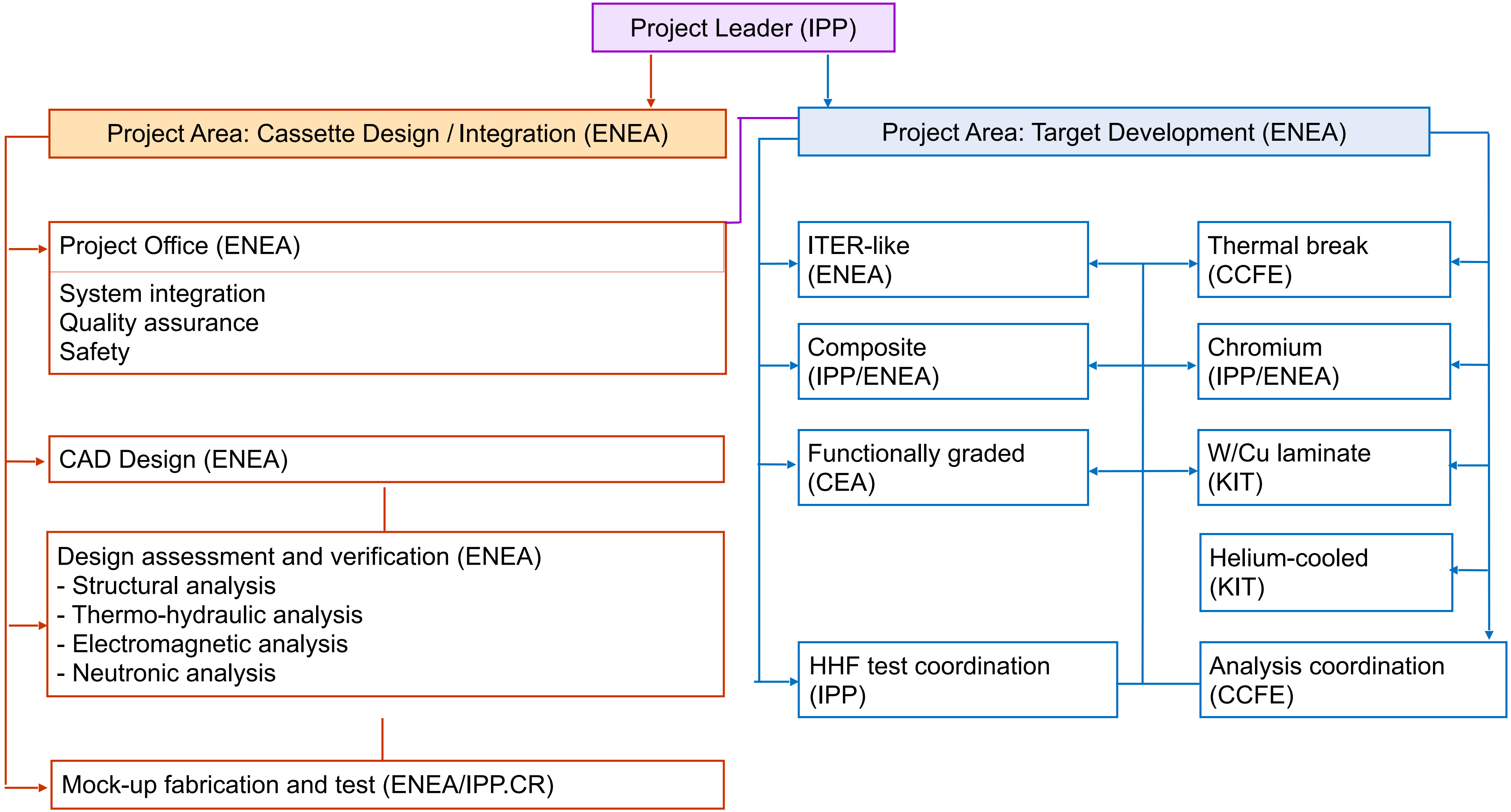
EFDA Task Force
Plasma-Wall-Interactions

WILMA



SETUP established at FZJ including initial tests

Project structure



Project Leader (IPP)

Project Area: Cassette Design / Integration (ENEA)

Project Office (ENEA)

System integration
Quality assurance
Safety

CAD Design (ENEA)

Design assessment and verification (ENEA)
- Structural analysis
- Thermo-hydraulic analysis
- Electromagnetic analysis
- Neutronic analysis

Mock-up fabrication and test (ENEA/IPP.CR)

