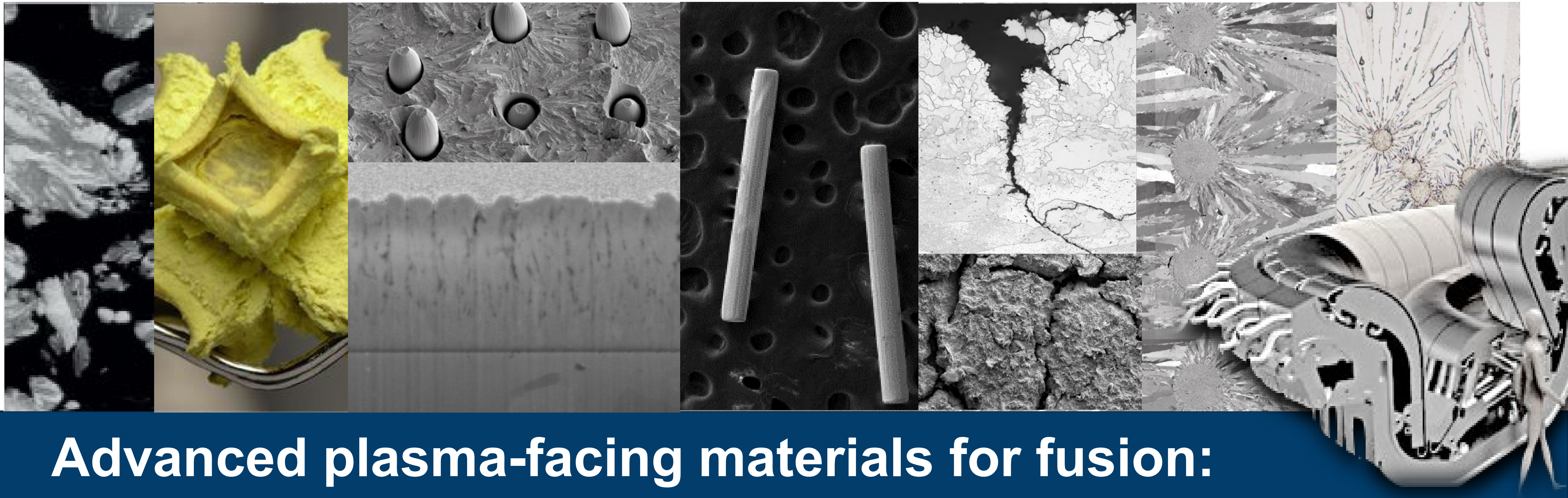

Advanced plasma-facing materials for fusion: Developments and perspectives

2021-09-28 I Ch. Linsmeier
J.W. Coenen, M. Bram, J. Engels, H. Greuner*, A. Houben, F. Klein, A. Litnovsky, Y. Mao,
G. Pintsuk, M. Rasinski, J. Riesch*, J. Schmitz, X. Tan, T. Wegener

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Outline

Introduction: the challenge for materials facing the plasma

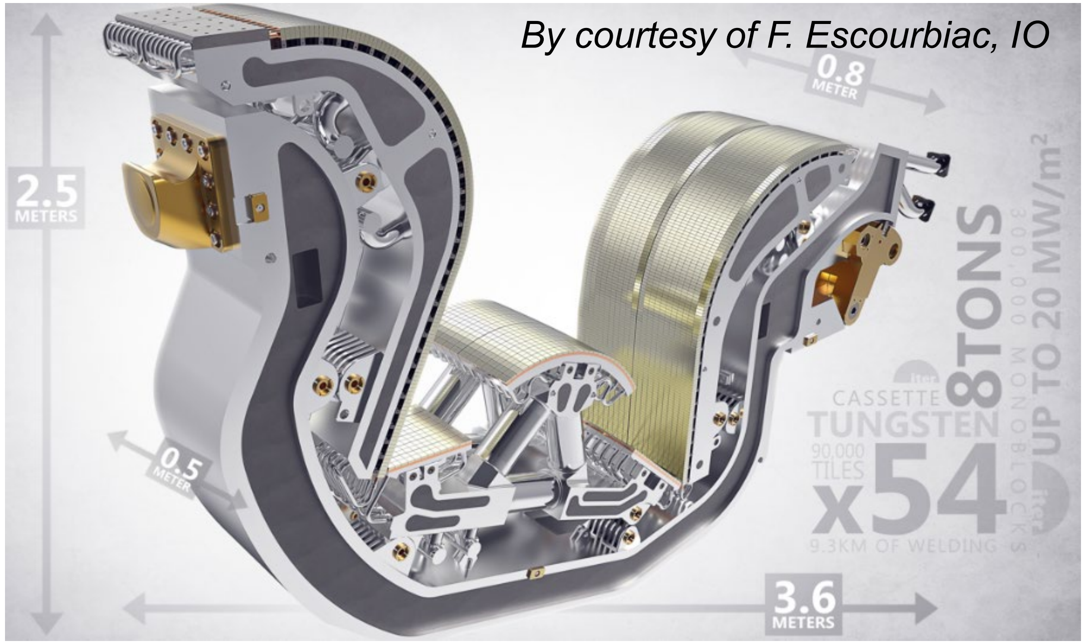
Research tailored towards new materials

- Extrinsic toughening: composite materials
- Intrinsic safety: smart alloys
- Hydrogen isotope permeation: barrier layers
- Irradiation damage: >15 MeV protons as fusion neutron proxy

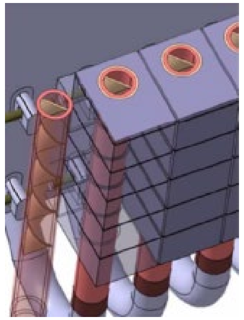
Summary and outlook

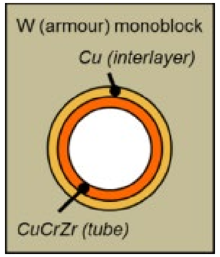
ITER divertor

Full-W armor: one divertor until 4 years into DD/DT phase


By courtesy of F. Escourbiac, IO

- fully actively cooled (water, 70 °C)
- dome: flat tiles
- vertical targets (2,000): monoblocks (320,000)
- themal performance up to 20 MW m^{-2} steady-state

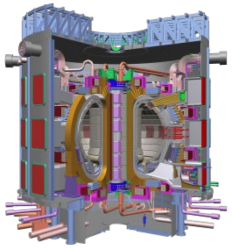




**Mono-block technology:
JA-DA, EU-DA**

From ITER to DEMO

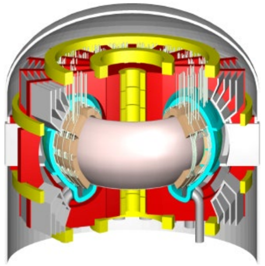
ITER



- operational flexibility (experimental device)
- transient heat flux events
- T-codeposition on „cold“ surfaces
- no energy conversion (70°C water coolant)
- low duty cycle
- low neutron dose (wall: ~1 dpa)

Need to apply available materials and technology

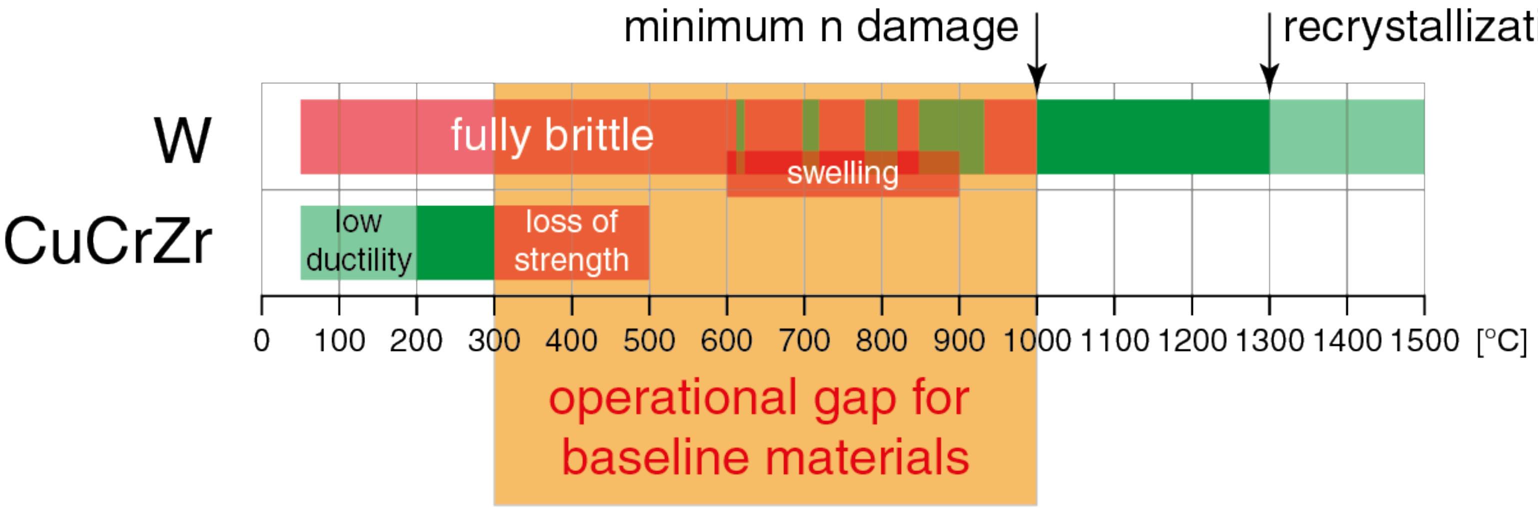
DEMO



- lifetime (erosion, ageing)
- very limited transient heat flux events
- energy conversion (coolant: ≥300°C water, ≥400°C He)
- high duty cycle
- high neutron dose (wall: 80…100 dpa, divertor: 2-5 dpa/fpy)
- low activation materials

Need for innovation in non-activating materials and technology

Baseline materials: Operational gap



Tungsten

- Operation mostly within brittle regime
- W→Re transmutation increases brittleness after irradiation

Cu alloy (heat sink, cooling tube)

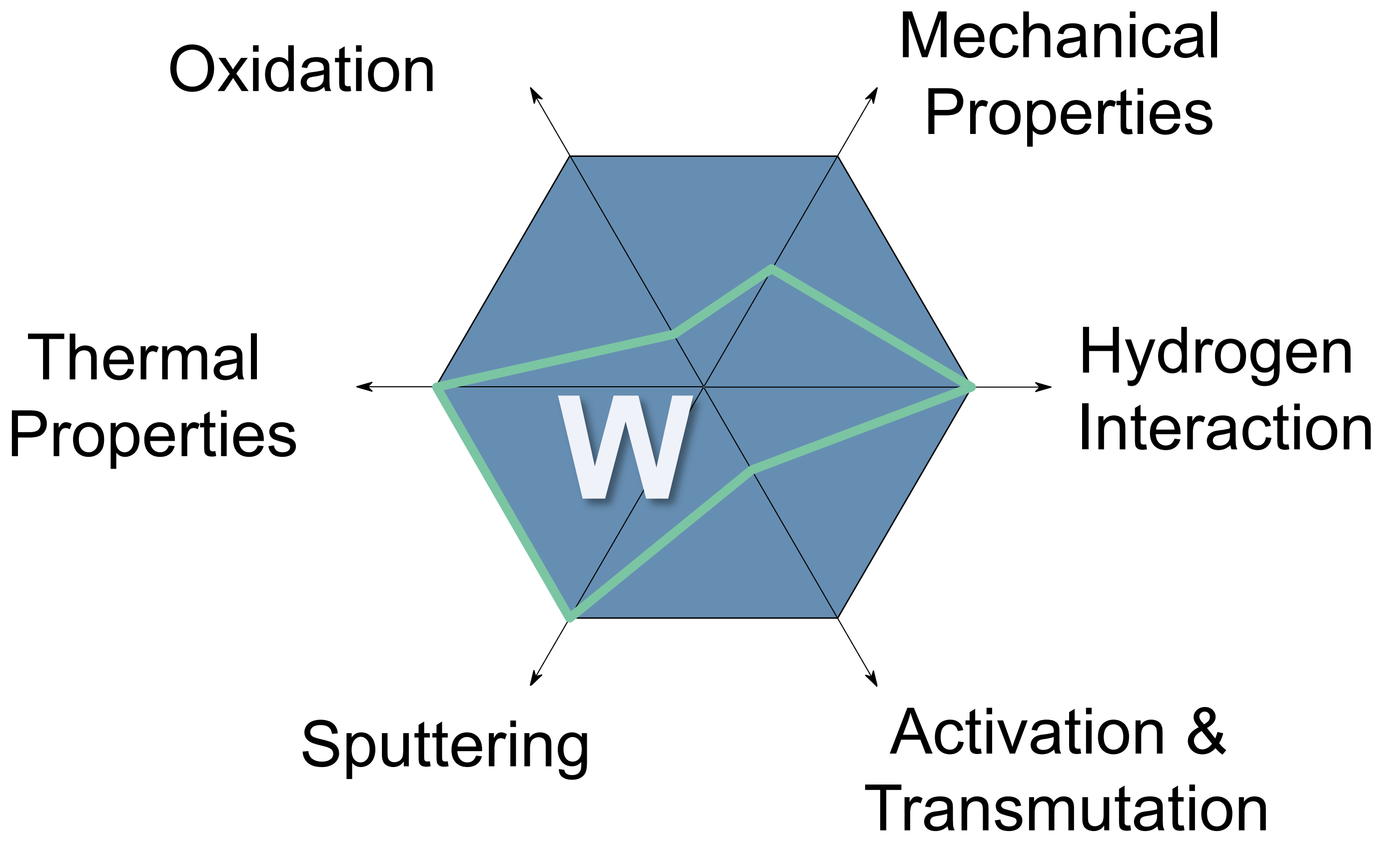
- narrow optimum regime
- loss of strength above 300 °C

