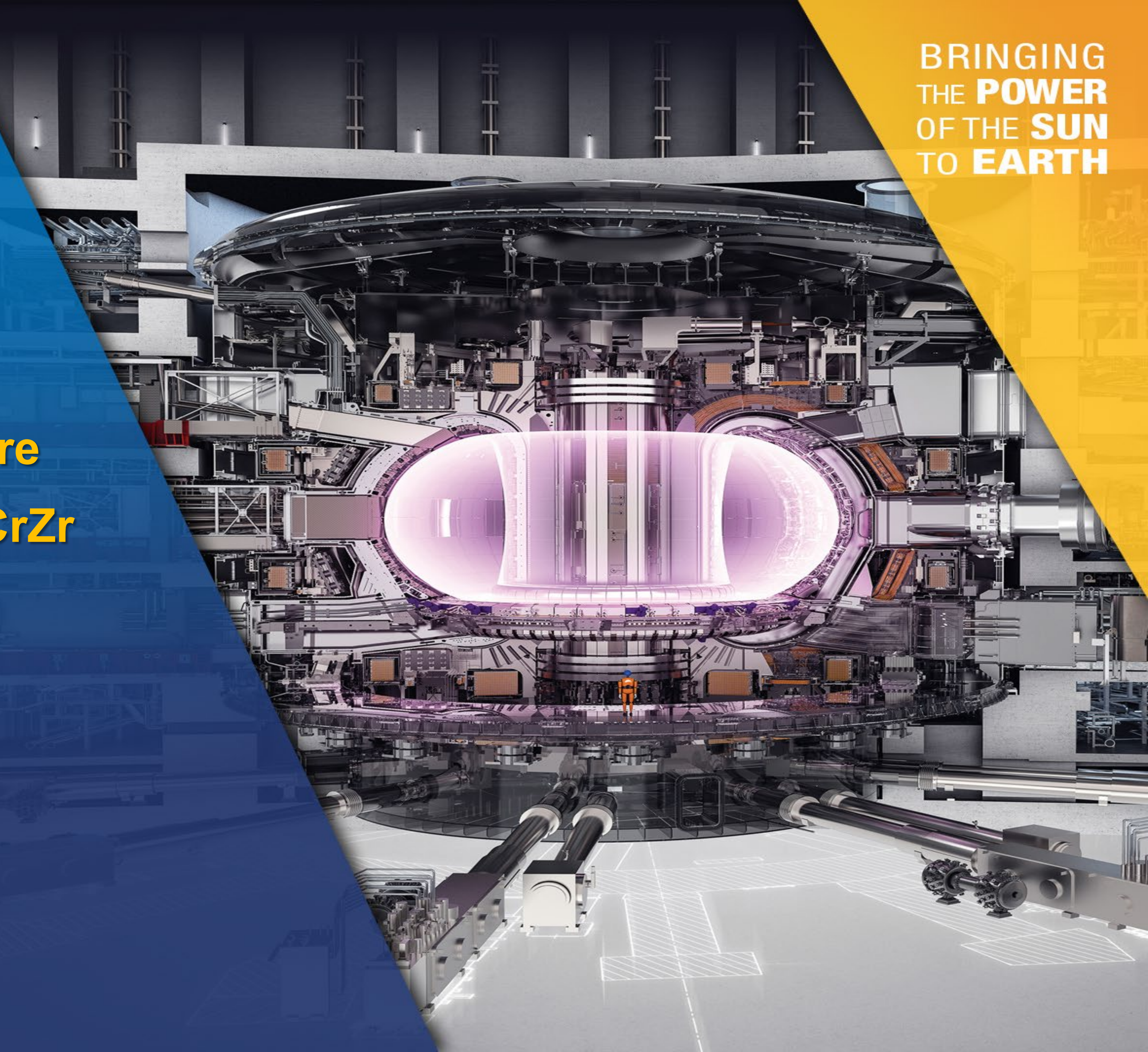
FUSION FOR ENERGY

BRINGING THE POWER OF THE SUN TO EARTH



Feasibility Study to Manufacture Tungsten and Tungsten to CuCrZr Gradient Joints

Stefan Wikman

Materials & Manufacturing
Group Leader

Why participate in Tungsten Development?

- Fusion is a quickly expanding field, spin-offs and much more than ITER.
- Achieve unique qualification of a material/process/component and be ready for the next step.