Project Area: Target Development (ENEA)

ITER-like (ENEA)

Composite (IPP/ENEA)

Functionally graded (CEA)

Thermal break (CCFE)

Chromium (IPP/ENEA)

W/Cu laminate (KIT)

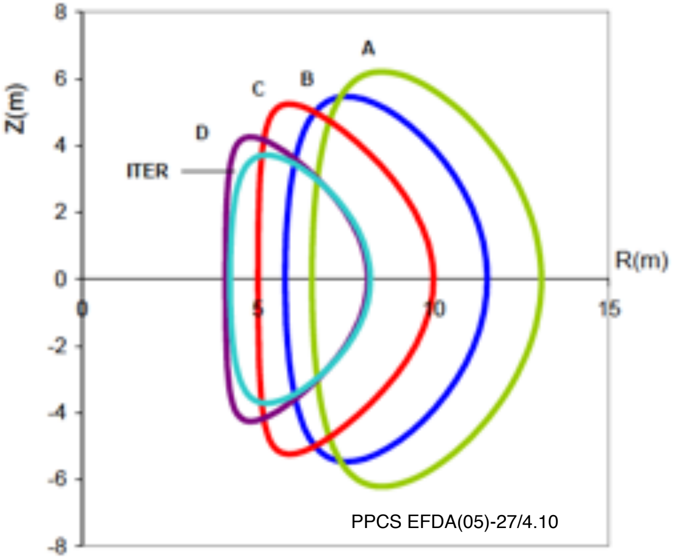
Helium-cooled (KIT)

HHF test coordination (IPP)

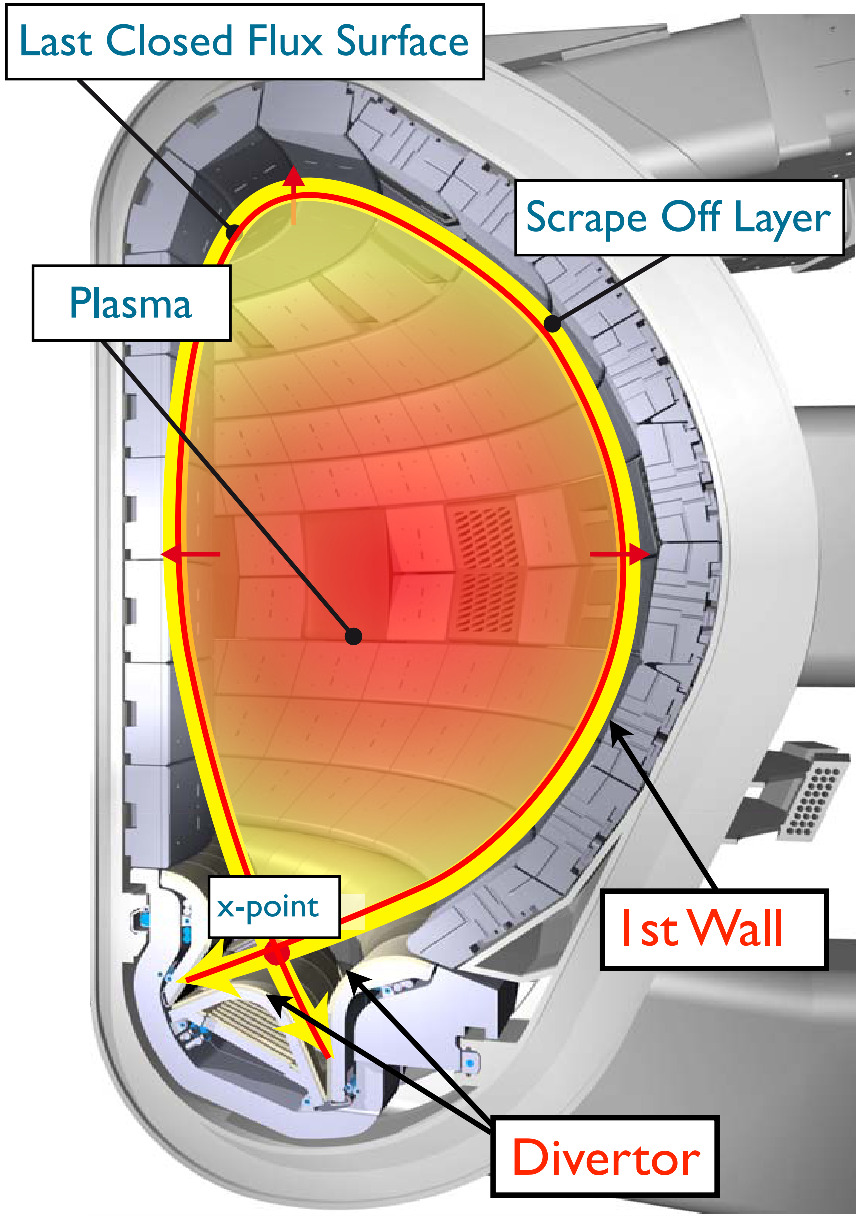
Analysis coordination (CCFE)