New material solutions:
Metal-matrix composites

Tungsten:	W fiber / W matrix
CuCrZr	SiC fiber / Cu matrix W fiber / Cu matrix

Advanced materials

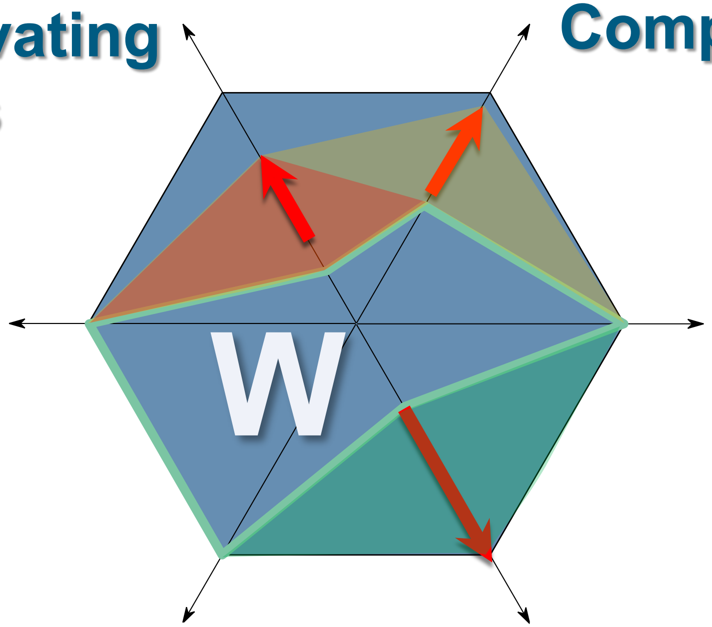
New solutions for existing challenges



Methods and concepts applicable to new materials and components

Advanced materials

New solutions for existing challenges



Self-Passivating Alloys

Metal-Matrix Composites

Thermal Properties

Permeation Barriers & Protective Coatings

Sputtering

Radiation damage analysis

Methods and concepts applicable to new materials and components

Research tailored towards fusion reactors

Research focus:

- material development
  - definition
  - preparation and characterization
  - optimization

- PWI issues
  - erosion
  - hydrogen isotope retention
  - lifetime

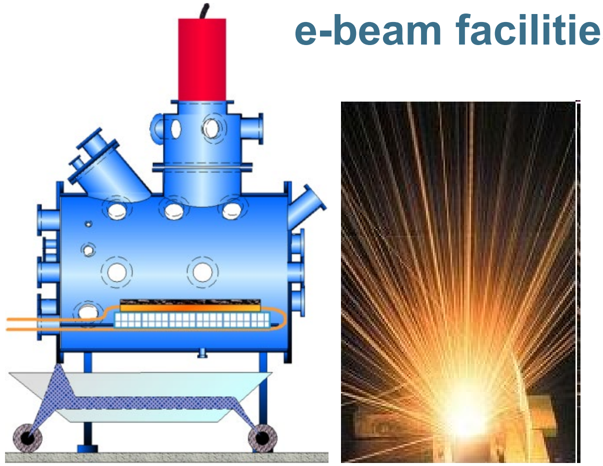
➡ **Materials and components test:**

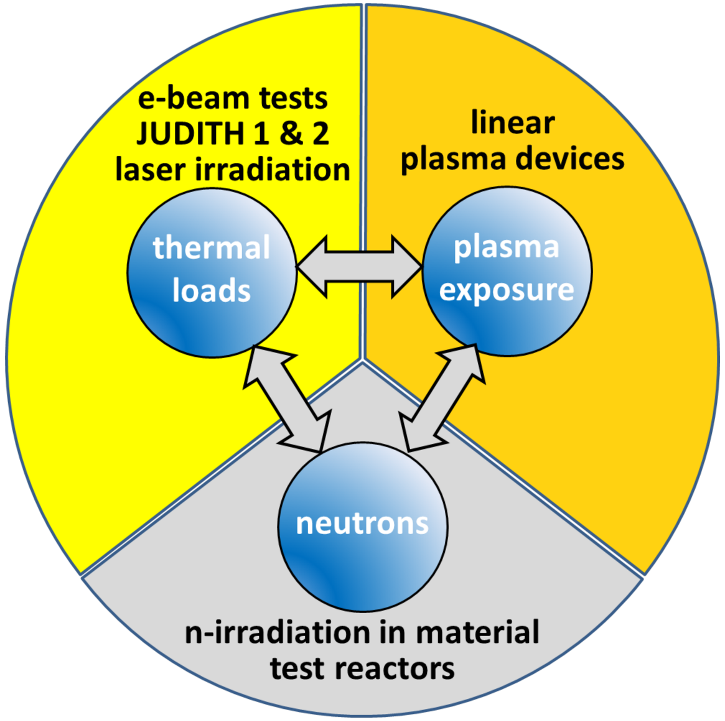
- neutron damage (simulation AND “real” neutrons)
- plasma exposure
- Off-normal events (e.g. ELM) simulation

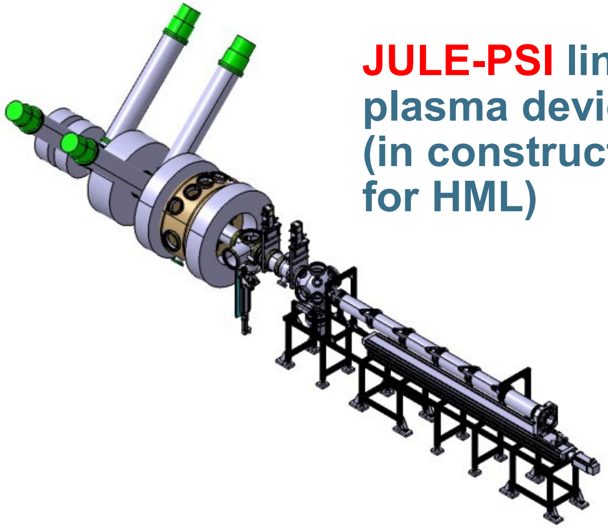
Material and component testing at FZJ

- Integrated characterization of thermo-mechanical and physical-chemical properties of neutron irradiated and toxic plasma-facing materials under high heat loads and plasma exposure, incl. **hot cell facilities**
- Selection of plasma-facing materials tested under n-irradiation and optimized for PMI processes (tritium retention, embrittlement, erosion)

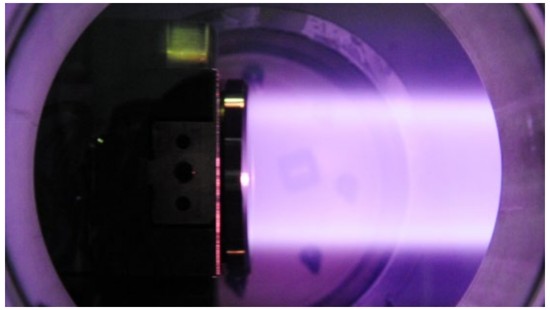
JUDITH 2 + 3
e-beam facilities



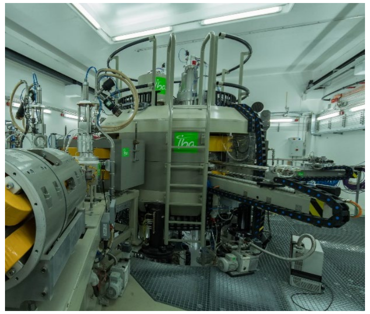




JULE-PSI linear plasma device (in construction for HML)



PSI-2 linear plasma experiment (outside HML)



Cyclotrons at FZJ / INM-5

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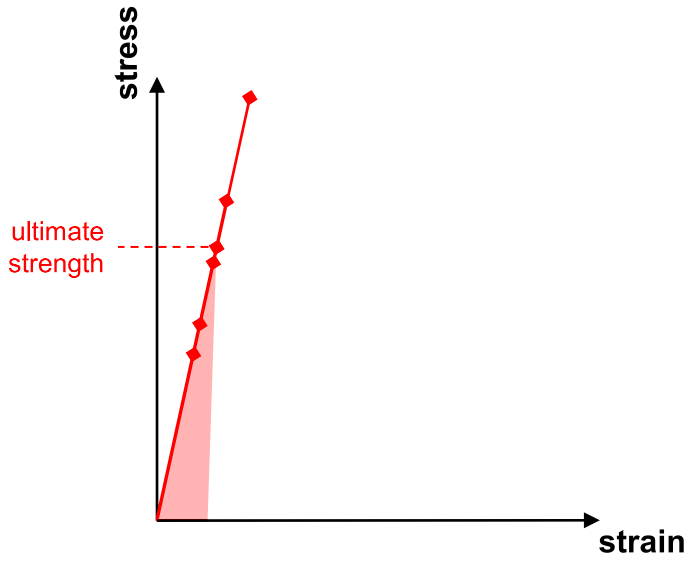
Summary and outlook

Metal Matrix Composites

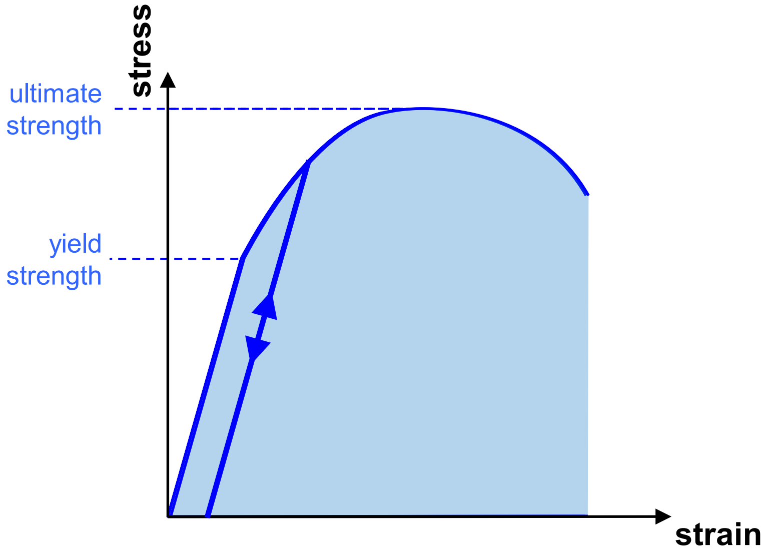
Tungsten-fiber reinforced tungsten

Bulk tungsten: brittle

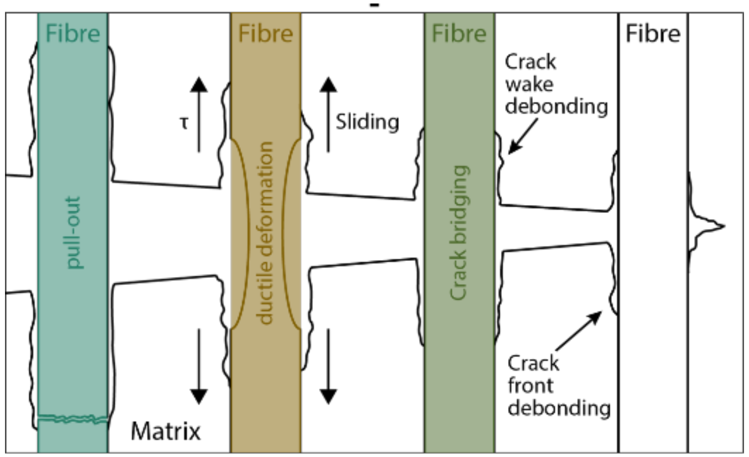


- No stress redistribution
  → Catastrophic failure, no damage tolerance (notch sensitivity)
- High scatter → weakest link scaling
- Limited fracture energy