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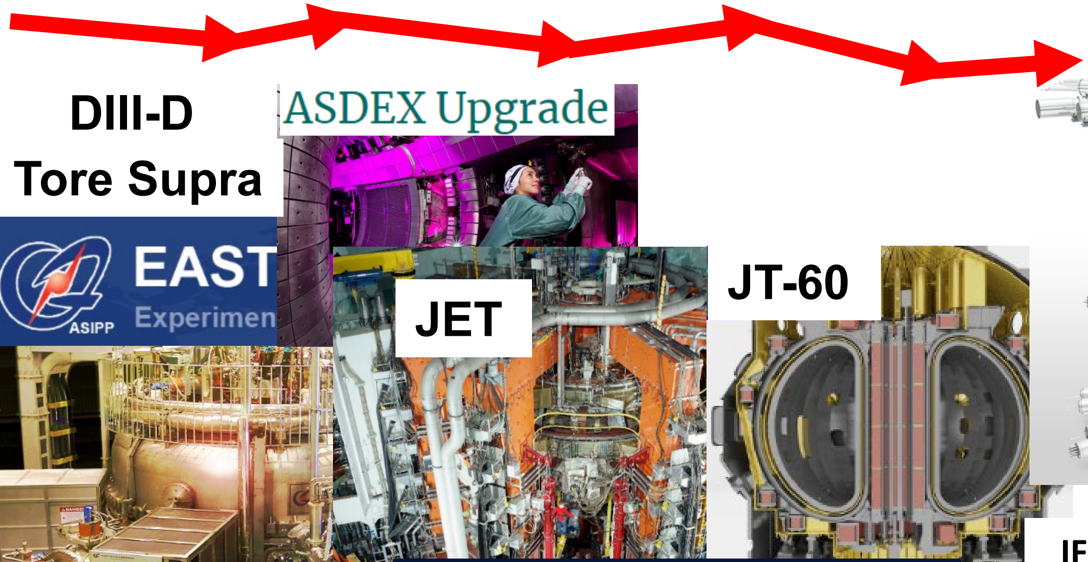
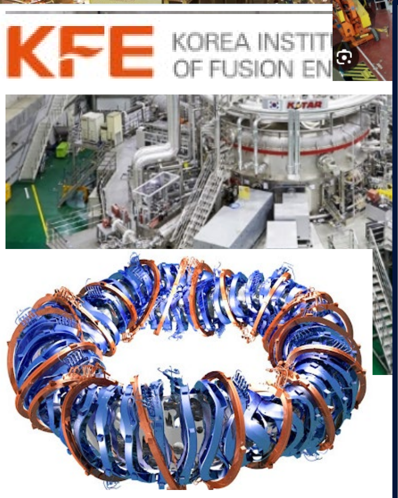
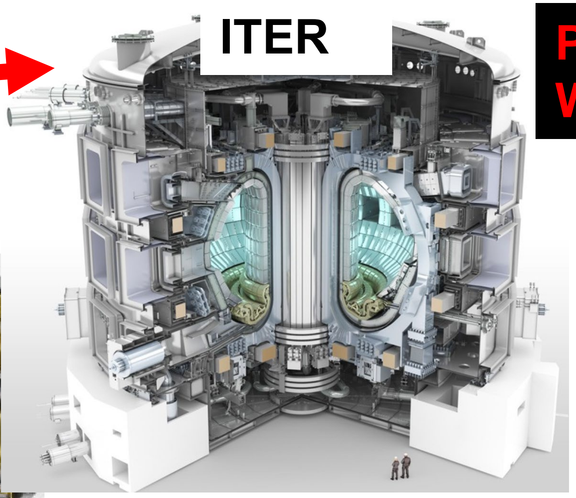




Wendelstein-7x

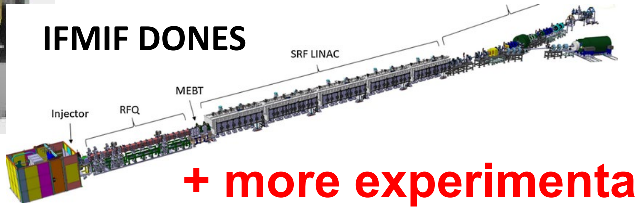
National Ignition Facility (NIF)
Successful plasma initiation

192 laser beams into a target of frozen deuterium-tritium

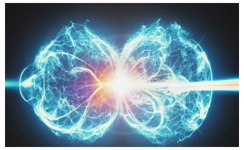


Plasma Facing Materials
W- & W-Alloys the prime candidate

Power Plant – still no defined concept



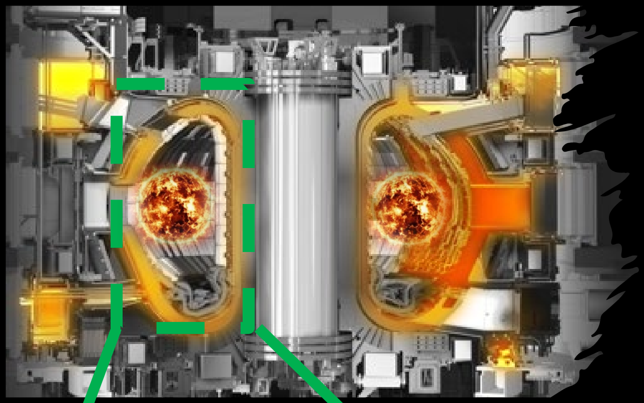
+ more experimental upstart enterprises adding up



