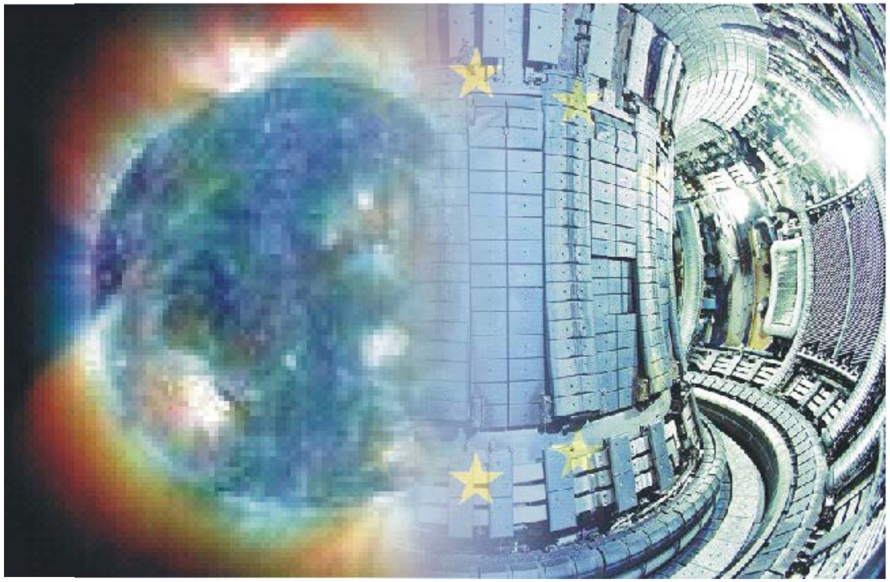
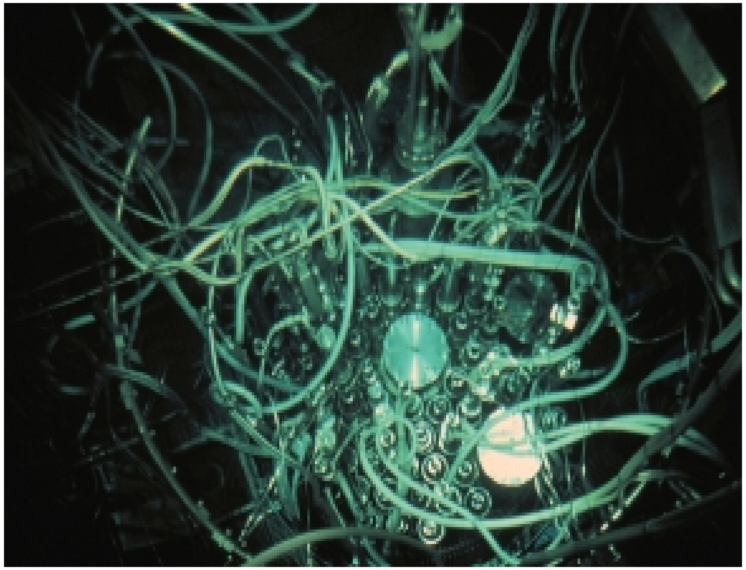
# Selecting materials for future energy sources: fusion reactor materials under irradiation

## Fusion Materials are not neutral to neutrons

Dmitry Terentyev, Fusion Project Manager

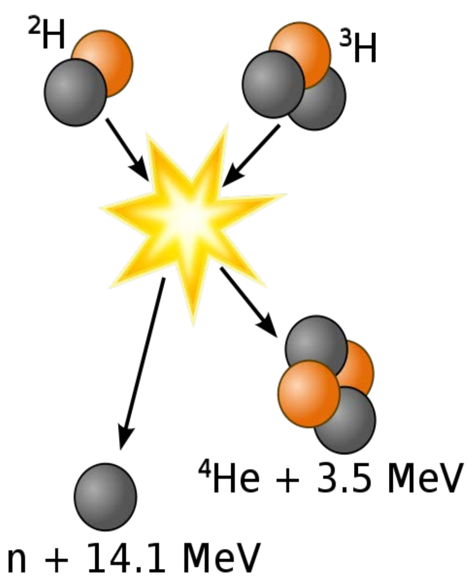
26/10/2015 Mol, Belgium



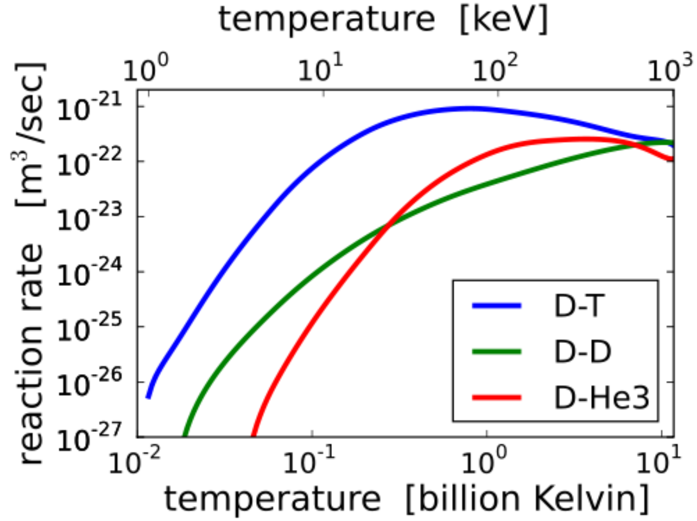


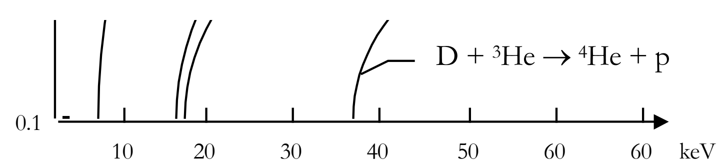
# What Thermo-Nuclear Fusion is about …

- Fusing light nuclei poses two major questions
  - How to reach billion Kelvin temperature ?
  - How to extract energy ?