W_f / W: pseudo-ductile



- Stress redistribution by extrinsic mechanisms
- High fracture energy
- Cyclic loading possible after damage → damage tolerance

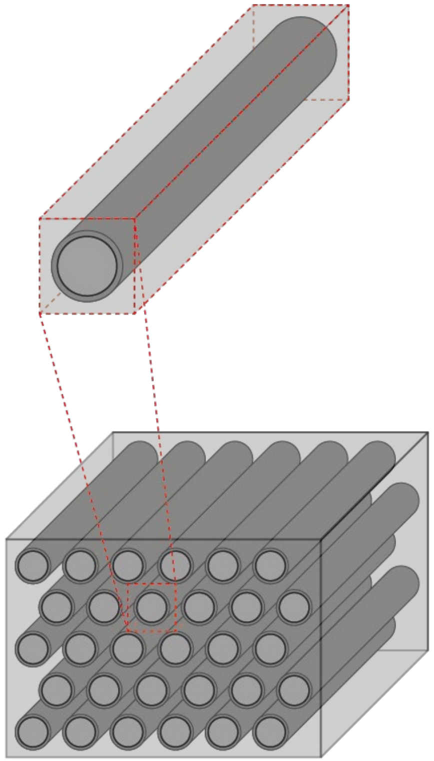


→ stress redistribution by local energy dissipation

Toughening by extrinsic mechanisms – similar to ceramic fiber-reinforced ceramic composites

– to increase fracture toughness

Architecture



Fiber

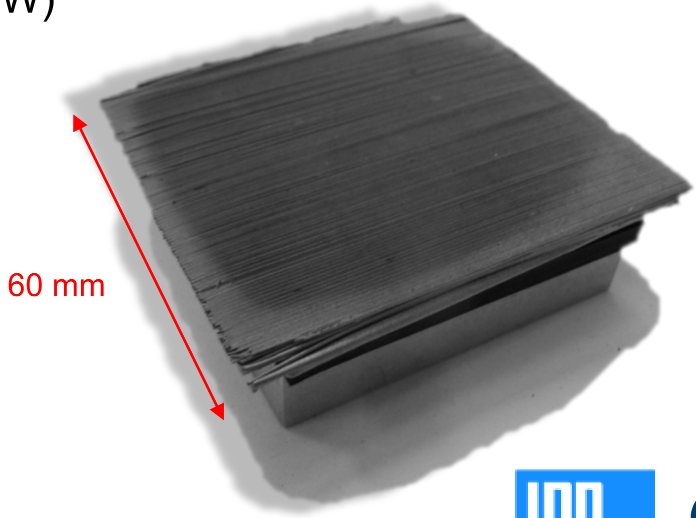
- High strength/ductility, temperature stability
- commercial, drawn tungsten wire (Osram GmbH, Germany): (17-)150 µm

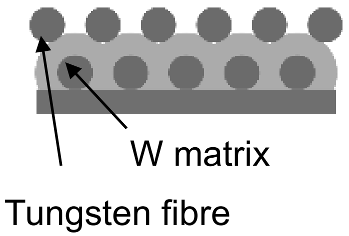
Interface

- Optimum bonding, stability
- e.g. oxide ceramic (yttria)

Matrix

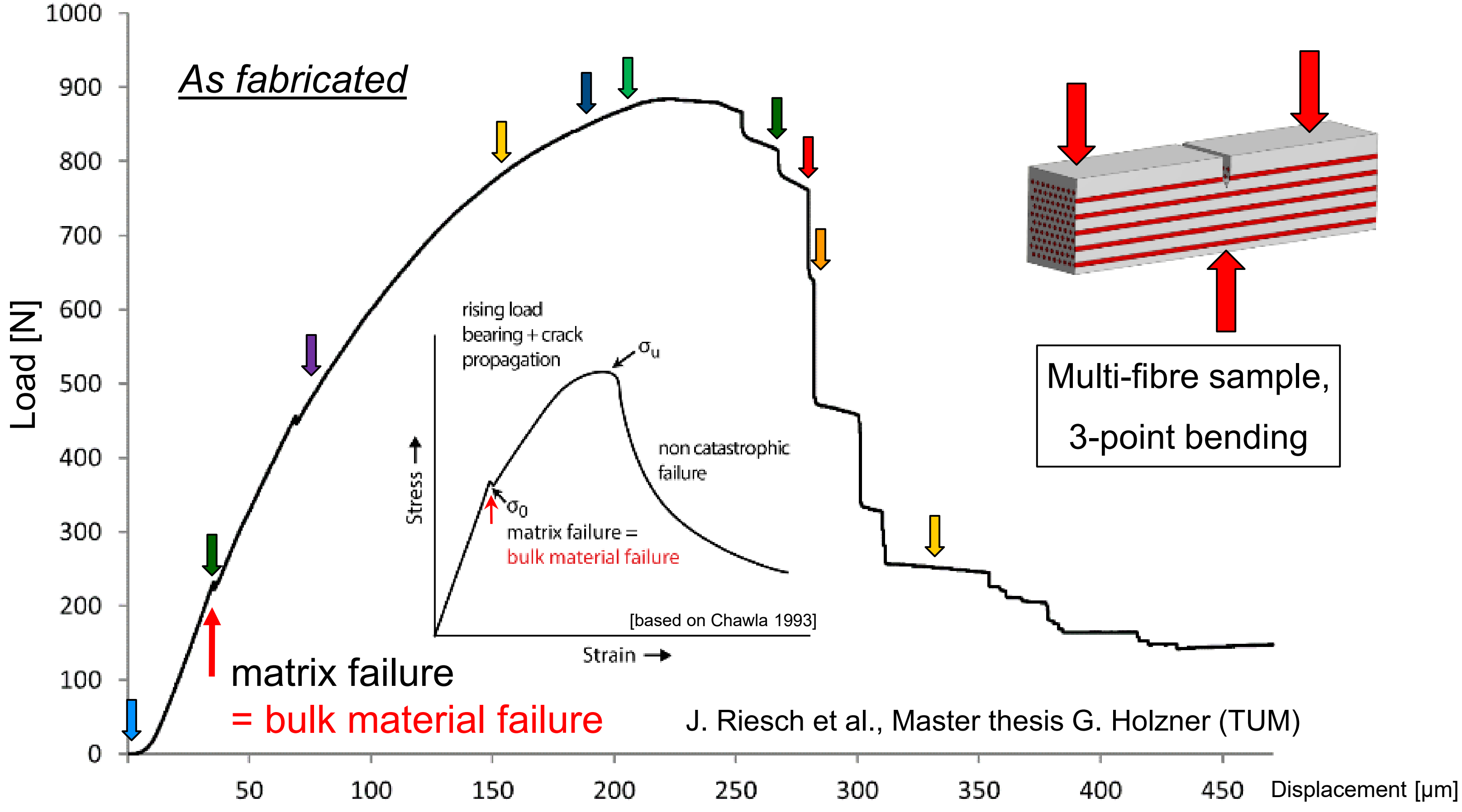
- Interface/fibre integrity, fibre architecture, density
- Chemical vapour deposition (CVD-Wf / W)
- Powder metallurgy (PM-Wf / W)





Tungsten fiber reinforced tungsten (W_f/W)

CVD – W_f/W Pseudo-ductility at room temperature



[based on Chawla 1993]