Fusion as Energy Source

Effects of making “little sun” on Earth

As good materials as reasonably achievable needed

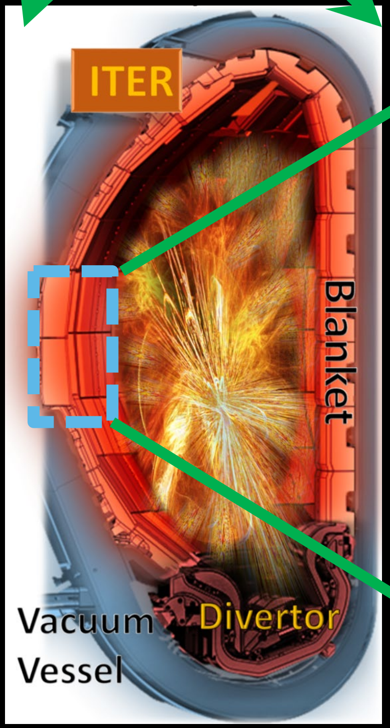


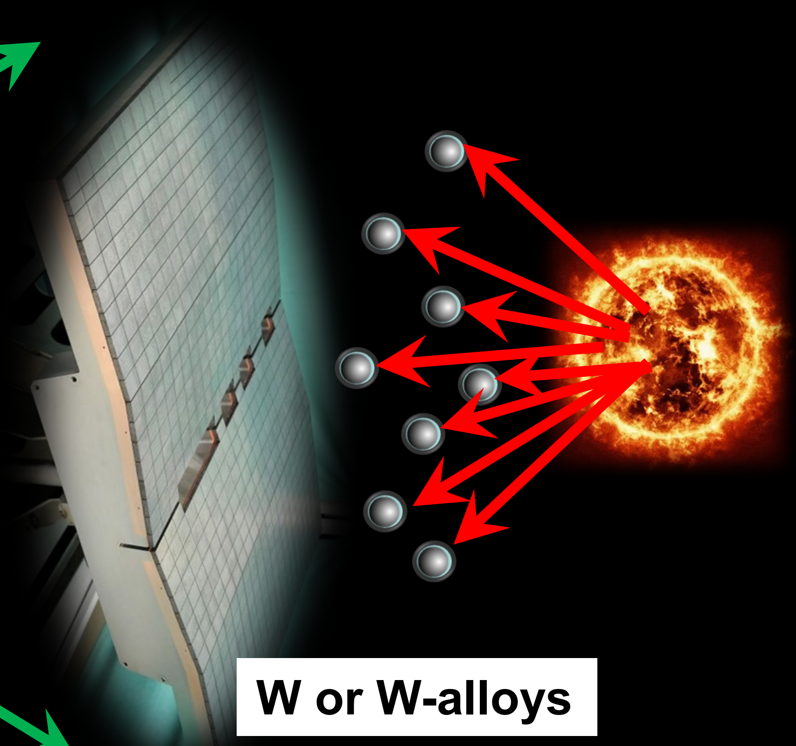
High energy neutrons will collide with the walls and generate

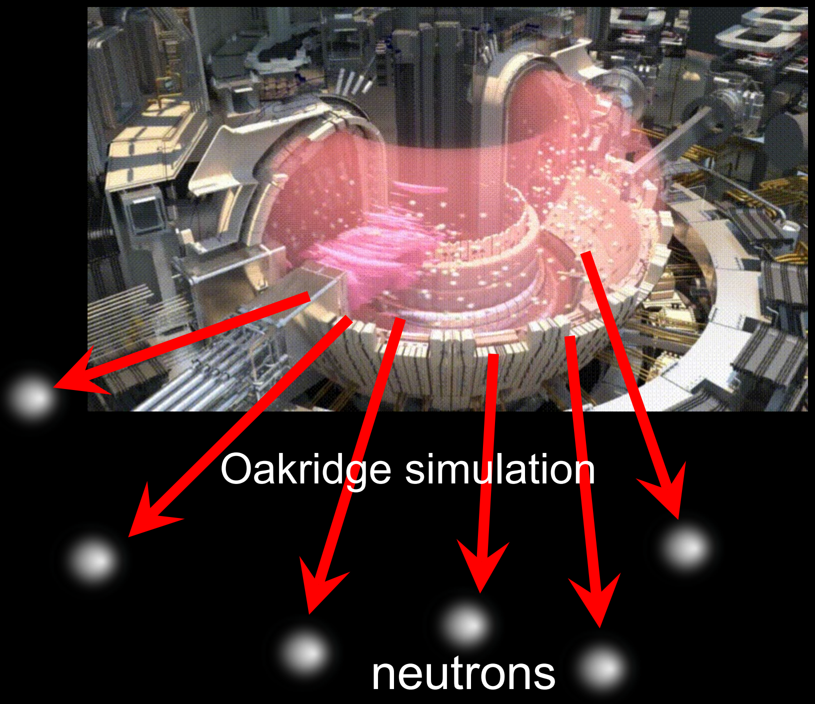
- Gamma γ
- Transmutation of atoms
- Damage
- Hardening and materials property changes

\+ Thermal loads from the plasma

Fission neutron (fission moment): “5000 – 20000” km/s
Thermal **neutron** to maintain fission: 2.2 km/s (0.025 eV)
Fusion neutron: 52000 km/s !!!!!
“Speed of light 300000 km/s”



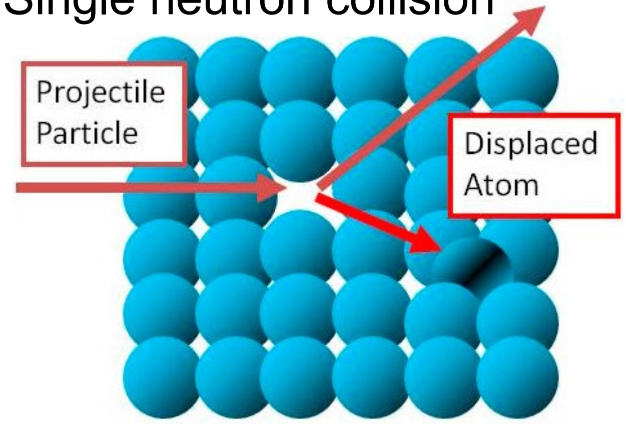




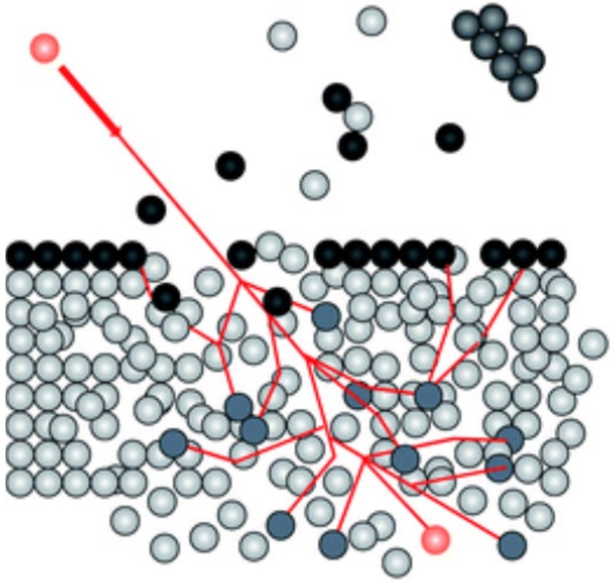
Why is plasma facing materials in an exclusive group?