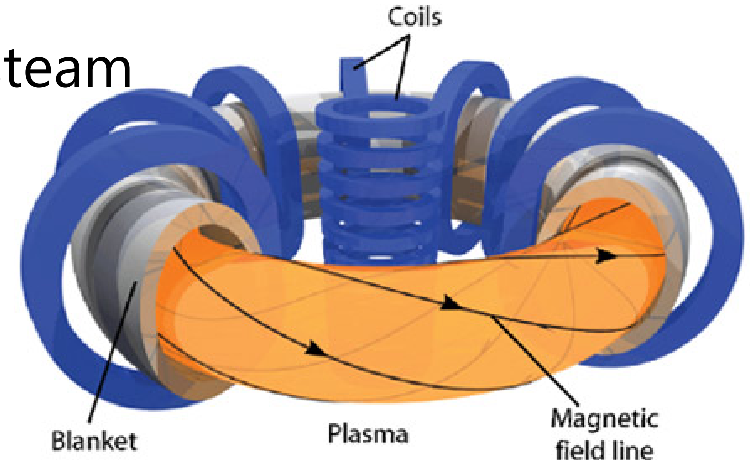

**Effective Cross Section (mb) of Fusion Reactions**

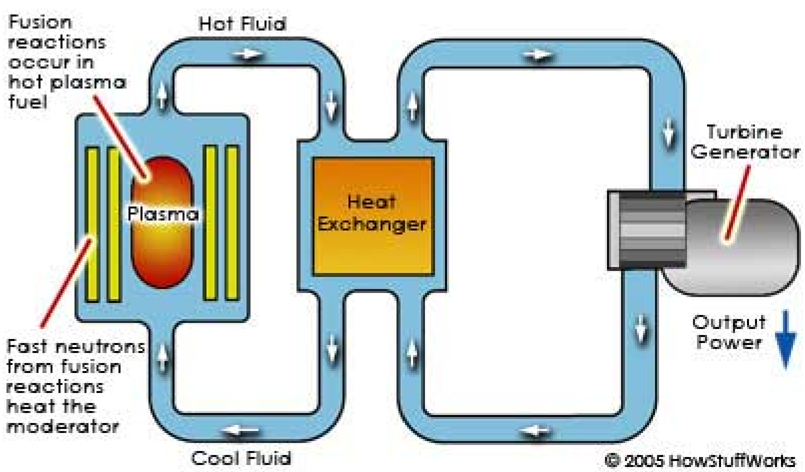


# Materials required to enable Magnetic Confinement

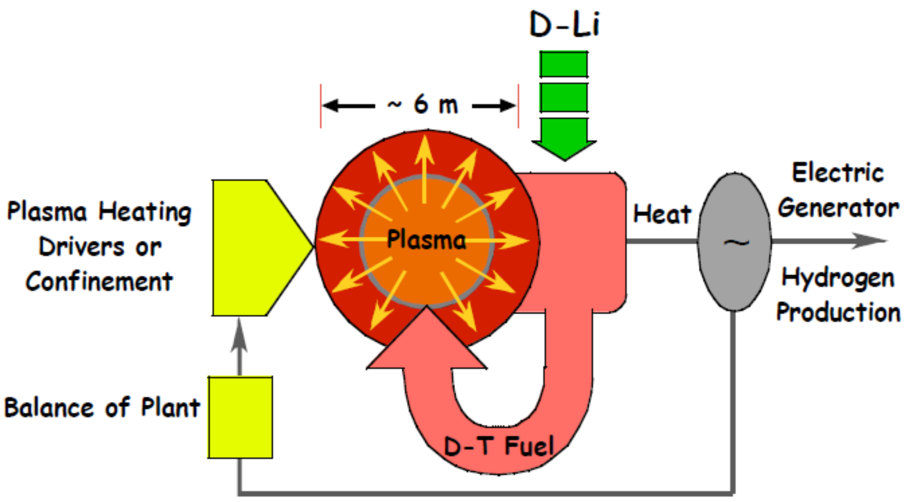
- Same reaction as in H-bomb
- Thermal energy boils water & makes steam
- $^3$H is not found naturally
  - **Fissile Material to produce $^3$H**
- Millions of degrees inside reactor
  - **High Temperature Material**
- High neutron flux
  - **Radiation Resistant Material**
- Net energy gain requires:
  - Fast extraction of heat
  - Long-term operation
- Precise control over fuel
  - Fuel must be held away from walls
  - In-situ diagnostics is needed: **Material for Plasma Diagnostics**

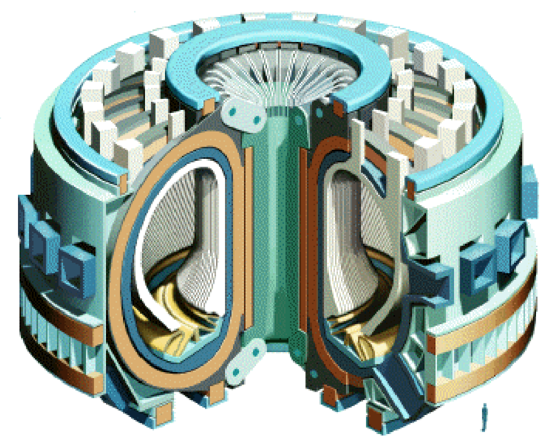


# Towards Commercially-justified Fusion...

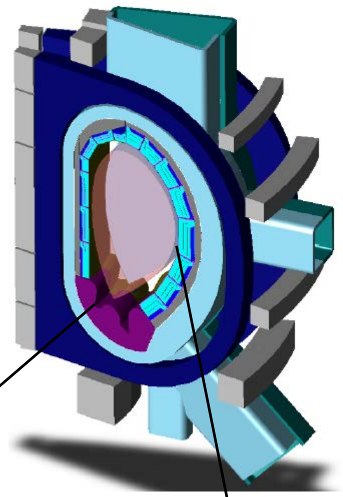
- Fuel self-sufficiency
  - D-Li : liquid metal technology
- Magnetic field
  - Super-conductivity, cryogenic
- Plasma-wall interaction
  - Thermal conductivity, sputtering
  - Melting point
- Vacuum chamber
  - Structural materials: high neutron does
  - Operation temperature: coolant
- Waste
  - Tritium retention
- Energy gain
  - Chamber volume / coolant temperature

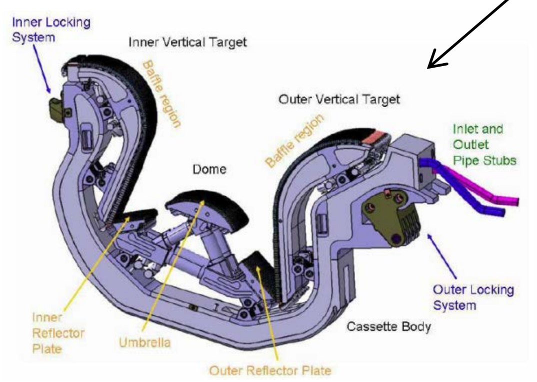


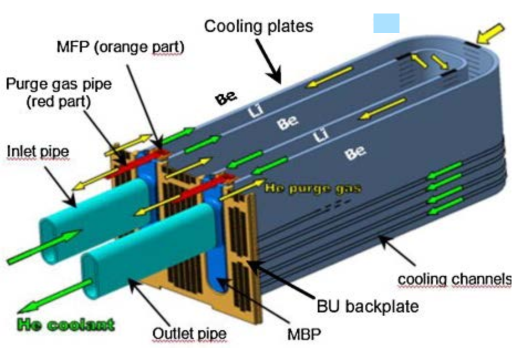



# Category of Materials & Technological Issues

- Defined by subject to irradiation damage:
  - **In-vessel** i.e. subject to **neutron irradiation**
  - Out of vessel (magnets, cryo, heat-exchanger, etc)
- Plasma-facing materials
  - Heat Evacuation
  - Plasma stabilization (divertor)
- Structural materials
  - Embrittlement
  - Creep
- Diagnostic/Functional
  - Reflectivity
- Fuel self-sufficiency
  - D-Li : liquid metal technology





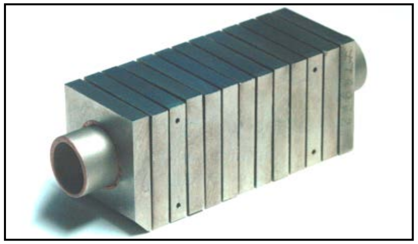



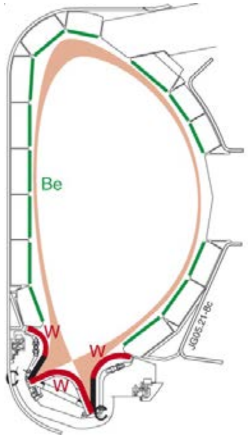

Breading Blanket

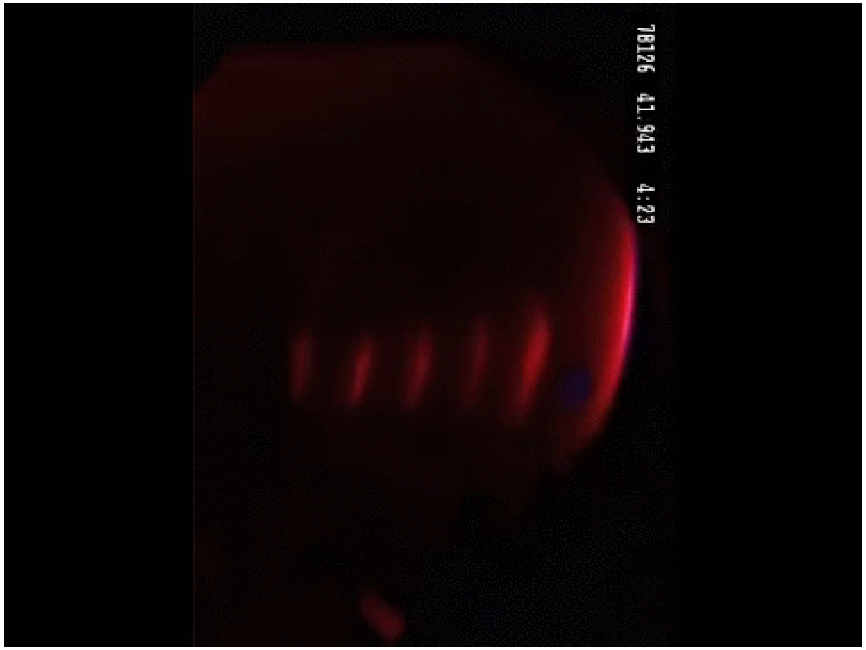
# High Heat Flux Materials

# High Heat Flux Materials: Basics

- Material: Tungsten
- Major Function/Issues:
  - Power  exhaust / thermal fatigue
  - Transient Thermal Loads
  - Shielding / Neutron embrittlement
- Irradiation dose:
  - ITER : 1 dpa end of life dose
  - DEMO: 4 dpa: Phase I
  - DEMO: 20 dpa: end of life dose
- Operation temperature:
  - ITER: 200 – 1000 C (+ disruptions)
  - DEMO: 400/600 – 1200 C