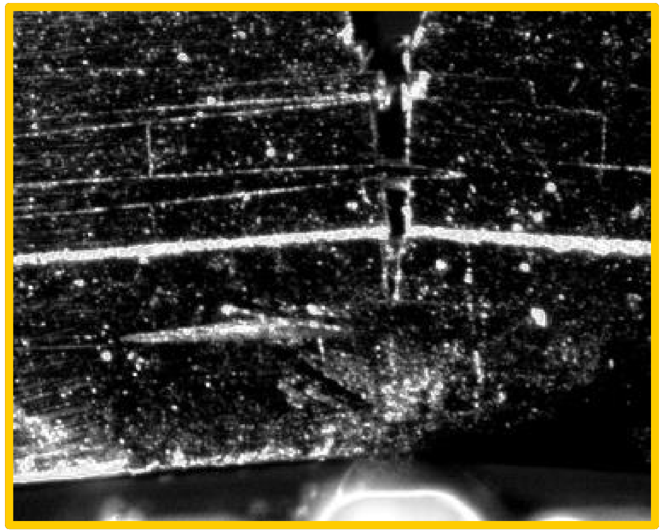
matrix failure

= bulk material failure

J. Riesch et al., Master thesis G. Holzner (TUM)

Multi-fibre sample,

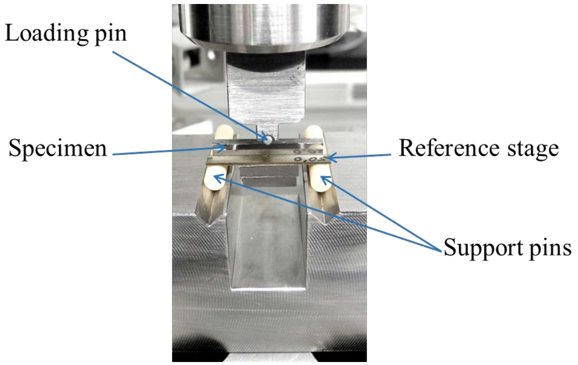
3-point bending

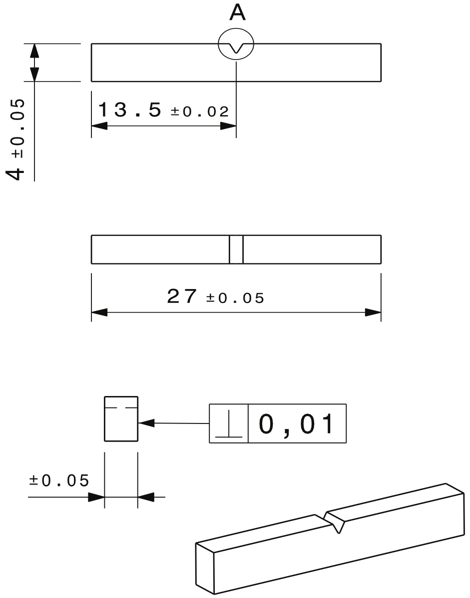


Metal Matrix Composites allow for new operational windows for refractories

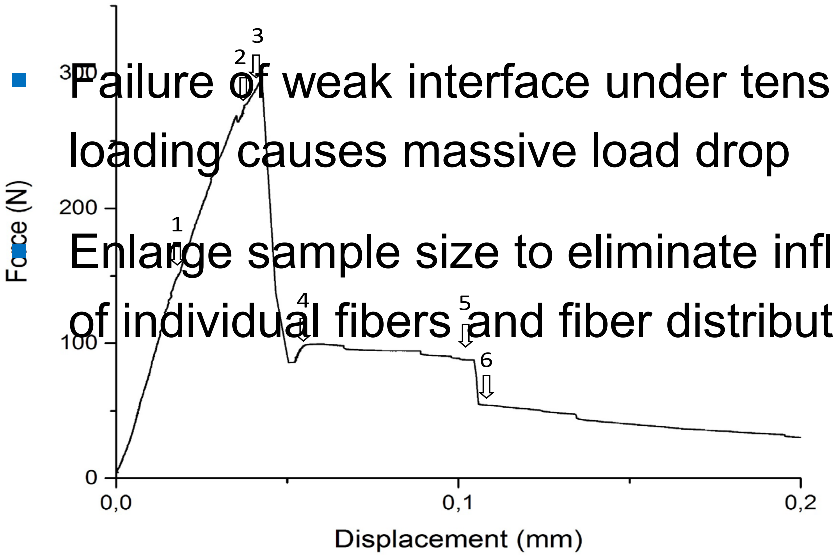
Stable crack growth

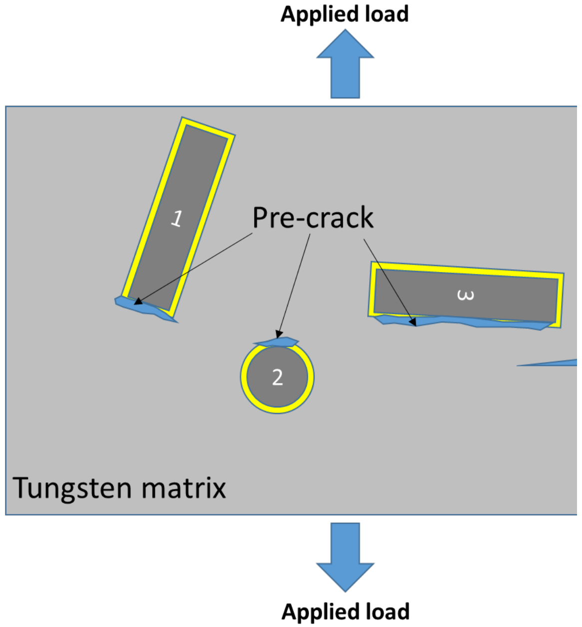
PM W_f / W

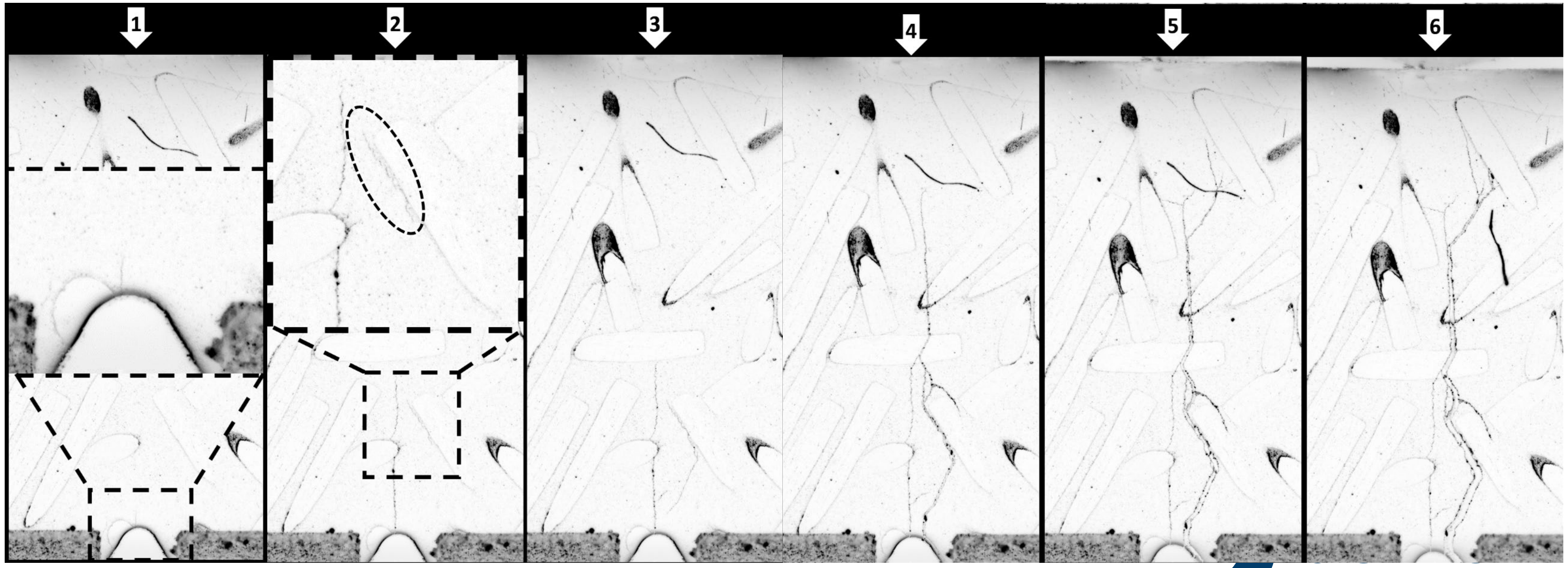




- Failure of weak interface under tensile loading causes massive load drop
- Enlarge sample size to eliminate influences of individual fibers and fiber distribution



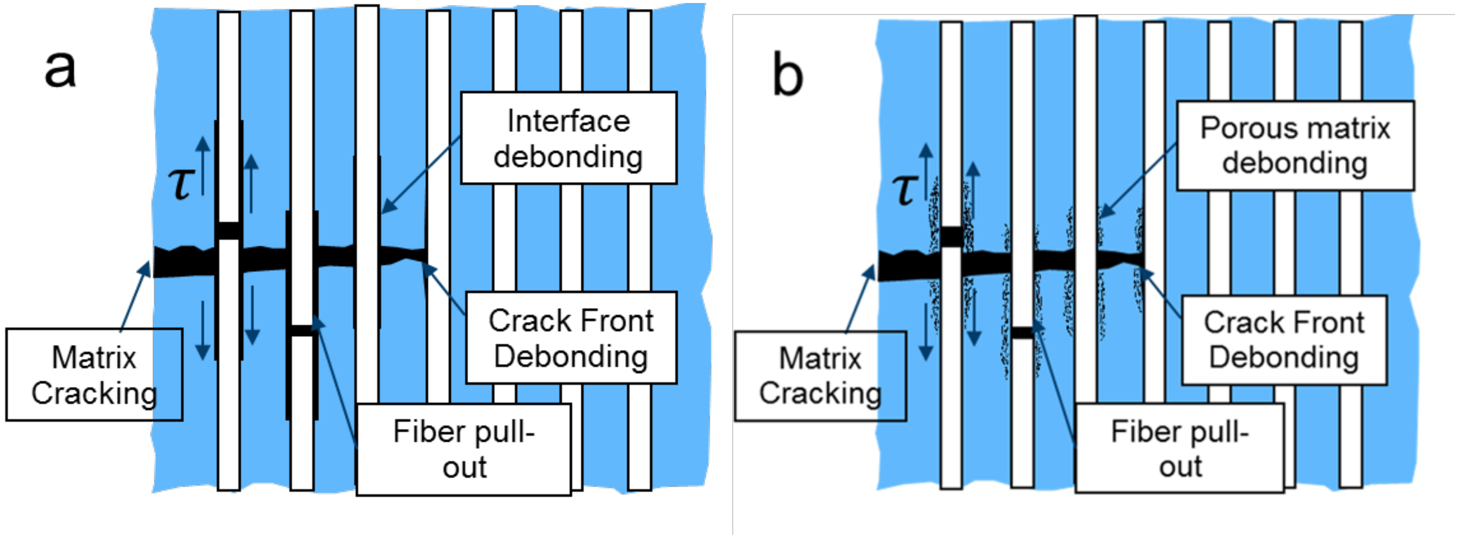




Porous matrix W_f / W by SPS

Controlled amount of fine scale matrix porosity obviates need for fiber coating

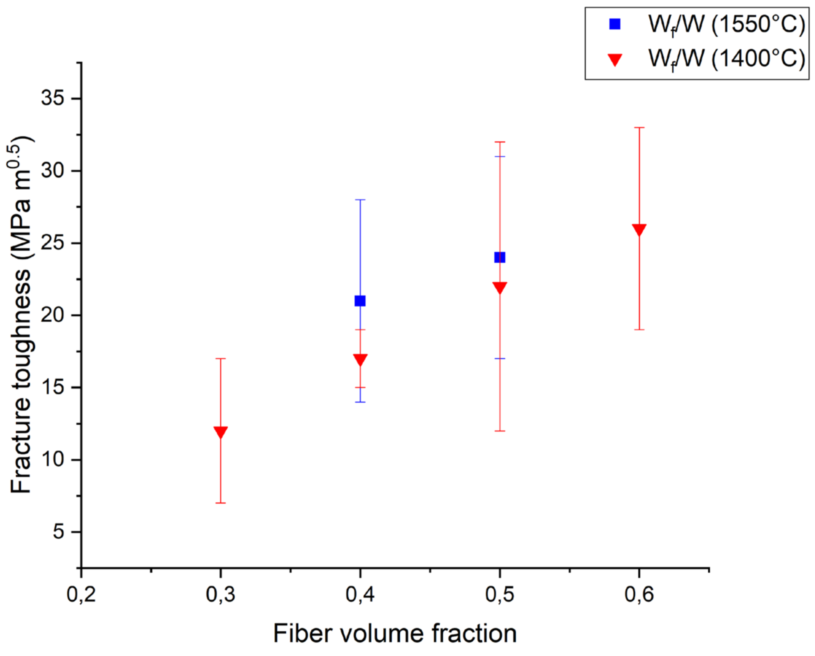
- Approach can be viewed as an extension of the porous coating concept
- Crack deflection occurs due to low fracture toughness of porous interphase

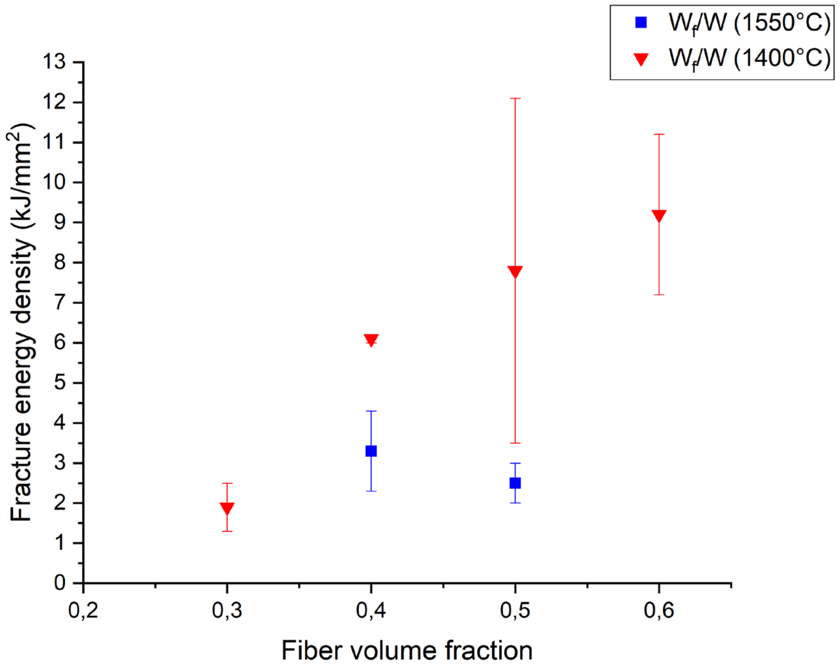


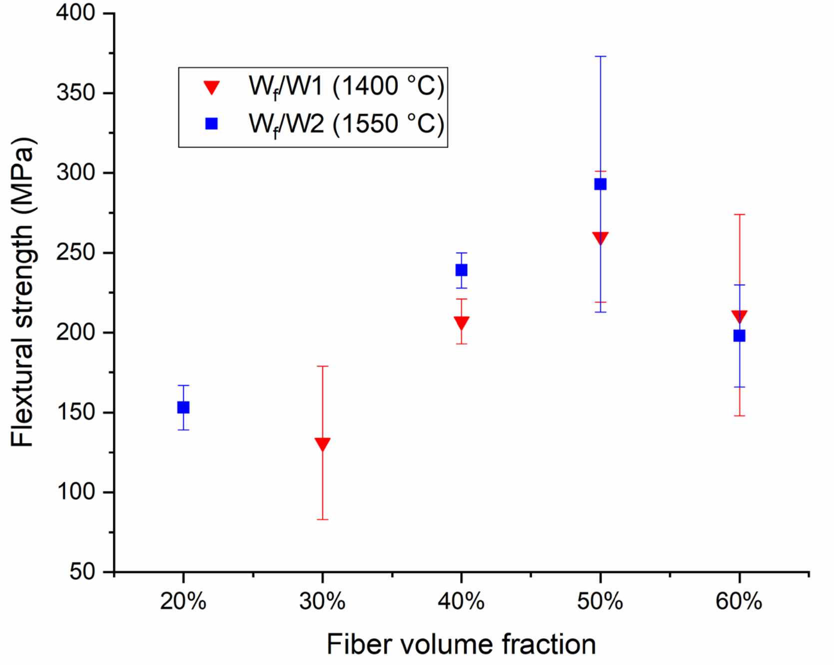
Compare to conventional W_f/W

+	No interface needed ➢ easy to produce	+	More homogeneous material ➢ no weak interface area
+	Lower process temperature ➢ less fiber recrystallization	-	Thermal conductivity reduced
		-	Retention?