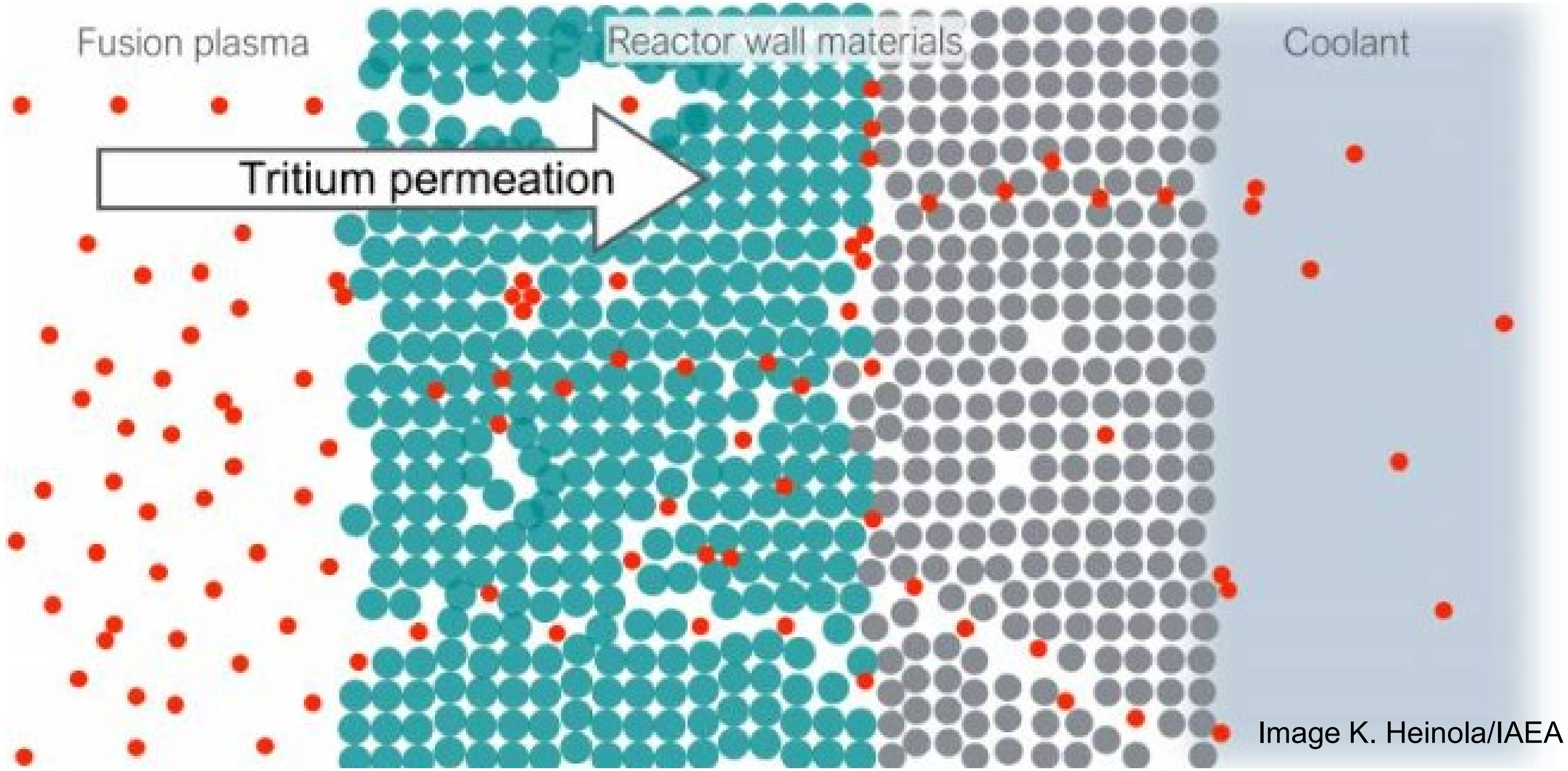
Neutron damage influence on vacuum properties and hydrogen retention