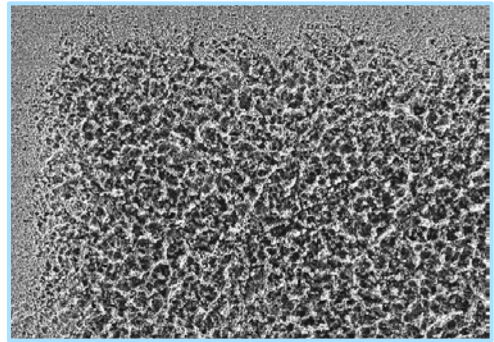




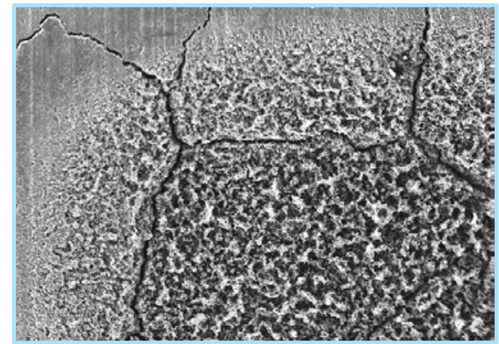



# High Heat Flux Materials: transient loads

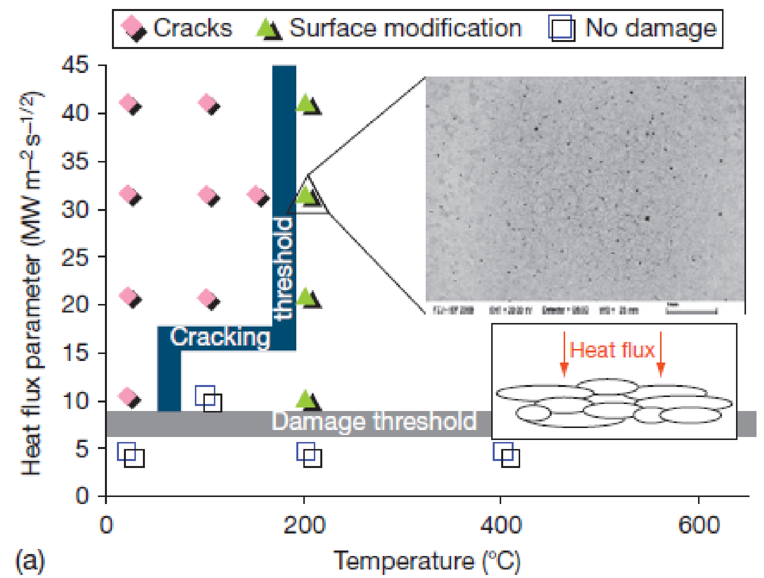
- Cracking induced by
  - Heat Transients
  - N-irradiation severs cracking
- Damage depends on Base temperature
  - Coolant temperature



Non-irradiated W sample

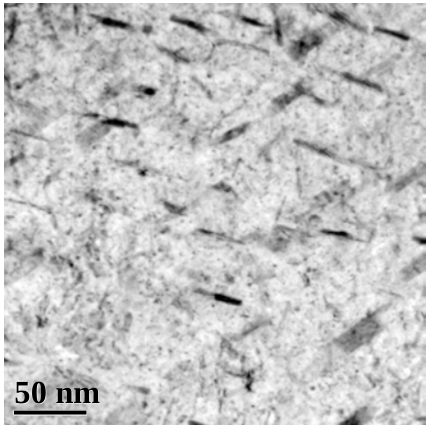


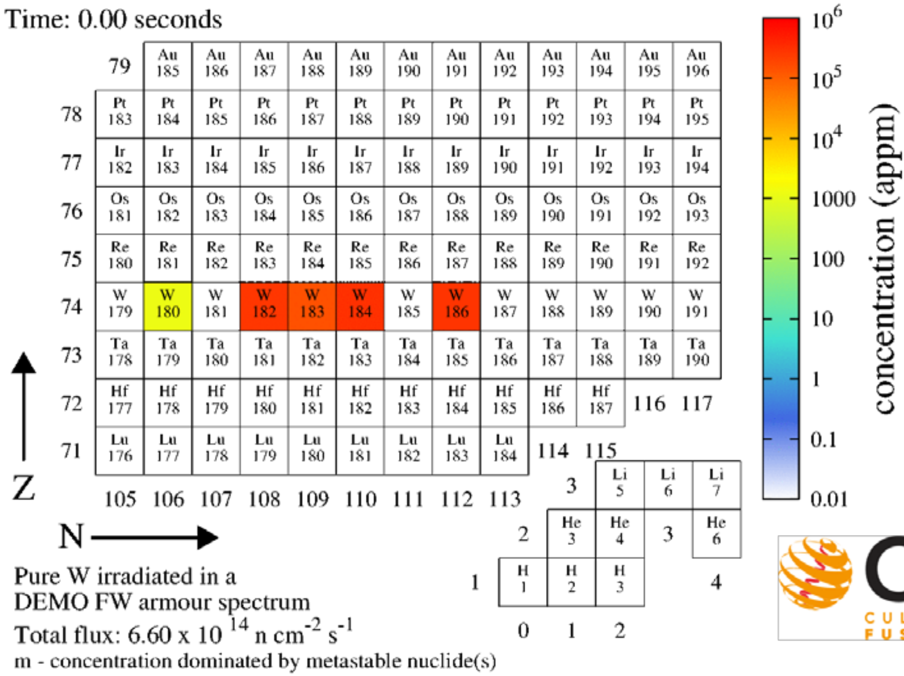
1 dpa W sample

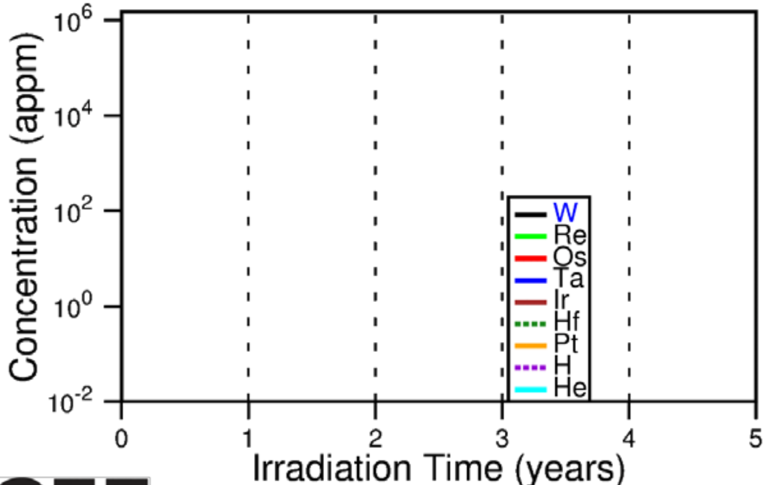


# Fission ≈ Fusion : not always

- Transmutation
  - Fast neutrons : He and He  (order 1-10 appm/dpa)
  - Thermal neutrons: W -> Re -> Os
- Impact of transmutation
  - Extra embrittlement (Re precipitation)



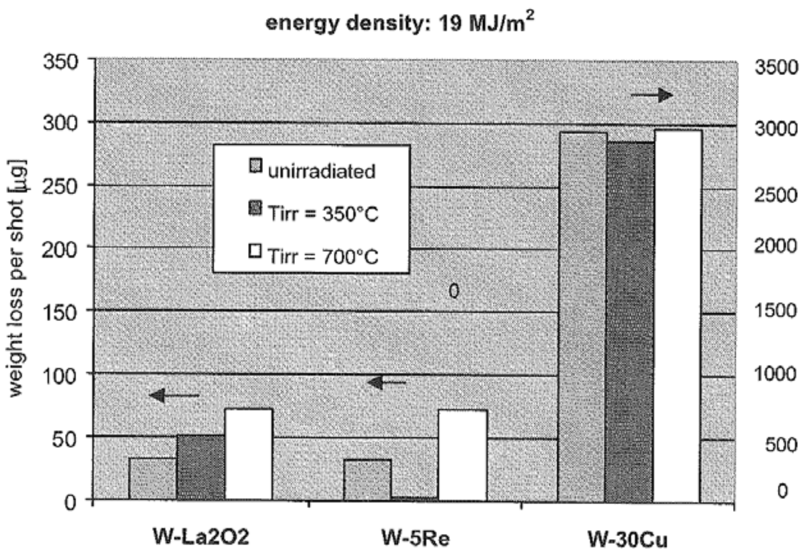

M. R. Gilbert et al., *Nucl. Sci. Eng* (2014)
M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

# Room for future study

- Irradiation dose
  - Most of experiments performed up 1 dpa
  - Demo Phase I requires: 4 dpa
- Irradiation temperature
  - Up to know 300 -750 C
  - Required temperature: at least up to 1200 C
- Transmutation
  - Transmutation to Re and Os
  - Fission over-estimates
- Technological aspects:
  - Miniaturization
  - **Combination of**

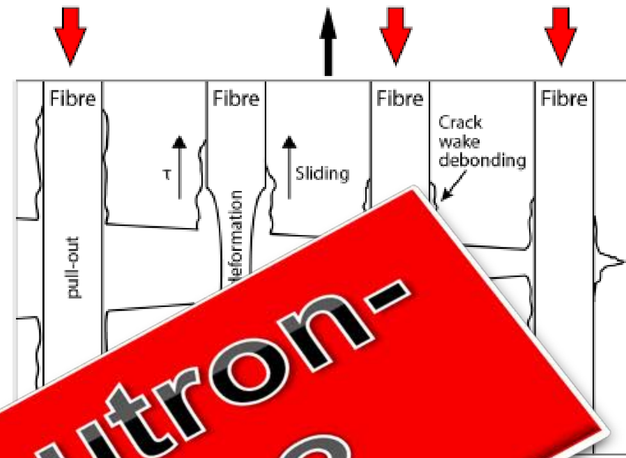
    **Irradiation facilities &**

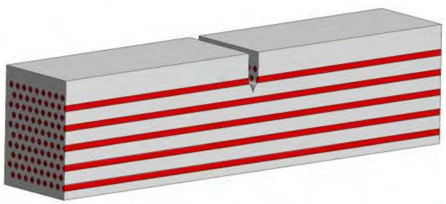
    **High Heat Flux testing facilities**