Mechanical properties of porous matrix W_f/W

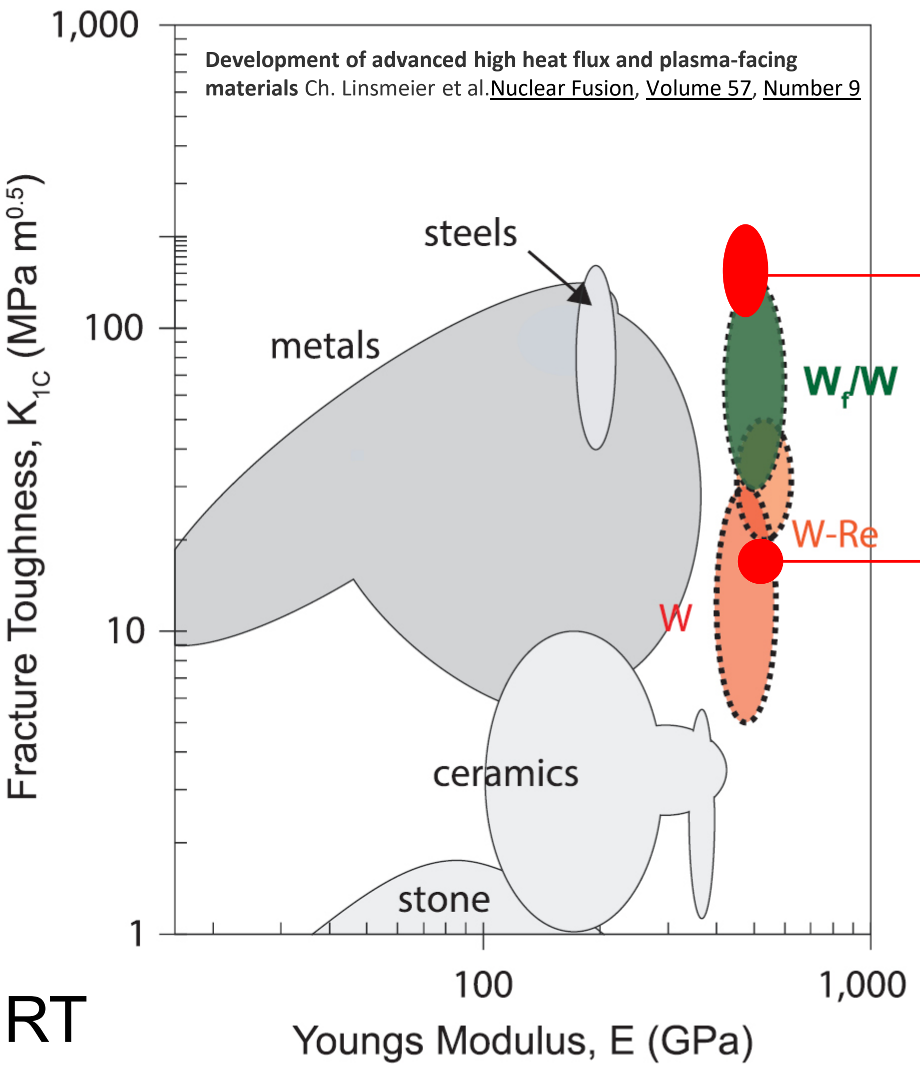






- improved AND tunable mechanical properties from 20-50 % fiber volume fraction
- strength loss above 50%: large voids and inhomogeneous densification (FAST)

Fracture toughness



Development of advanced high heat flux and plasma-facing materials Ch. Linsmeier et al. Nuclear Fusion, Volume 57, Number 9

at RT

H.Gietl 2018

As produced CVD W_fW K_Q

H.Gietl & Yiran Mao 2018

Heat treated CVD W_fW K_Q
Sintered PM W_f/W K_Q

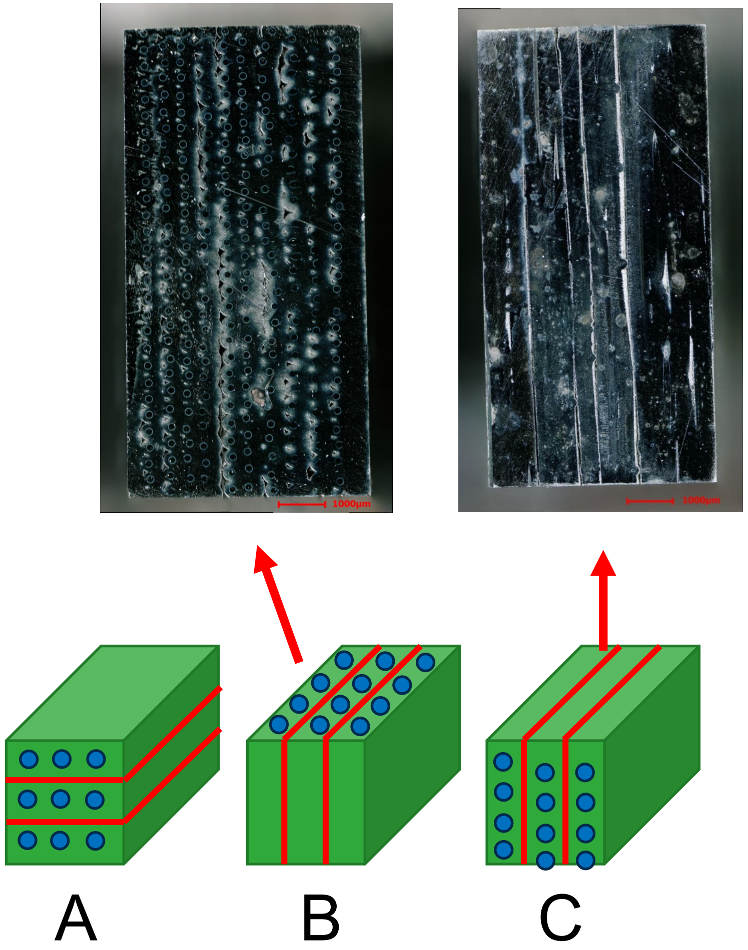
PLUS:

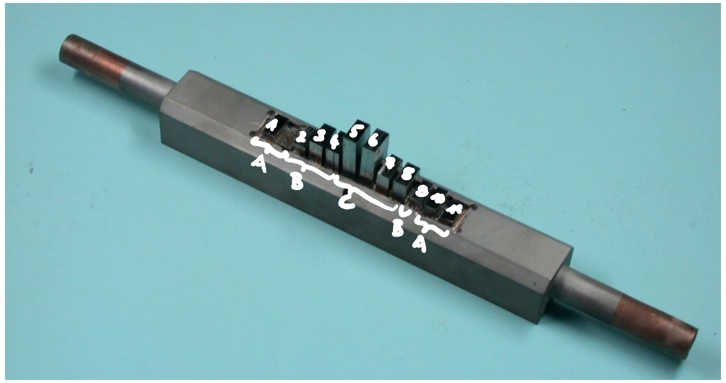
Stable crack growth in W_f / W

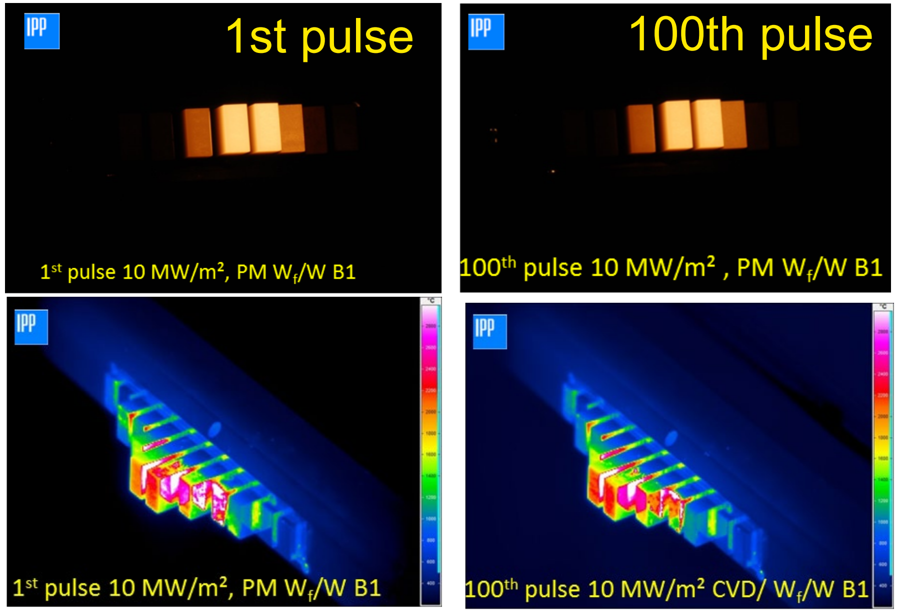
(vs. statistical failure in brittle bulk W)

High heat flux test: CVD and PM W_f / W

Small tiles brazed on actively cooled structure

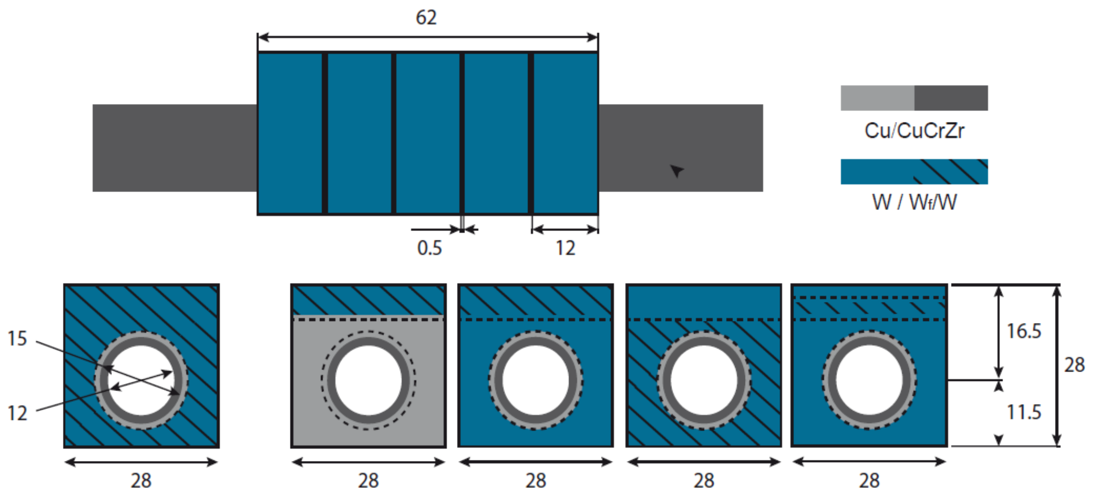


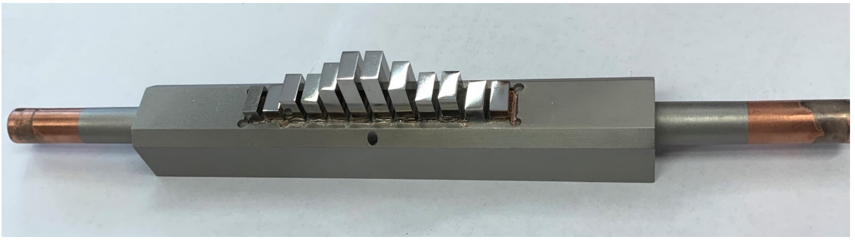




Upscaling of the production

- Large dimension samples need to be produced
  - more accurate mechanical testing
  - mock-up production