A Step Forward

	JET	ITER	DEMO*
P/R (MW/m)	11	25	94-130
Wth/R (MJ / m)	3	x20 → 60	125-395
operation time (s/ yr)	$4.0 \cdot 10^4$	$4.0 \cdot 10^5$	x60 → $2.4 \cdot 10^7$
Averaged neutron fluence (FW) (MW a/m^2)	~0	~0.3	x30 → ~10
Twall (K)	500	500	x2 → 1000

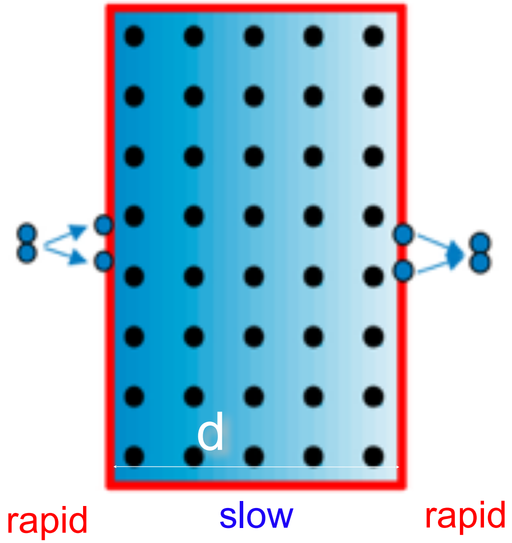


PPCS EFDA(05)-27/4.10



Permeation

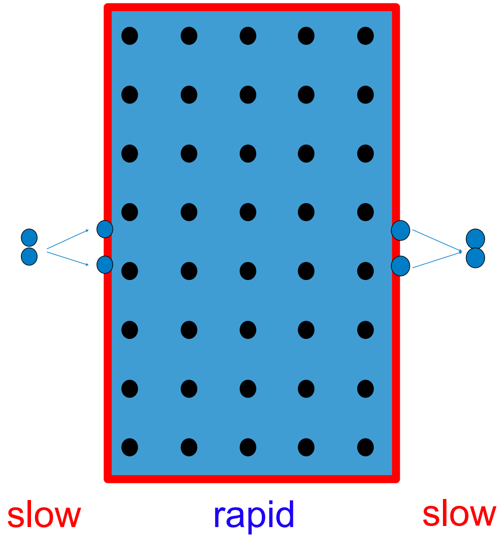
Diffusion-limited:
Dependent of thickness