Single neutron collision



Chain reactions of cascade collisions





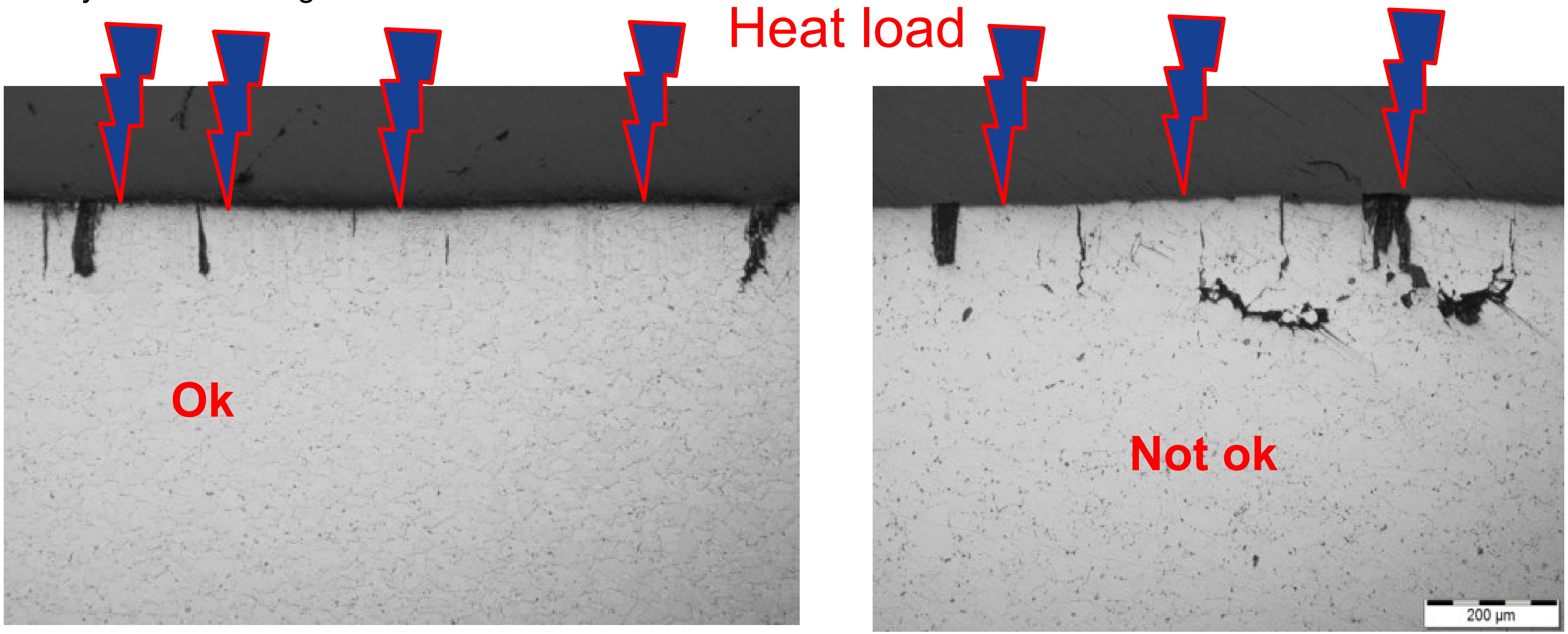
Tritium is rare and valuable -> priority to avoid losses into walls.

Neutrons are important -> kinetic energy heating & tritium breeding
But… fast neutrons generates damage.

Why is plasma facing materials in an exclusive group?

Crack propagation and avoiding or controlling melting is important

Case study: Plasma facing materials



Material designed for crack propagation
(Heat Flux Testing to benchmark all grades at FZJ, Germany)

Tungsten properties & Ductile to Brittle Transition Temperature, DBTT
Background to W-development

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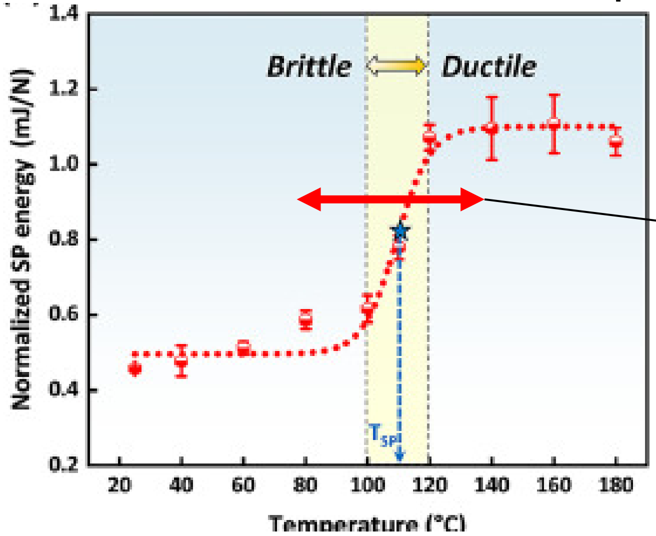
Tungsten has the highest ultimate strength of the pure metals
Mechanical properties strongly dependent on manufacturing route
Ultimate Strength (typical): ~1500 MPa
Yield Strength (typical): ~ 940 MPa (450 - 1640 MPa reported)

Ductile to Brittle Transition Temperature



This curve can be modified left/right by many means for W

❖ **Impurities impact on tungsten DBTT**

Impurities, as carbon and oxygen, play a significant role in tungsten's DBTT.

Carbon embrittles intergranular structures, increases dislocations, and generates intercrystalline forces. Oxygen, when reaching the same concentration as carbon, affects DBTT in single-crystal and polycrystalline tungsten.

❖ **Grain size impact on tungsten DBTT**

Tungsten grain size affects DBTT, with growing grains demonstrating higher DBTT.

❖ **Influence of neutrons on DBTT**

Neutron irradiation shifts DBTT to higher temperatures.