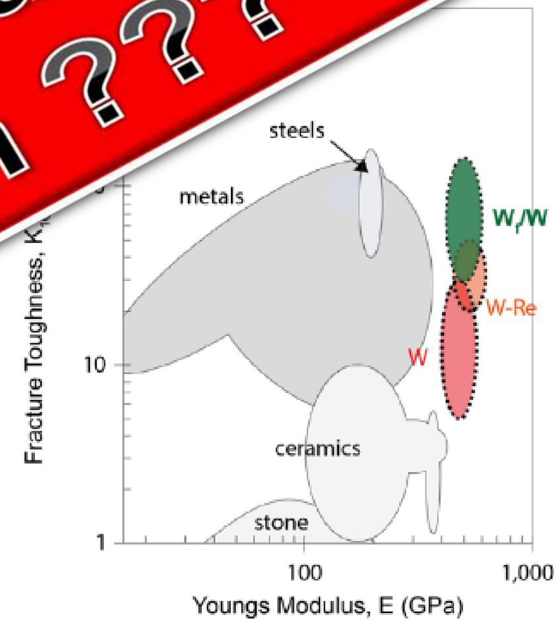
# New concepts to mitigate W brittleness

- Reinforcement by adding fibers
- Principle of operation:
  - High strength fiber (with limited ductility)
  - Matrix is considered as brittle
  - Fiber-pull out offers pseudo-ductility