$$J = \frac{DK_s}{d}\left(\sqrt{p_h} - \sqrt{p_l}\right)$$

$$\Rightarrow J \sim \sqrt{p}$$

Surface-limited:
Independent of thickness



$$J = \sigma K p$$

$$\Rightarrow J \sim p$$

J : diffusion flux

D : diffusion constant

K_s : equilibrium constant

σ : surface quality

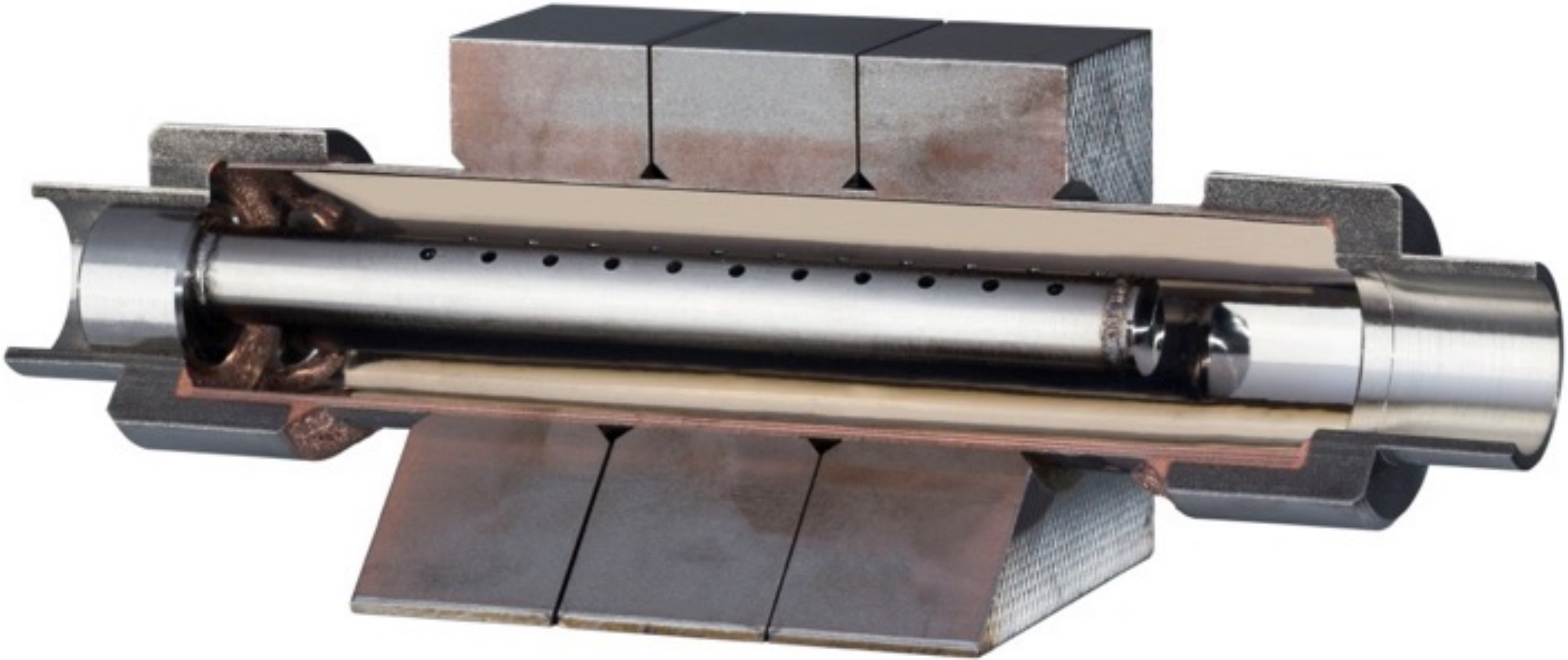
n : information about limiting process: diffusion or surface