❖ **Effect of tungsten fabrication on DBTT**

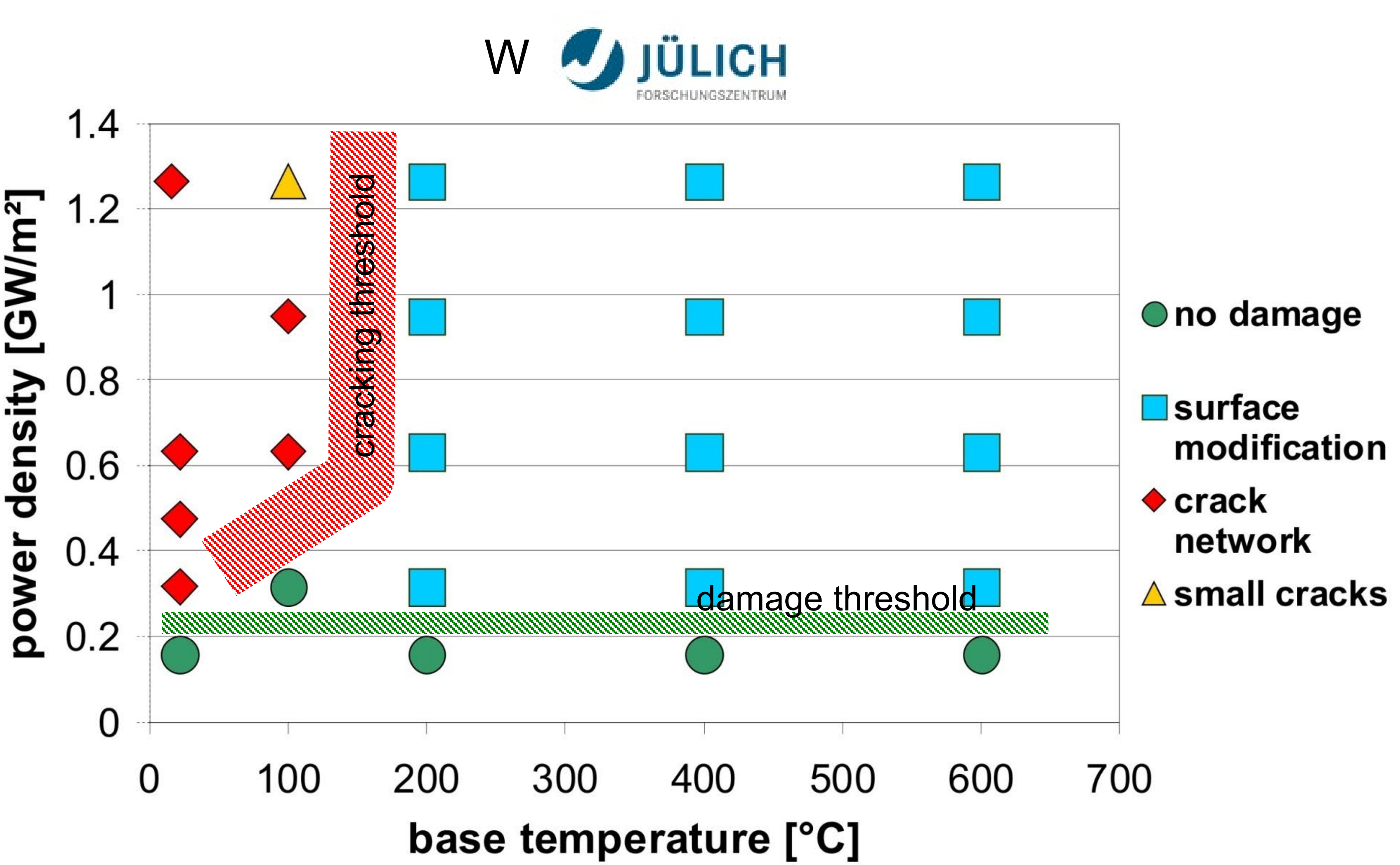
Fabrication methods significantly influence tungsten's DBTT. Annealing temperature, duration, and cold work also affect DBTT.

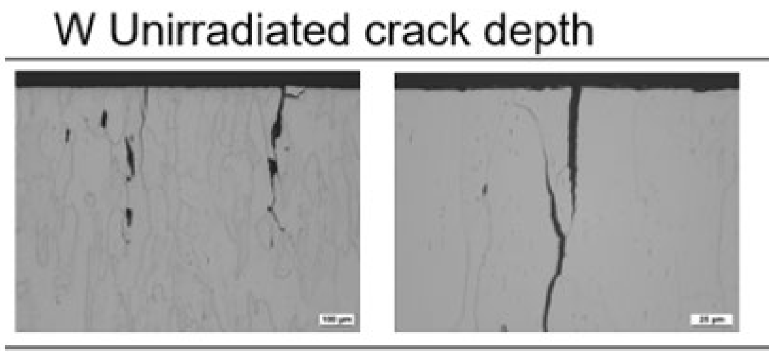
❖ **Surface condition impact on tungsten DBTT**

Surface treatments improve tungsten's DBTT by removing scratches, cracks, and impurity top layers.

Transient heat load tests on tungsten

Example with randomly picked W-grade





100 cycles with a duration of 1 ms; absorption coefficient: 0.46

Tungsten development for the Divertor

Basic conventional route (today other routes available as AM for example)