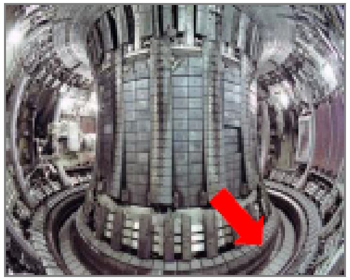
Ductile at Room Temperat



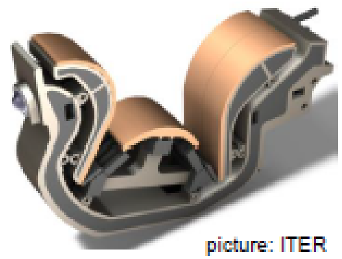

**Impact of Neutron-irradiation ???**

# Structural Materials

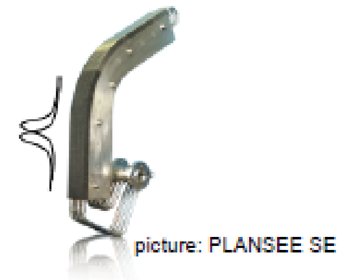
# Structural Materials: application



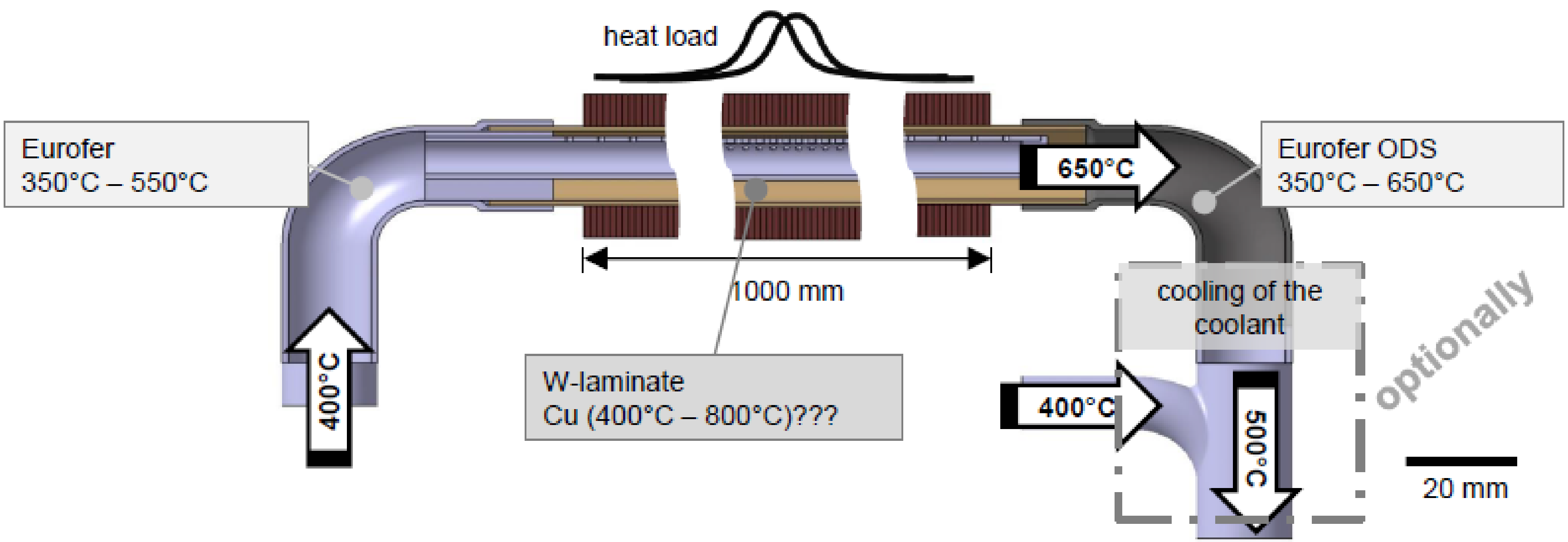
Tokamak fusion reactor




Divertor cassette:
inner/outer vertical target, dome

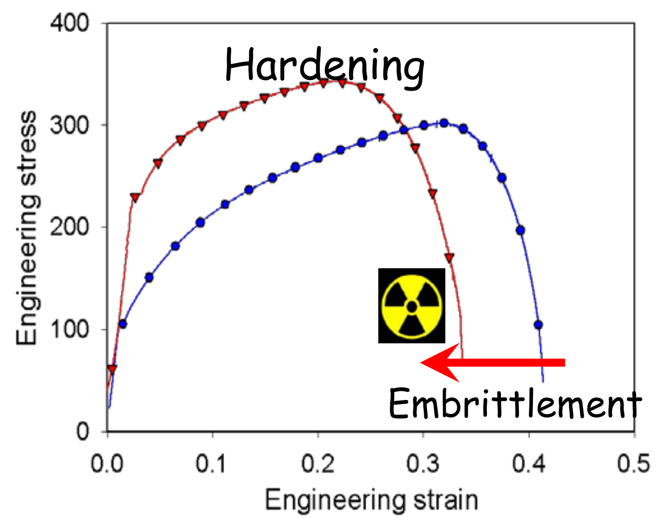


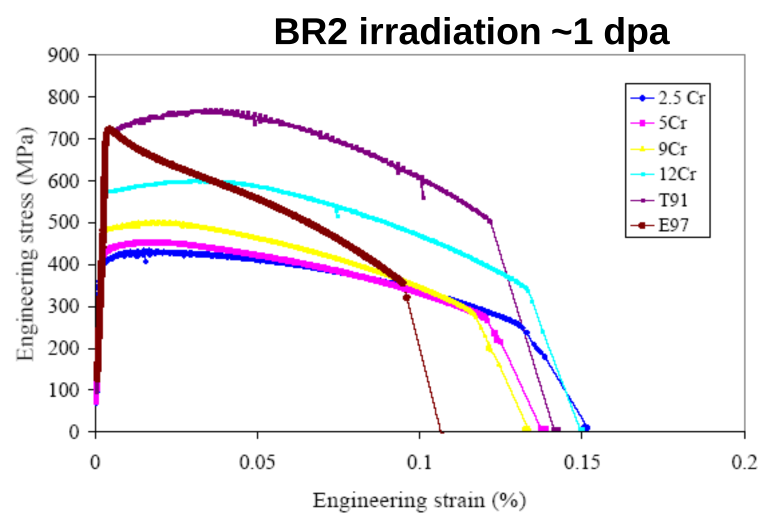

inner/outer vertical target



# Structural Materials: basics

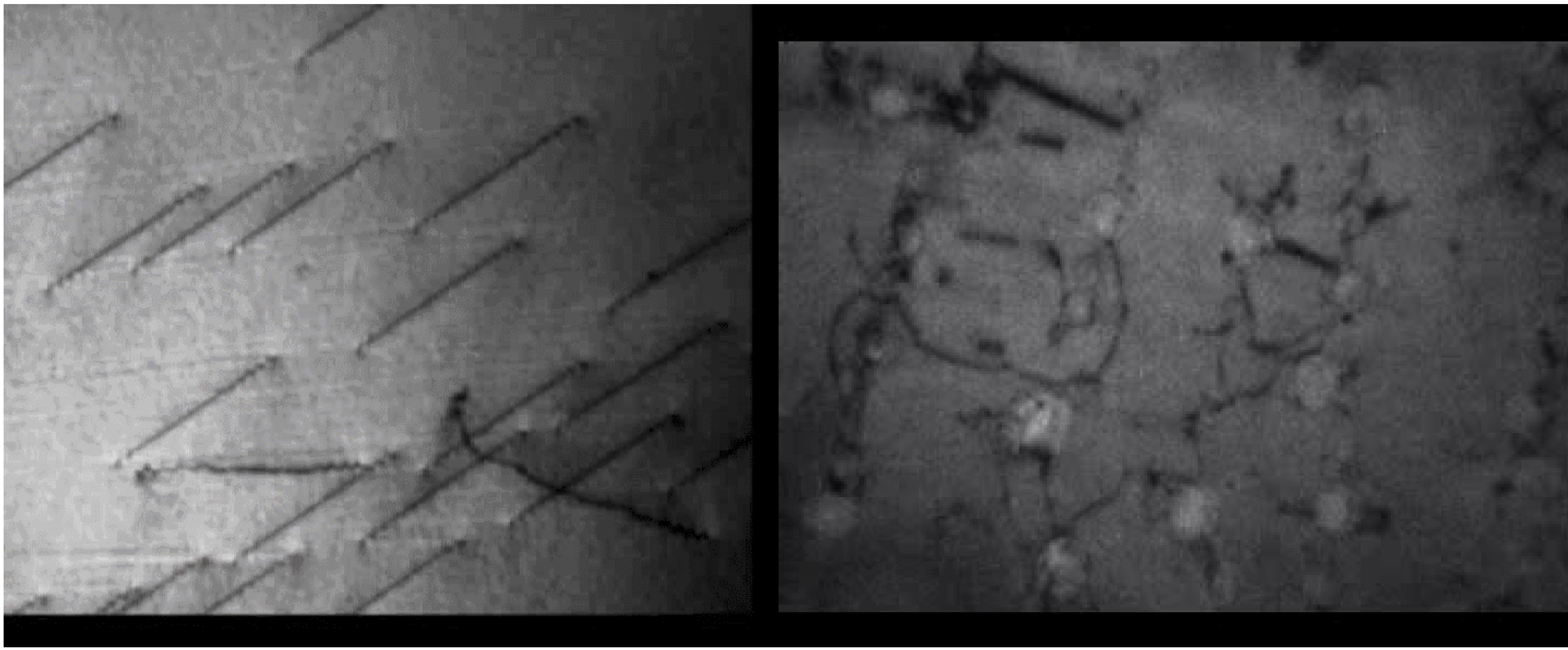
- Material: Ferritic Martensitic Steels
- Major Function/Issues:
  - Mechanical load
  - Low T: Hardening & Embrittlement
  - High T: Swelling & Creep
- Irradiation dose:
  - ITER : 2.5 dpa end of life dose
  - DEMO: 20 dpa: Phase I
  - DEMO: 60-80 dpa: end of life dose
- Operation temperature:
  - Current: 350- 550(650)
  - Target: 300 - 650 C



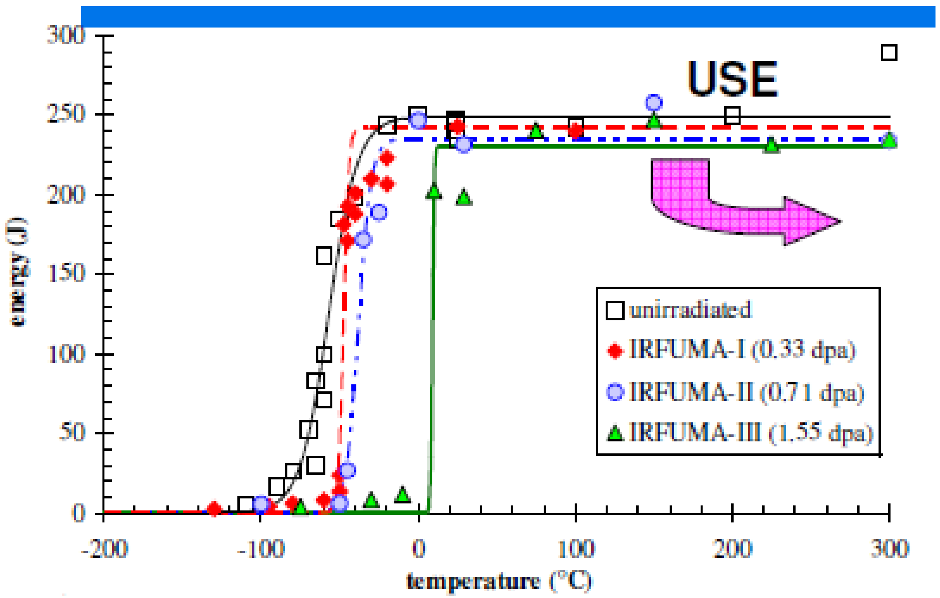
# Structural Materials: irradiation induced degradation

Reference material | Irradiated material

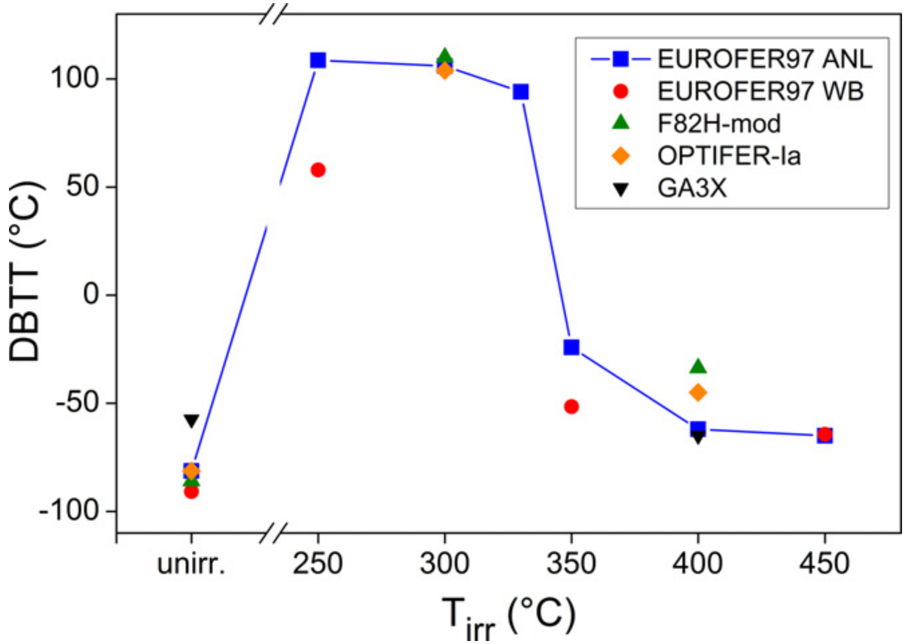


- Material deforms by dislocation movement
- Neutron damage induces defects obstructing its movement
- Increasing temperature helps annealing impact of N-irradiation

# Structural Materials: irradiation induced degradation




IRFUMA@BR2 300C, 0 – 2 dpa



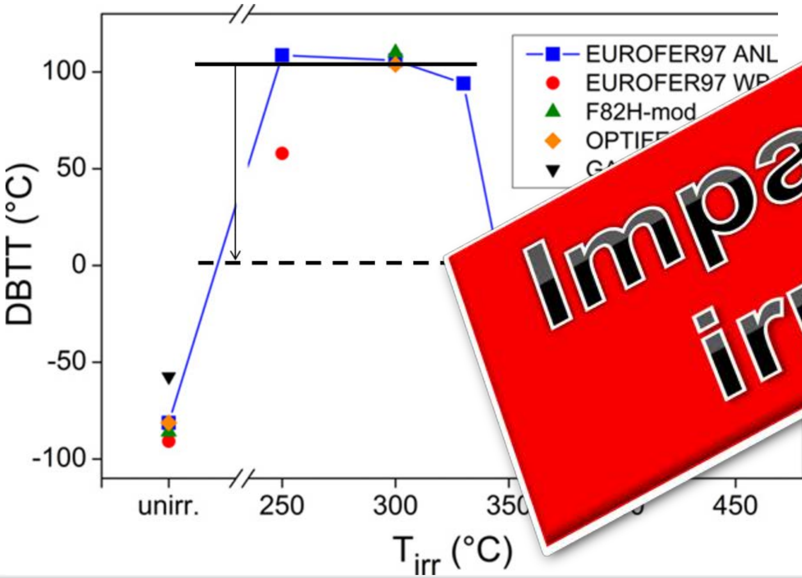

ARBOR@BOR60 330C, 15-70 dpa

- Material deforms by dislocation movement
- Neutron damage induces defects obstructing its movement
- Increasing temperature helps annealing impact of N-irradiation