$$\underbrace{\hspace{10em}}$$

Measurement result: $J = ap^n$

W/Cu

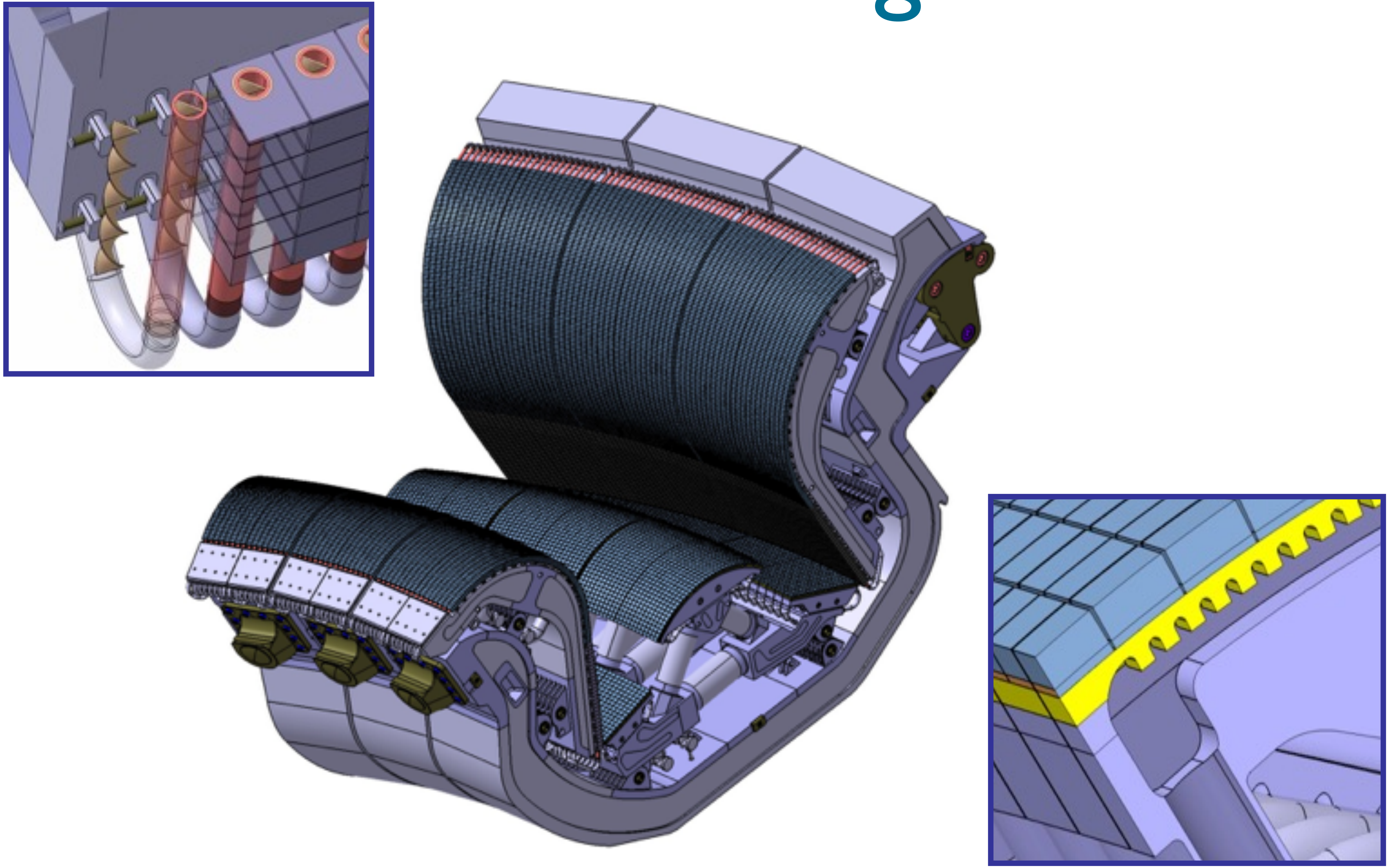
- Water and helium cooled divertor design



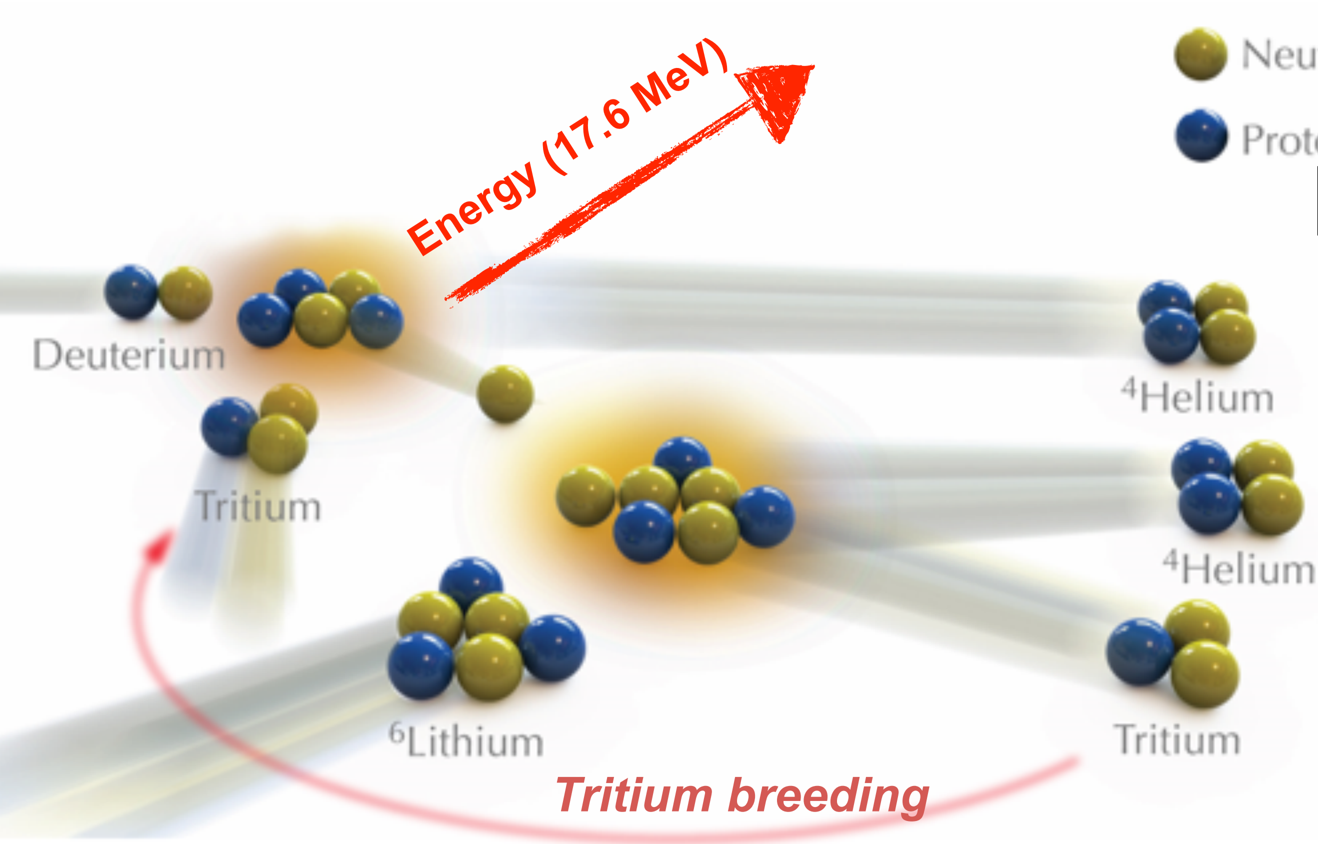
DEMO 1 Concepts still rely on using Copper