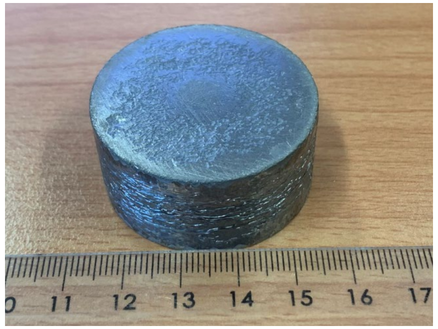




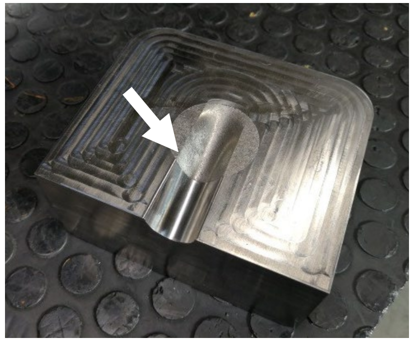
Sample with 300 mm diameter and 12 mm thickness in processing - 16.32 kg W_f/W

Production upscaling

FAST facility at IWM,
RWTH Aachen



Porous W_f/W 40 mm x 20 mm
~86% density, 40% fibers



Application in metal casting:
Melt-guiding part

Large-scale FAST facility at
U Hefei/China

Pure W, 100 mm x 10 mm
~88% density

Porous W_f/W, 105 mm x 30mm, ~89% density,
40% fibers

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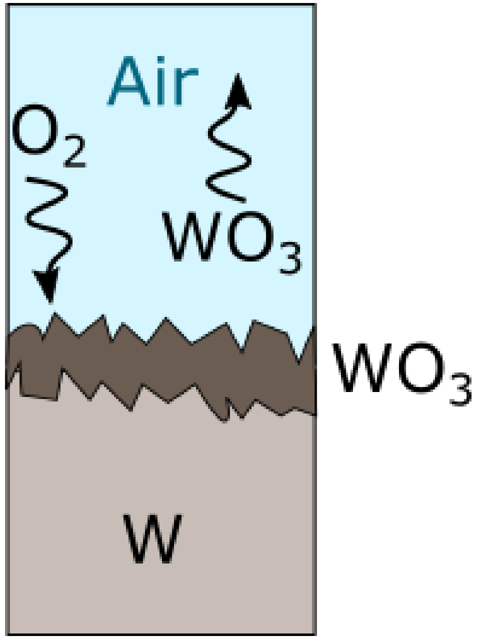
Summary and outlook

Tungsten based smart alloys

Fusion accidents & oxidizing environments

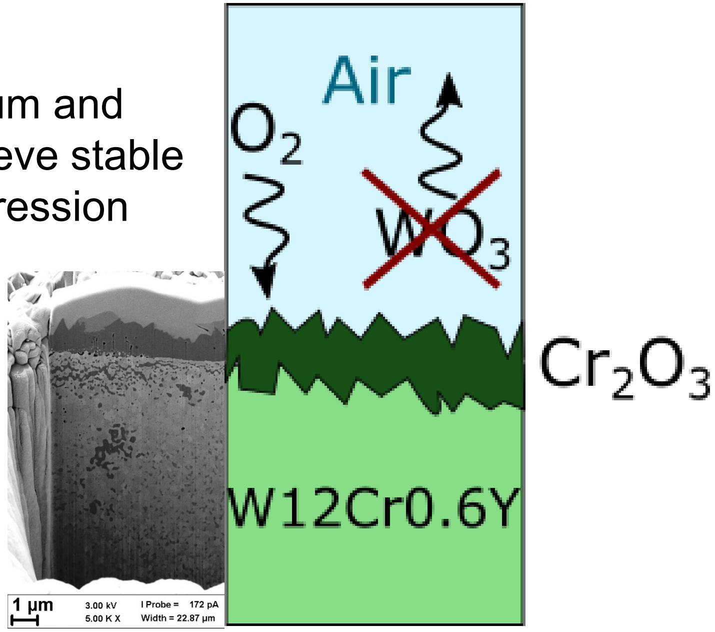


Challenge:
Suppress oxidation when utilizing refractories under oxidizing or accidental conditions. e.g. solar thermal power / fusion / furnace

1000˚C, 1 bar,

80 vol.% Ar+20 vol.% O_2, 10 hours

Utilize Chromium and Yttrium to achieve stable oxidation suppression



Develop a passivating alloy for intrinsic safety and oxidation resistance

RENNER

ceit IK4 Research Alliance

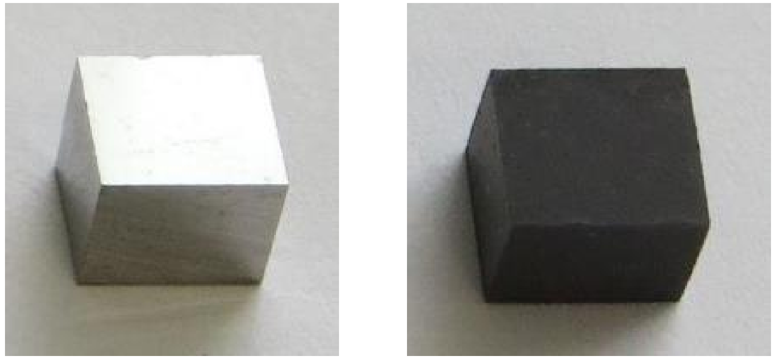
JÜLICH Forschungszentrum

W and W alloys

incl. self-passivating tungsten

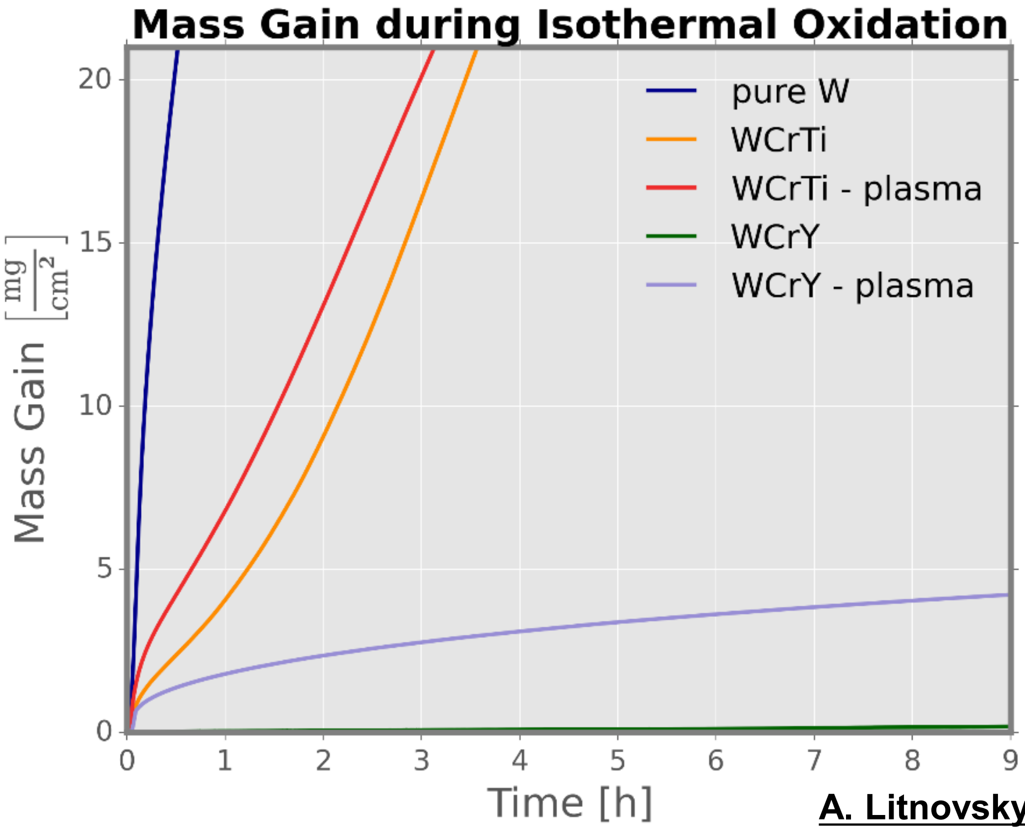
FAST production together with IEK-1

W-11.4wt%Cr-0.6wt%Y



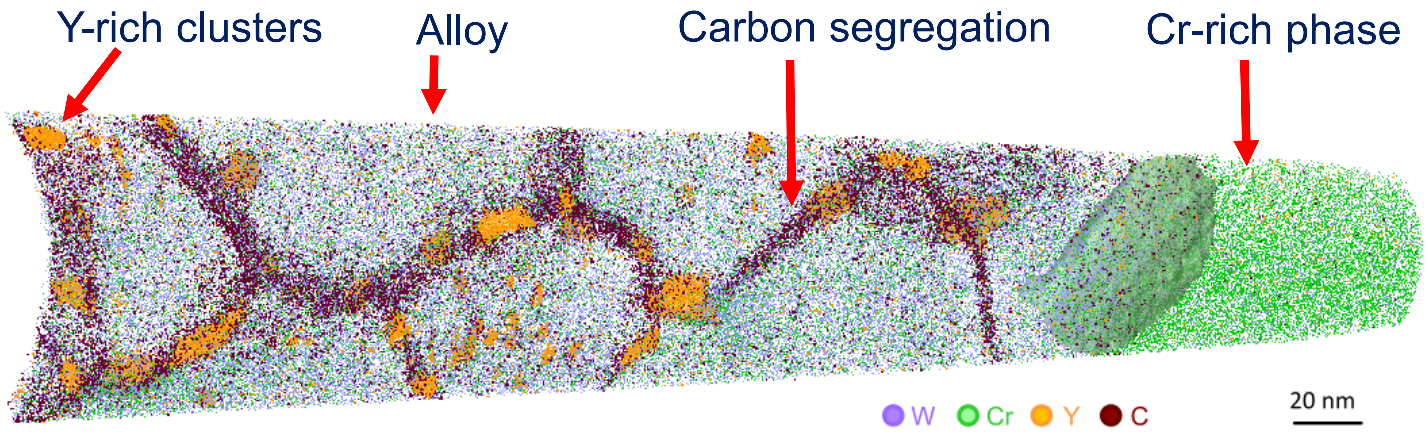
1000°C, 1 bar,

80 vol.% Ar+20 vol.% O_2, 10 hours



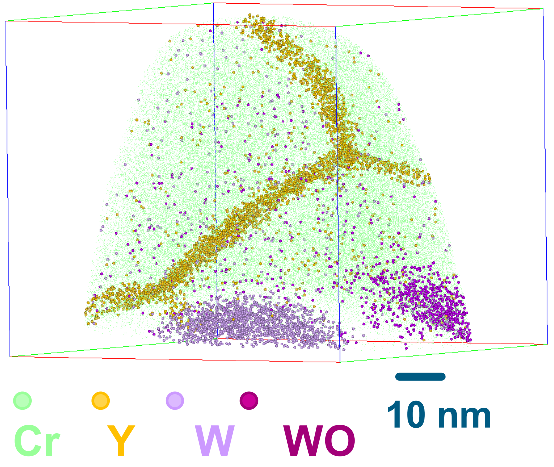
A. Litnovsky et al., Physica Scripta, T170, (2017)

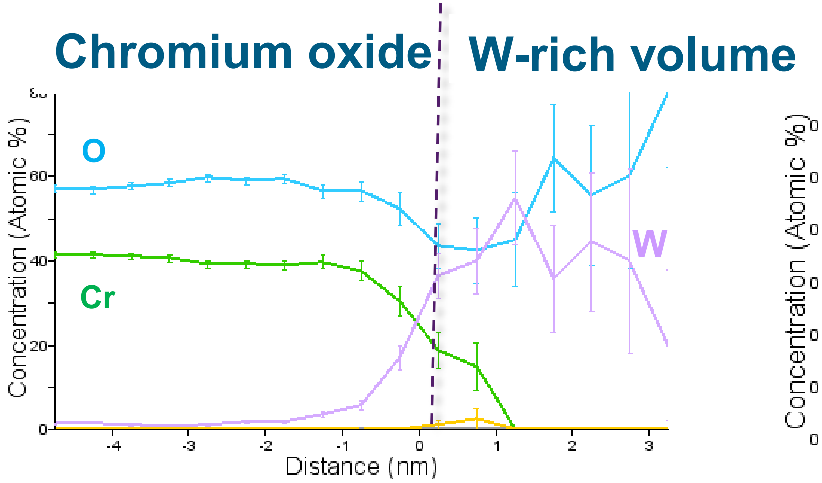
Fundamental investigations using APT on Bulk Material