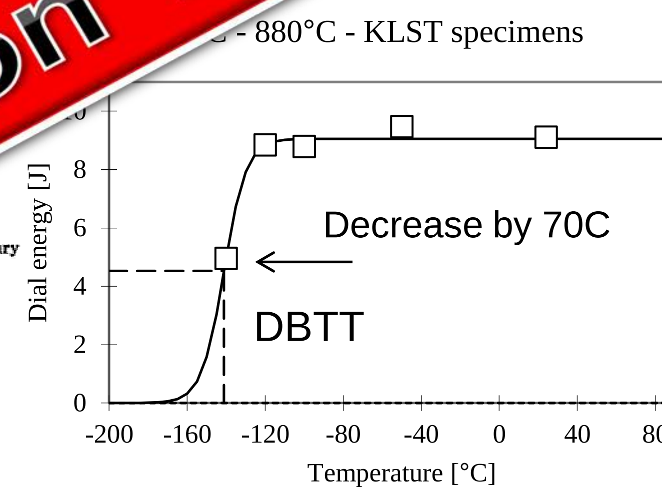
# Structural Materials: new developments

- Options for improvement
  - Low-Temperature by Thermo-mechanical treatment
  - High-Temperature by Particle strengthening (ODS and C
- Questions to be addressed:
  - Stability of precipitates under n-irradiation
  - Alternation of μ-structural evolution d
    modification

**Impact of Neutron-irradiation ???**

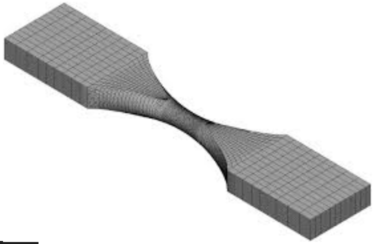




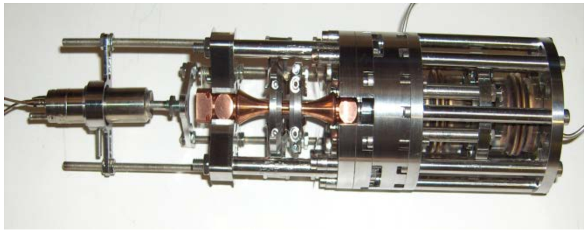


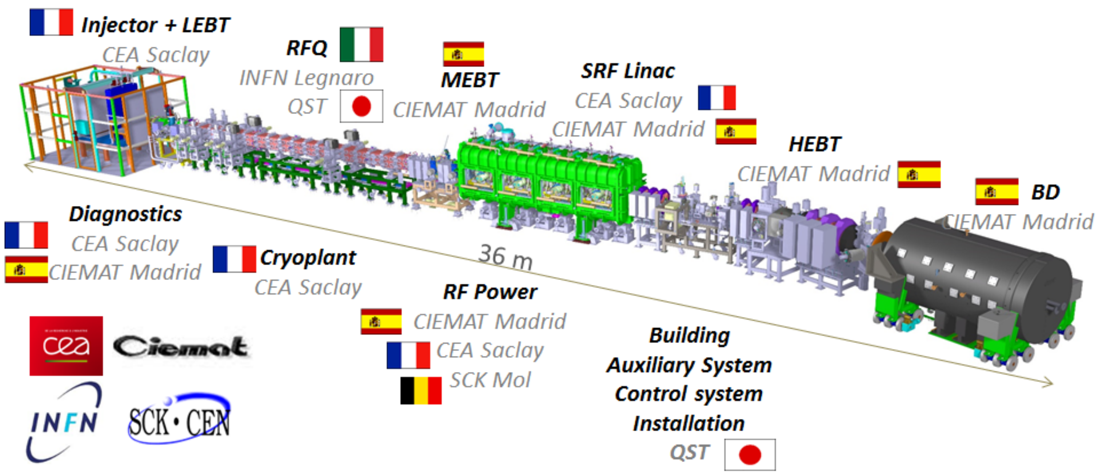
# Structural Materials: near term challenges

- Low T: 20 dpa is the must to qualify steels for DEMO
  - Miniaturization
  - High flux & well T-controlled irradiation
  - Appropriate He-dpa ratio
- High-T: operation at 650 C
  - In-situ creep tests



In-pile creep tests in BR2



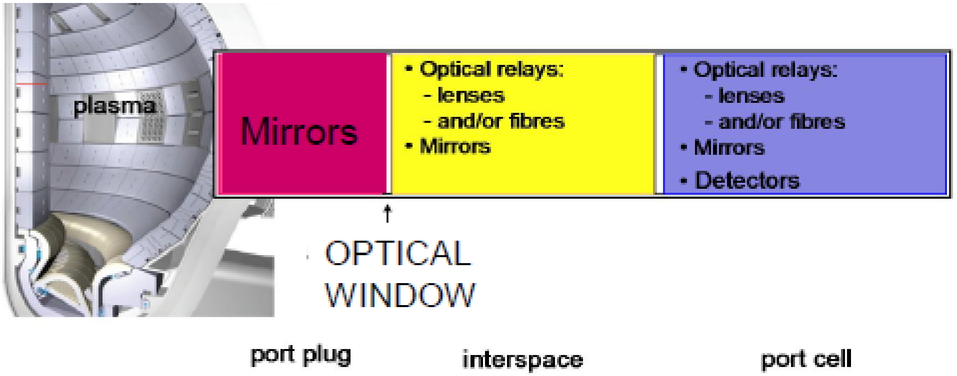



Dedicated high flux fusion neutron source is needed (IFMIF)

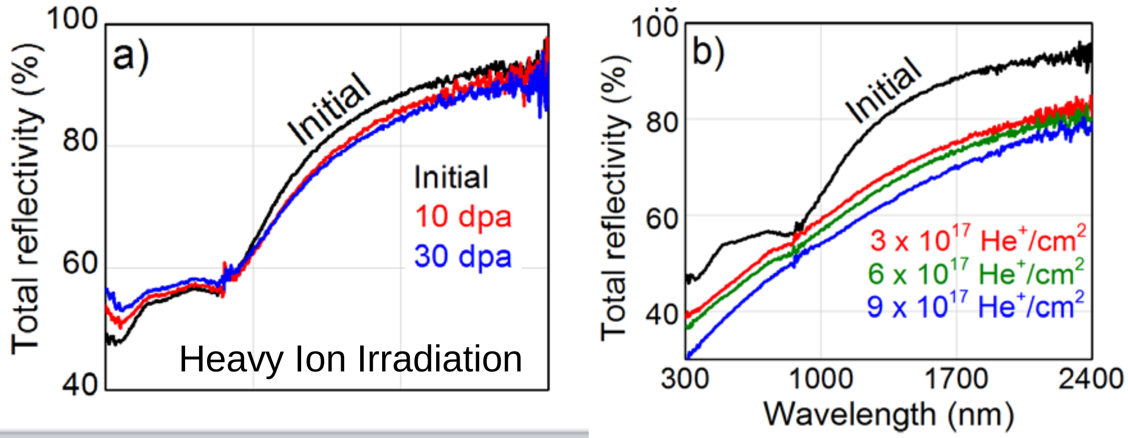
# Diagnostic/Functional Materials

# Functional materials

- Materials: Sapphire, Silica, Spinel (other ceramics) + Metals
- Purpose: diagnostics of plasma for precise control
- Major Function/Issues:
  - Reflectivity,
  - electrical conductivity
  - permittivity
  - N-irradiation: amorphysation
- Operation temperature
  - 200-300 C
- Required dose:
  - 0.1 – 2 dpa




| Neutron/γ loads ($W.m^{-3}$) | HIGH ($10^3$ to $10^7$) | « LOW » < $10^3$ | « VERY LOW » |
|---|---|---|---|



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Impact of Neutron-irradiation ???