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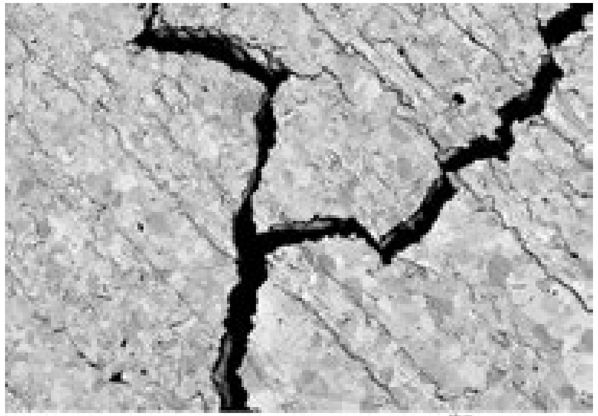
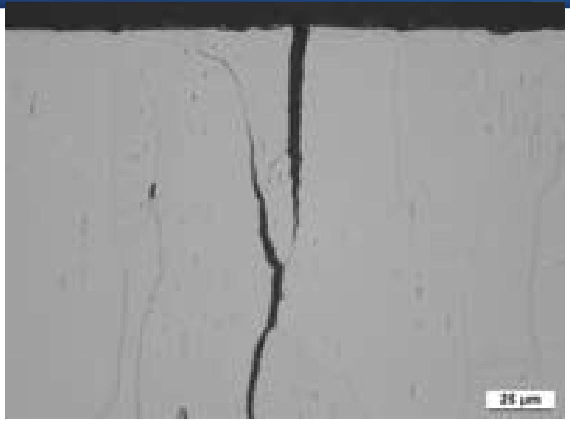
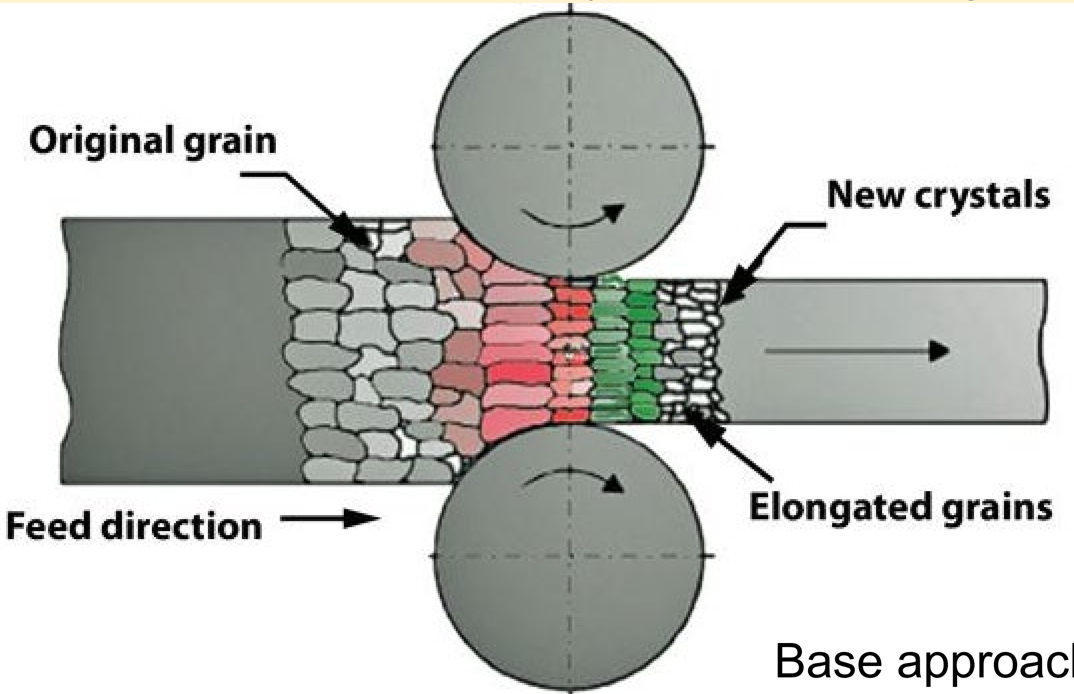


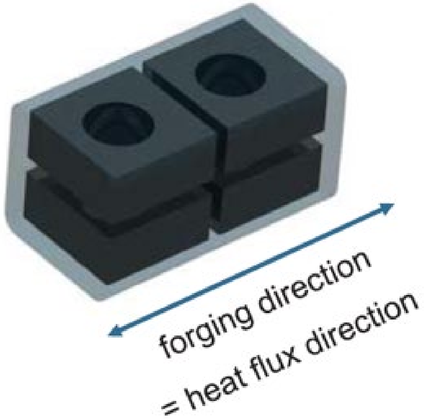


If we know W will eventually crack, then design for it

Many variants tested
3D printing
Sintering
Forged
Hot rolled
Injection molding
…



Base approach



Review Tungsten & Beryllium

Materials properties

	W	Be	Fe	Cu	B
Density [g/cm3]	19.3	1.85			
Melting Temp. [°C]	3420	1275			
Thermal conductivity [W/m°C]	164	216	*16.3 (316L*	*398*	
Thermal expansion coeff. [µm/m°C]	4.4	11.5	*17 (316L)*	*16.7*	
Neutron scattering cross section [barn*]	4.6	6			
Neutron capture cross section [barn*]	18.4	0.0092	*2.56*	*3.78*	*760*

~10x more weight (if same thickness)

~ joining W to Cu/CuCrZr more demanding

~ 25% difference at RT

~ re-design for thermal chock fatigue of joints

~ 2000x difference for neutron interaction nuclear heating & significant increase of secondary gamma radiation

Barn*: Possible incidents with neutron passing through area of 10^{-28} m^2

Qualification for ITER

- **Definition of Design Criteria –** *What properties shall be met to withstand operational conditions?*
  - *✓ Ok, based on pure W and Divertor results reliable*

- **Definition of Acceptance Criteria –** *What is an acceptable defect/performance?*

  An acceptance programme can never fully guarantee the performance of “million” tiles in the machine. Hence the acceptance programme has to be balanced against:

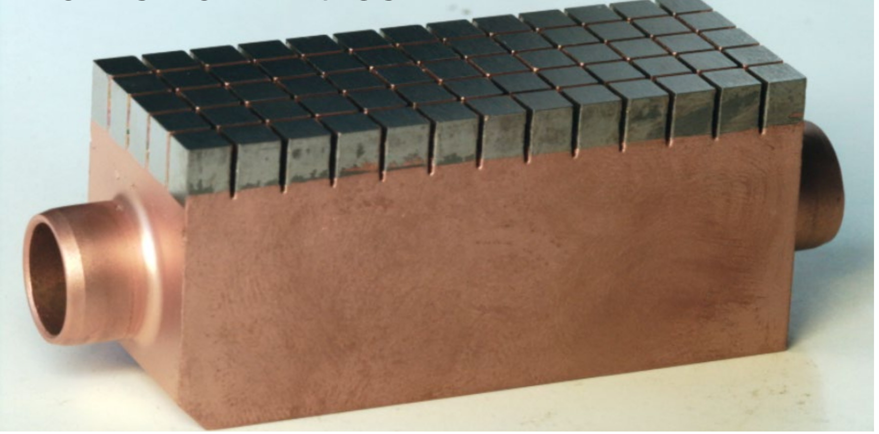
  - The ease with which the components can be replaced, and/or
  - The ability of the components to operate with detached tiles/other defects