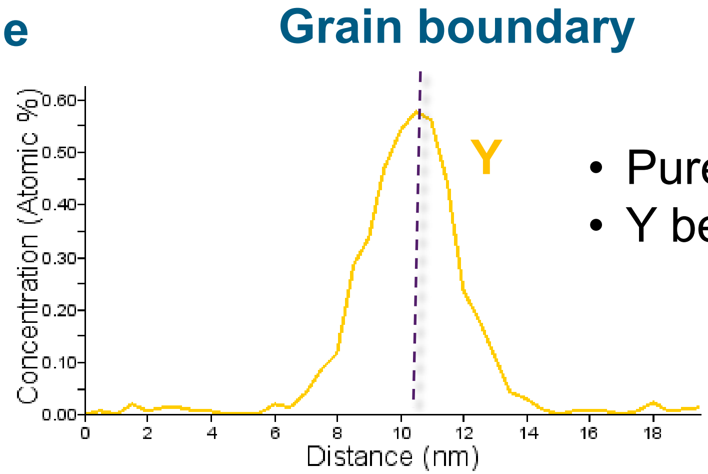


- Submicrometer WCr grains
- Y-rich nanoclusters

Protective oxide layer



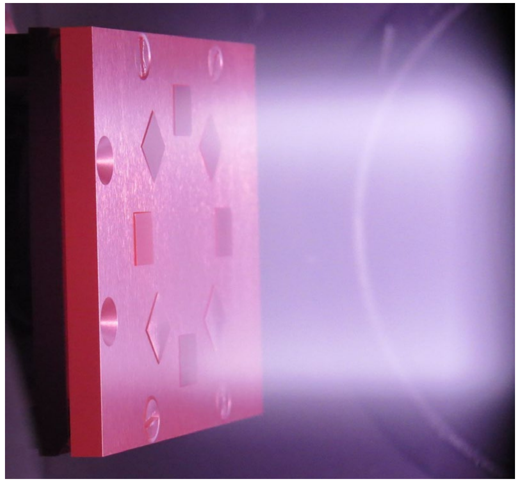




- Pure dense Cr_2O_3
- Y between Cr_2O_3 grains

Smart alloys under DEMO-relevant conditions

D steady-state plasma

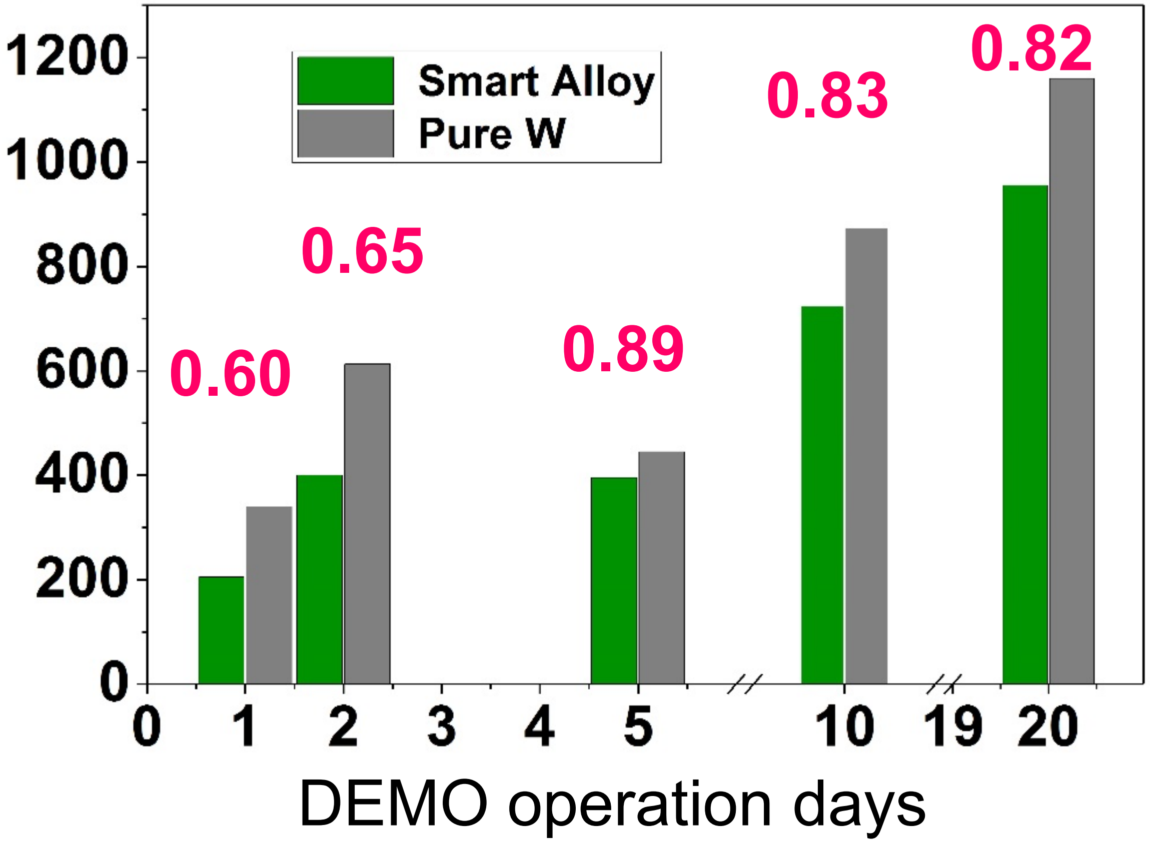


- ➢ T_{sample}: 600-650°C
- ➢ Ion energy: 120 eV
- ➢ Smart Alloys and pure W
- ➢ Identical exposure conditions

$R = m_{alloy}/m_W \sim 0.82$

- **Higher mass loss for pure W**

Mass loss, microgram



- **No additional loss of Cr, Y**

Industrial upscaling

- Sample size: 10 cm × 10 cm ×6 mm
- Sample mass: 760 g
- Maximum sintering temperature: 1460°C
- Pressure: 50 MPa
- Temperature ramp: 200°C/min
- DC current

Parameters of laboratory scale sintering preserved in industrial upscaling

Minor technical corrections in sintering cycle needed

Further sintering planned

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Summary and outlook

Hydrogen isotope permeation

Hydrogen diffuses easily in metals – Important in various application fields

Fusion – Safety issue

- 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

Concentrated solar power

- Hydrogen from thermal decomposition of heat carrier
- Diffusion through glass into insulating vacuum

⇒ Efficiency reduction of plant

Alternative chemical energy carriers, Hydrogen system

- Thermochemical synthesis: syngas, water gas shift reaction (H_2, CO, CO_2, CH_4)
- Loss of H_2: reactors, power plants
- Transport and storage of hydrogen

⇒ Wide ranges of temperature and composition for H_2 permeation

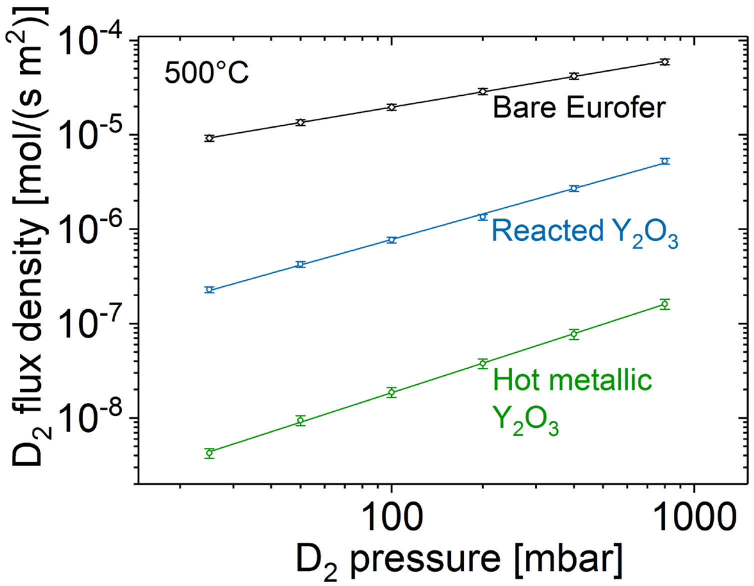
Comparison of deposition modes: Y_2O_3

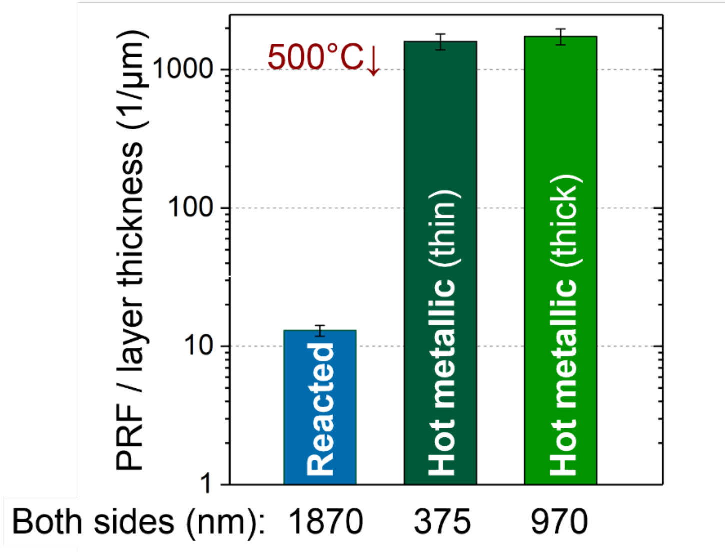
→ Regime: Reacted Y_2O_3: $J \sim p^{0.75}$, Hot metallic Y_2O_3: $J \sim \sqrt{p}$ → diffusion limited

→ The performance is strongly dependent on deposition mode:

  → Large differences in microstructure

  → The permeation reduction factor ($PRF = J_{sub}/J_{barrier}$) is different by two orders of magnitude



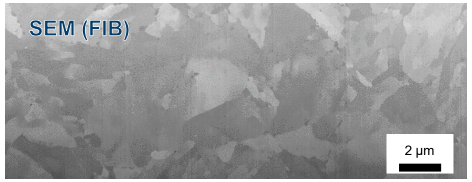


Improvement of microstructure → Performance strongly enhanced!

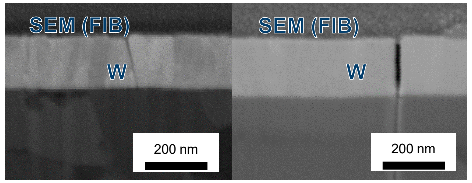
Tungsten nitride

A new tritium permeation barrier ?