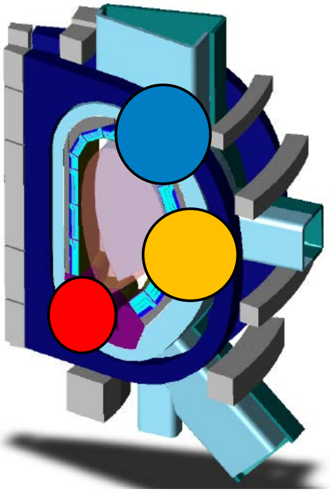
# Solutions to address challenges for Fusion Materials Development:

# BR2 and more …

# Different Materials require different solutions …

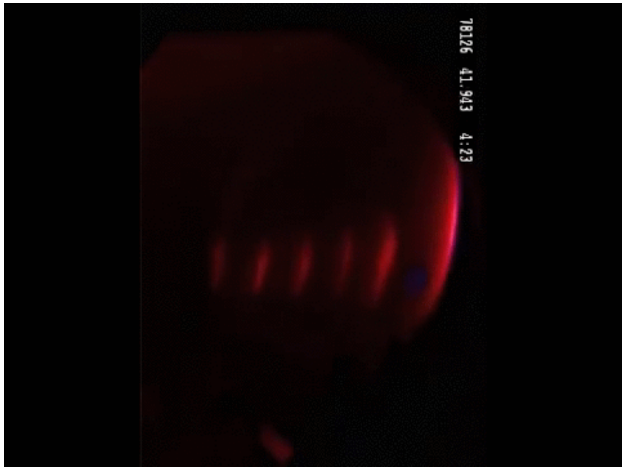
High Heat Flux
T=400-1200C
Dose: up to 10 dpa

Structural
High-temperature
Up to 650C
Dose: up to 20 dpa



Structural
Low-temperature
From 300C
Dose: up to 20 dpa

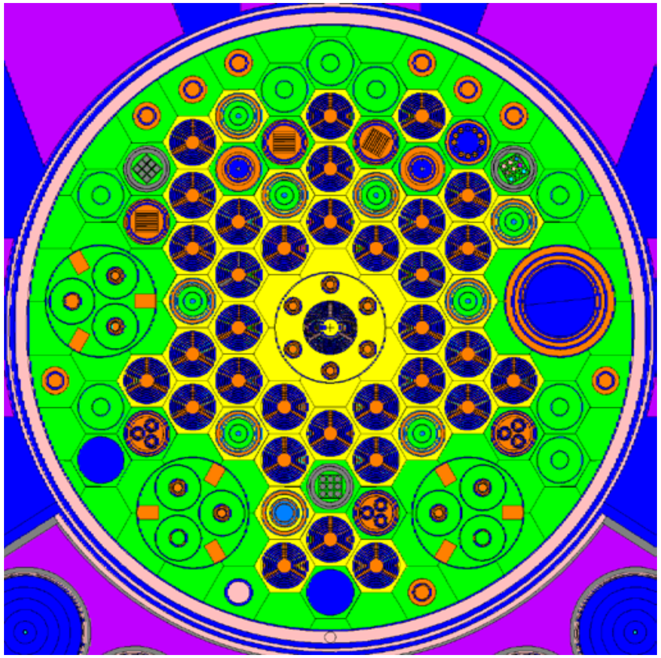
Functional/
Diagnostics
T=200-300C
Dose: up to 2 dpa

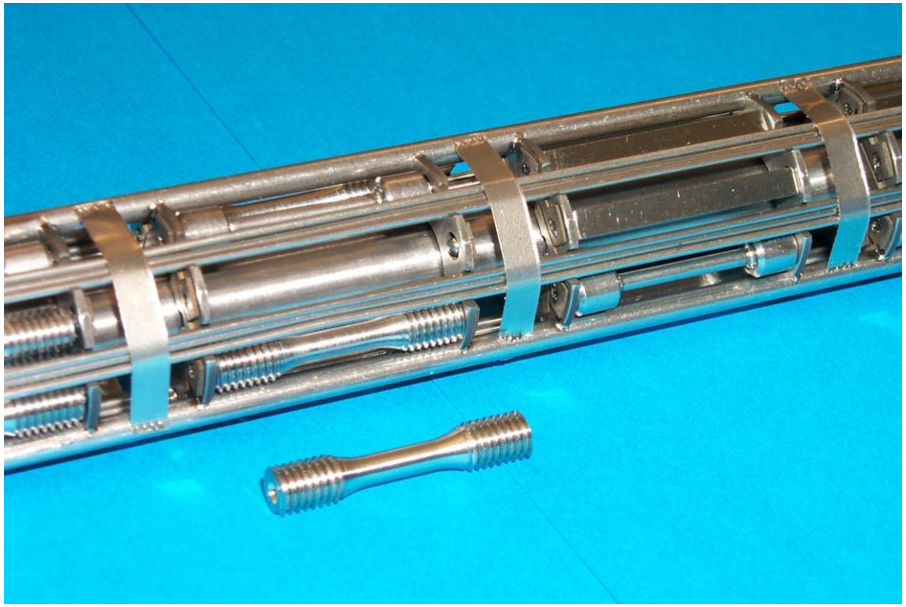


# Irradiation devices for Fusion Materials

RIG: MISTRAL

- 200-300(350)°C irradiation temperature
- Active T-control; 5-PF position
- 0.5-0.7 dpa/cycle (Fe);  4 dpa/y; 5 years to deliver end-of-life DEMO I
- Inter-cycle mounting

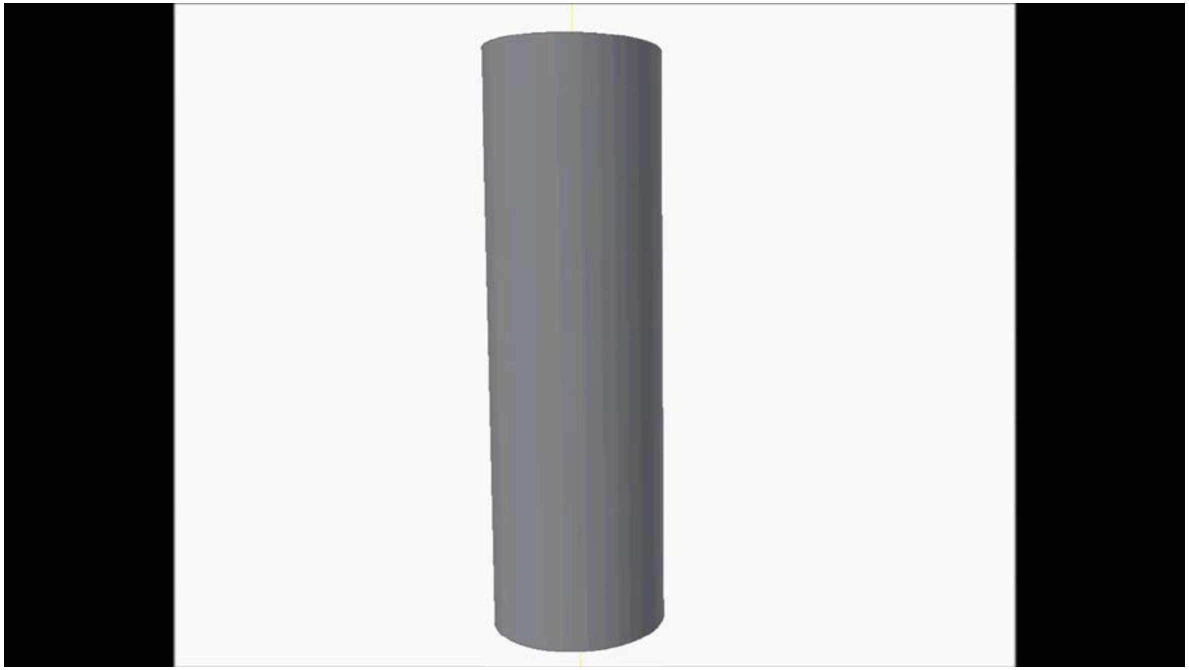


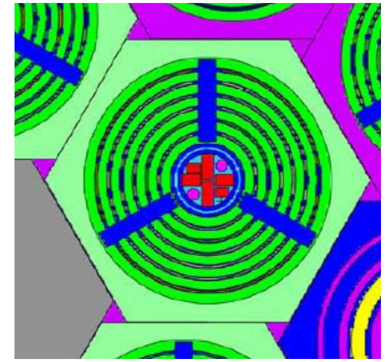


Application:

- Qualification & Screening of Structural Steels for low-temperature
- Diagnostic/Functional materials
- Heat Sinks Materials

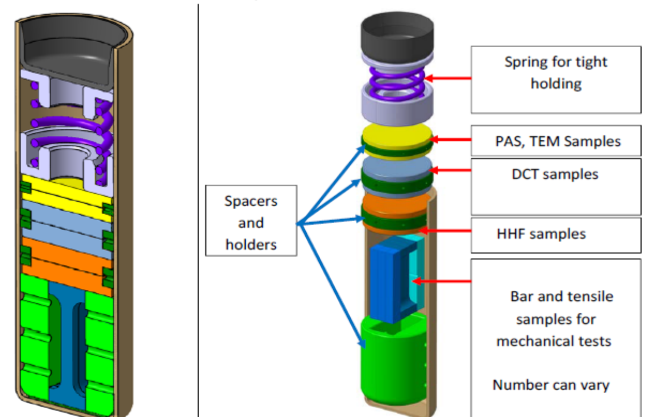
# Irradiation devices for Fusion Materials





Application:

- Screening:
  - Low-T steels
  - High-T steels
  - Tungsten
  - Diagnostic/Functional




BAMI: BAsket of Material Irradiation

- 80-1200°C irradiation temperature
- Passive T-control, post-measurement
- 0.5-0.7 dpa/cycle;
- Screening Irradiation with small and large dose increments
- Available in Reflector and Fuel channel