- **Qualification According to Codes & Standards**

  Variants of tests based on manufacturer and design (i.e. heat flux testing and lots of data to compare/extrapolate with Divertor data)

- **Irradiation Campaigns at ITER Relevant doses**
  - *✓ Ok, based on pure W and Divertor results reliable*

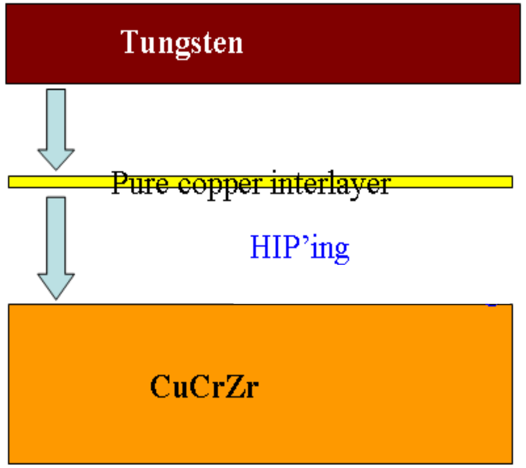
How small W-tiles?



First Wall heat load less than for the Divertor!

Joining by HIP is developed and reliable!

W to heat sink joints



Gradient Joint of W to CuCrZr

100% funding as aim is industrial feasibility and reproducibility for series production

Benefits:

+ No sharp joint interface with stresses from different thermal expansion

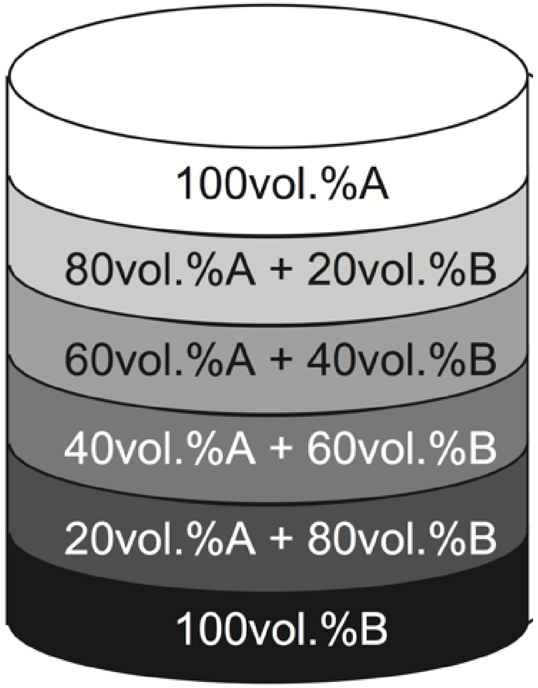
+ Diffusion of materials into each other more natural

+ Foster EU capacity and growth in the field

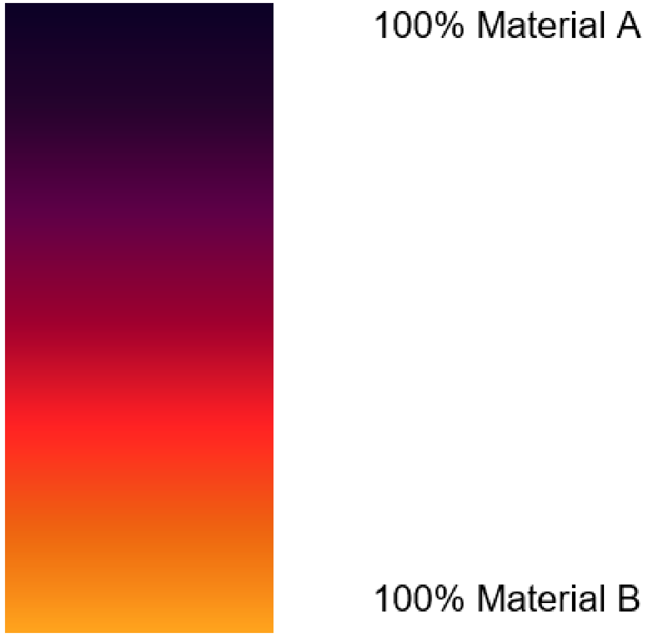
Tested in lab scale, but no industrial production yet and no suppliers on market

Aimed at 3 SME to develop in parallel
The EU W manufacturer to take the lead (not aimed at subcontracting a manufacturer)
Can collaborate/include labs/uni's for testing

A: Material A
B: Material B



Stepwise approach for gradient joint.



"Linear" composition changes for gradient joint.

Scope of work

Stage 1: Demonstrate reproducibility to manufacture Tungsten only with achieved good materials properties utilizing SME's developed manufacturing process. Aim is to ensure integrity of W **with 12 mm** thickness. Square tiles width around 20x20 TBD. Check Mechanical Properties and Microstructure.

Pure W-tiles are included in the present ITER baseline design – can be candidate for ITER First Wall

Stage 2: Demonstrate reproducibility of Tungsten/CuCrZr gradient material. At this stage, the CuCrZr is introduced to the manufacturing process. Gradient joint of at least 3 mm TBD.

Stage 3: Manufacture specimens for mechanical characterization and perform materials characterization of the joints. Specimens shall also be manufactured for future heat flux testing to be organized by F4E.

Gradient joints may also be of interest for ITER.

Follow-up projects:
- Exposure to heat flux and neutrons.
- Development of new W-alloys or other alloys

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