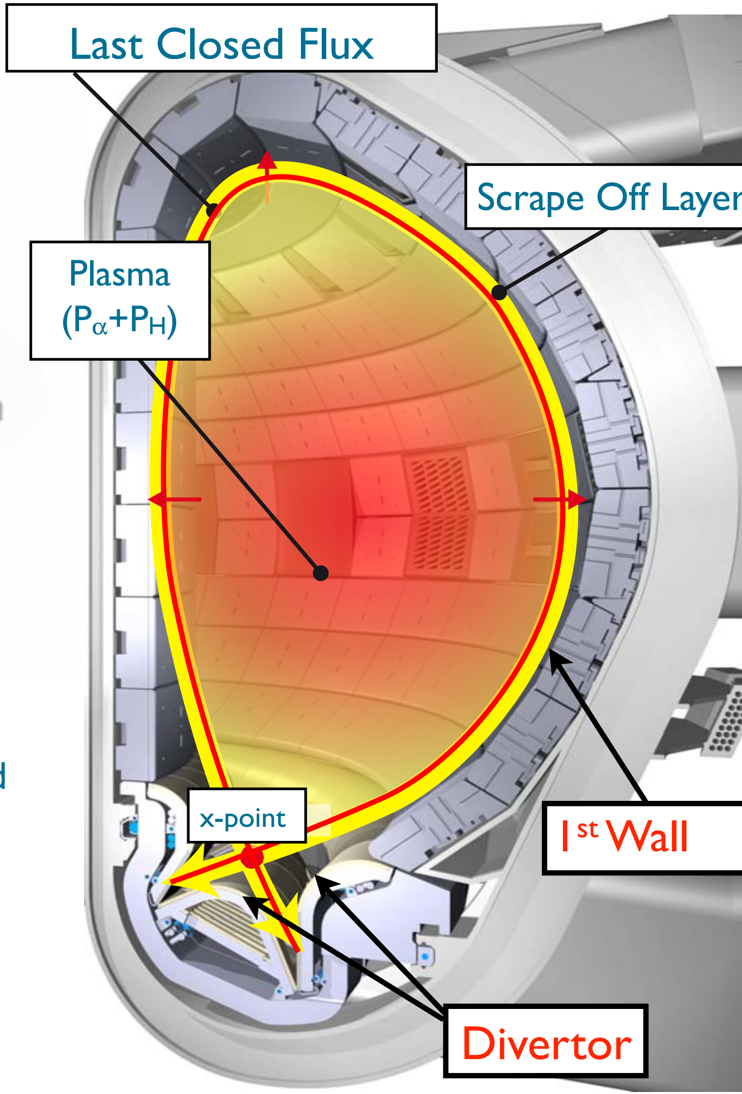
Material supplied .Reiser KIT

Divertor target



Fusion Condition





- α-particles (3.5 MeV) heat the plasma and consecutive energy and particles must be absorbed by the Plasma Facing Materials *(PFM)*
- Lifetime of PFMs due to plasma wall interaction: erosion, degradation / *steady state operation / Transients*
- Neutron stability *of structural materials*

source: EFDA, Fusion Electricity (November 2012), p. 5