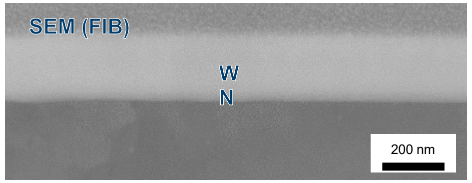
Deuterium permeation studies on Eurofer97 with different WN layers:
- Comparison of different systems in order to understand the barrier effect



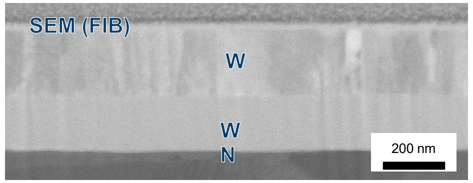
Polished Eurofer97 (Eu97):
- Reduced activation steel (DEMO)
- Martensitic/ferritic (~ 9% Cr, 0.1% C)
- Crystal structure: distorted bcc
- ‘Mirror’ polished
- Used as substrate



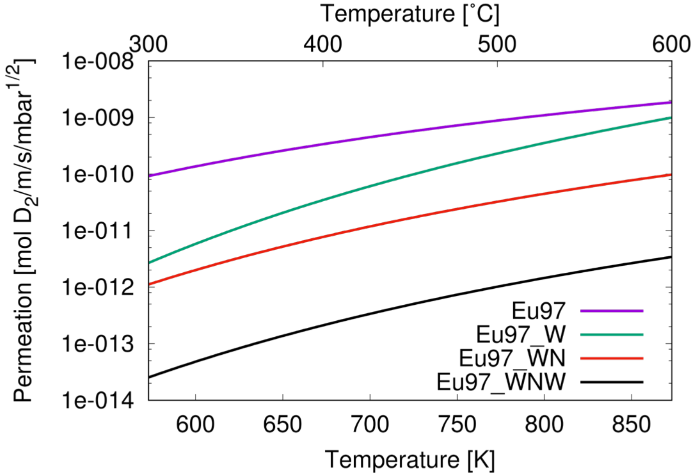
Eurofer97 with W layer (Eu97_W)
- Magnetron sputter deposition
- Layer thickness: 180 nm
- Cracks: different thermal expansion coefficients of Eu97 and W, left: after annealing, right: after measurement

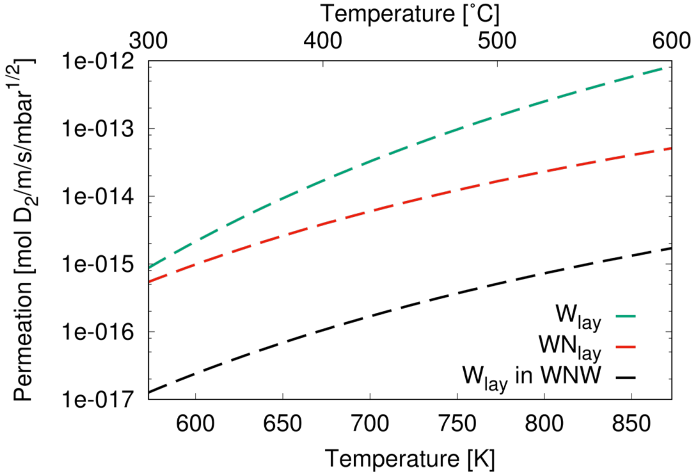


Eurofer97 with WN layer (Eu97_WN)
- Reactive magnetron sputter deposition
- Layer thickness: 210 nm
- Smooth layer
- No cracks after measurement



Eurofer97 with WNW layer (Eu97_WNW):
- Thickness: WN: 170 nm, W: 220 nm
- Microstructure of W layer similar to Eu97_W sample
- No cracks after measurement





- WN and WNW layers are very suitable permeation barriers
- A thickness and substrate independent calculation of the layer permeation is possible
- D permeation through non-cracked W layers is nearly two orders of magnitude lower as through WN layer

Outline

Introduction: the challenge for materials facing the plasma

Research tailored towards new materials

- Extrinsic toughening: composite materials
- Intrinsic safety: smart alloys
- Hydrogen isotope permeation: barrier layers
- Irradiation damage: >15 MeV protons as fusion neutron proxy

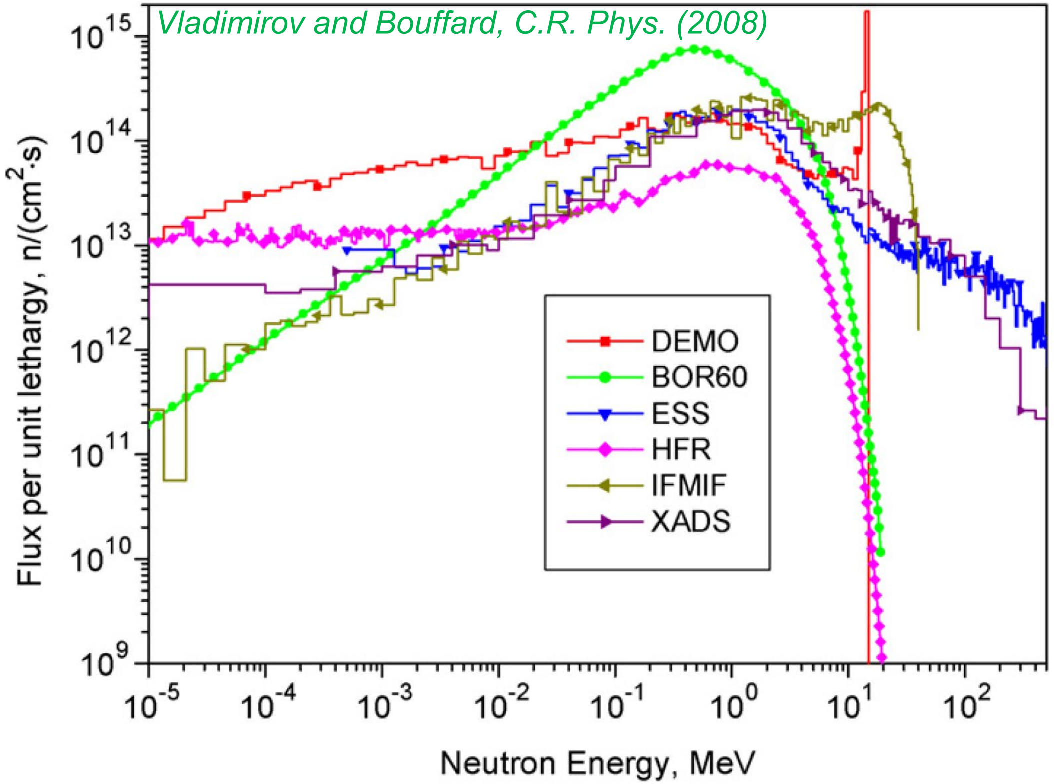
Summary and outlook

Radiation damage to fusion materials

Damage induced by fusion neutrons

- displacement damage (scattered and recoiled particles)
- transmutations (low-Z: H, He formation; high-Z: new elements)

BULK damage due to long range of neutrons matter (dimension: mm)



Path to materials for the realization of fusion energy

- ITER
- IFMIF - DONES

time scales: 10 years and longer

Solution: fast protons as fusion neutron proxy

Radiation damage: comparison for tungsten

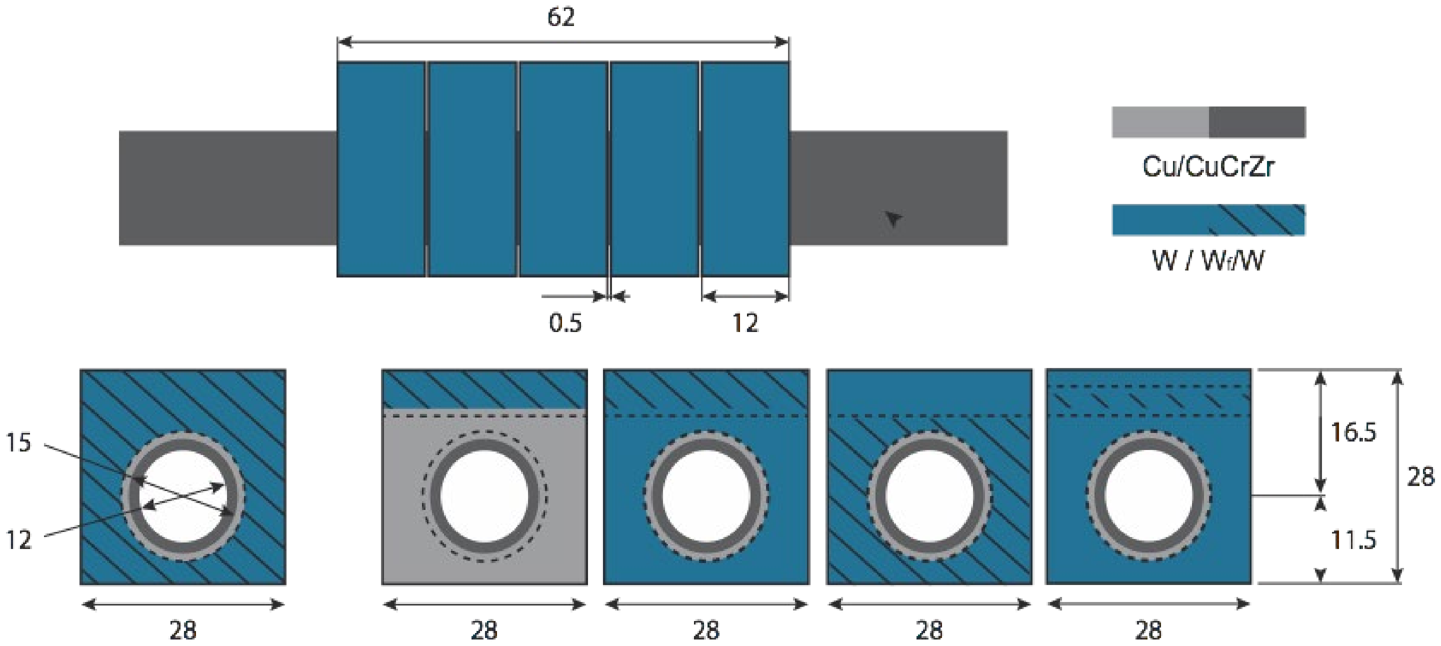
Description (for 1 dpa)	**Heavy Ion Accelerators**	**Fission Reactor (HFIR)**	**Spallation Sources**	**30 MeV Protons**	**DEMO Reactor's First Wall**
Maximum PKA energy	>> 1 MeV	40 – 150 keV		600 keV	300 keV
Required time	~ Hours	~ 1 year		2 days	3 months
Thickness / depth / range	1 -10 µm	200 µm, up to 4 mm	200 µm, up to 4 mm	500 µm	-
Hydrogen production	0	0.01 appm	1 appm (expected)	29 appm	1 appm
Helium production	0	0.01 appm	0.1 - 0.01 appm (expected)	7.2 appm	0.5 appm
Rhenium production	0	50,000 appm	300 - 500 appm (expected)	401 appm	700 appm
Remarks	No relevant transmutation	Thermal neutrons lead to biased damage	Spallation produces large number of transmutated products not actually produced in DEMO	Hot Material Laboratory Required	[Gilbert et al.]

Building a component

Advanced materials add operational space to conventional approaches

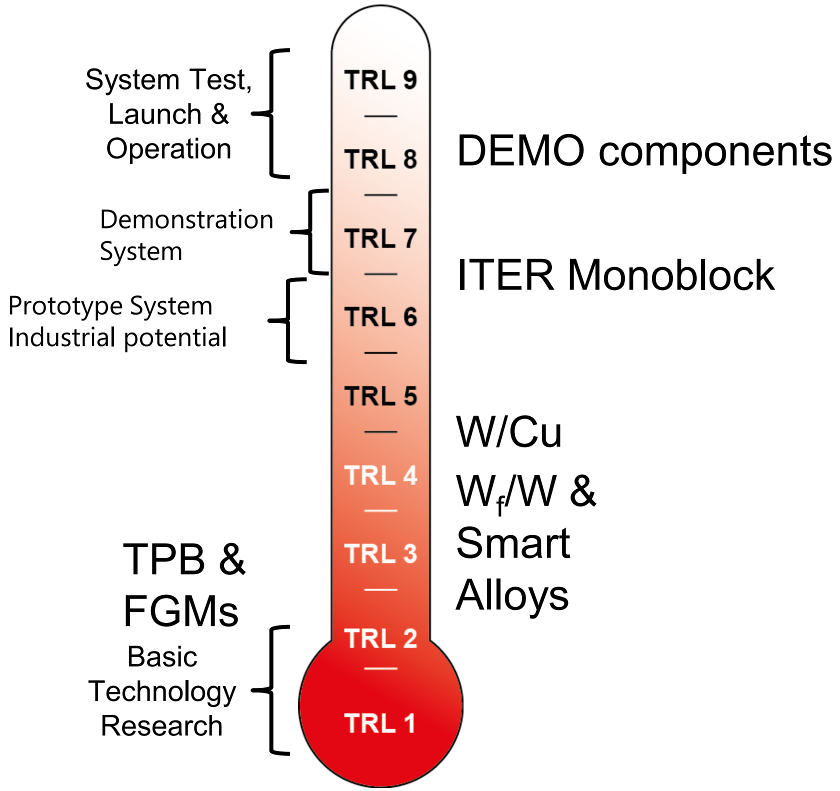
Now combine them …

& WF_6



The next steps

- Integrate efforts towards new materials to components
- Understand neutron effects on materials in new test campaigns
- Build mock-ups and test components
- Test samples and components under systemic loading conditions:
  - linear plasma devices
  - confinement devices
- Integrate new concepts in DEMO design



System Test, Launch & Operation

Demonstration System

Prototype System Industrial potential

TPB & FGMs

Basic Technology Research

TRL 9

TRL 8

TRL 7

TRL 6

TRL 5

TRL 4

TRL 3

TRL 2

TRL 1

DEMO components

ITER Monoblock

W/Cu

W_f/W & Smart Alloys

Technology Readiness Level (TRL)