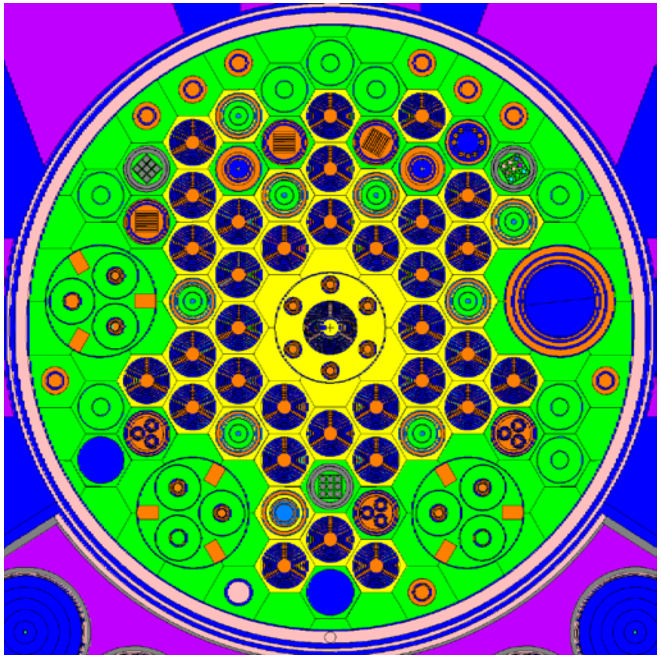
# Irradiation devices for Fusion Materials

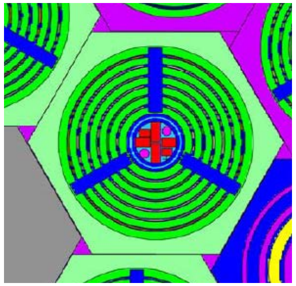
RIG: High Temperature High Flux (HTHF)

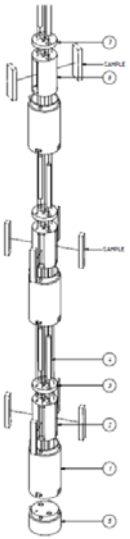
- 400-1200°C irradiation temperature
- Active T-control; inert environment
- 0.2 dpa/cycle (W); 1 dpa/y;

1 year to deliver ITER end of life dose

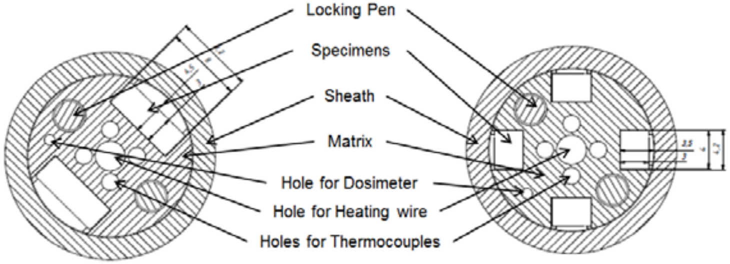
5 years to deliver end-of-life DEMO I







1 - Graphite sheath
2 – Graphite matrix for mini-Charpy
3 – Graphite cover
4 – Graphite pen
5 – Graphite centering plug
6 – Graphite matrix for flat tensile
7 – Graphite cover




Application:

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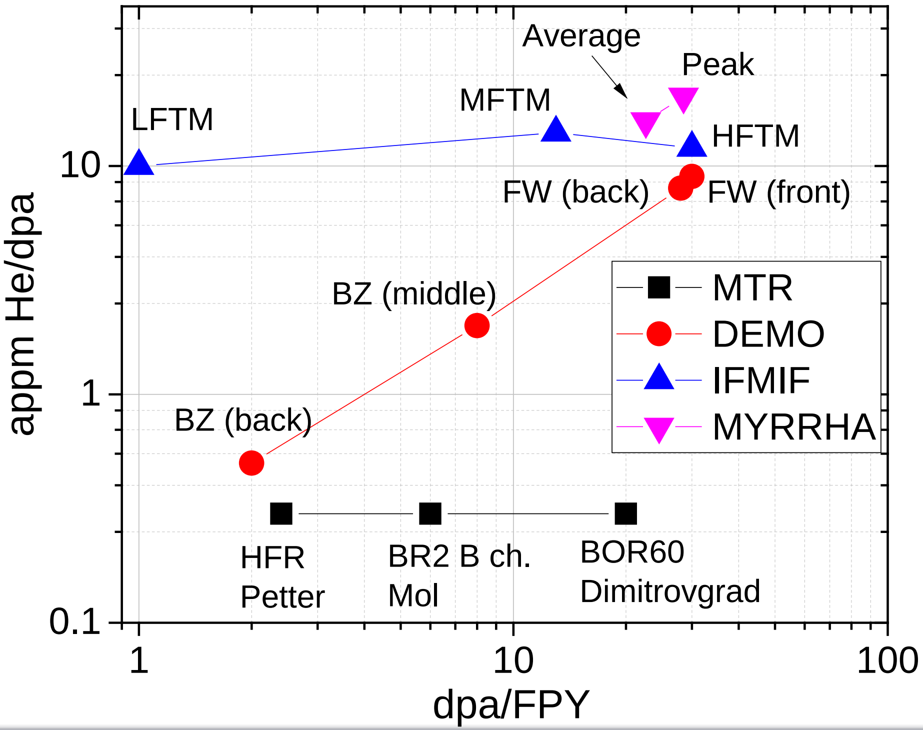
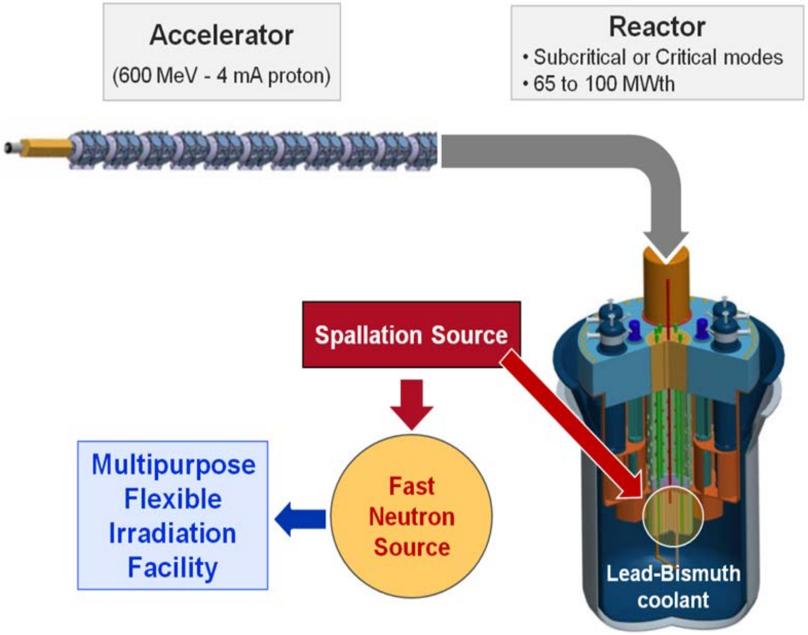
# MYRRHA for Fusion Material Irradiation

- Proton irradiation
- 50 dpa/EFPY volume 0.4L
- 20 dpa/EFP volume 2.3 L
- Sample Surface Temperature 100°C – 650°C
- DT over the sample < 20 °C
- appm He / dpa up to 20



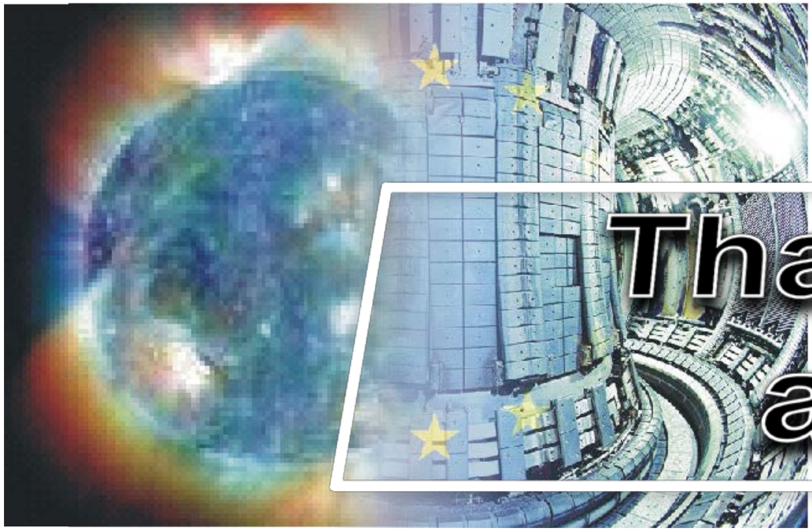




Application:

- Structural Steels
  - Low T
  - High T
- Low-T Tungsten application
- Heat Sinks

28 EU Partners





Thank you for attention

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