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Nuclear analysis and assessment of irradiation effects on the Divertor Plasma Facing Components of the DEMO fusion reactor

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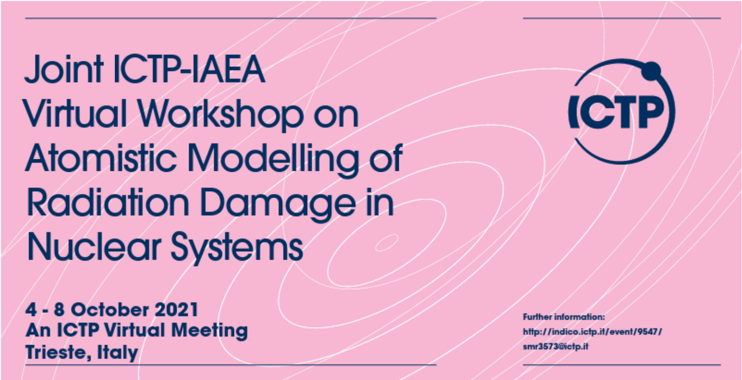

CRESCO Project

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Summary

- **Motivation of this study**
- **Nuclear analyses: 3D MCNP model and principal results**
- **Assessment of the PFC performance under irradiation**
- **Conclusions**

Motivation of this study

- **DEMO (DEMOnstration Fusion Power Plant):** will be the first Fusion Power Plant to produce electricity and breed tritium.

$$D + T \rightarrow {}^{4}He\,(3.5\ MeV) + n\,(14.1\ MeV)$$

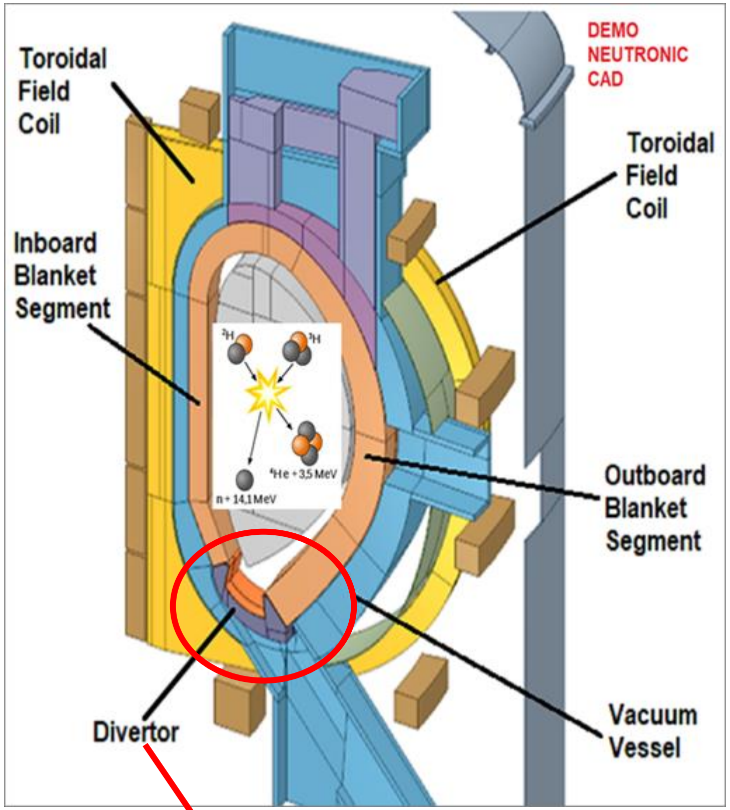
- 14 MeV - Neutrons have an isotropic and random diffusion being not confined by magnetic fields.

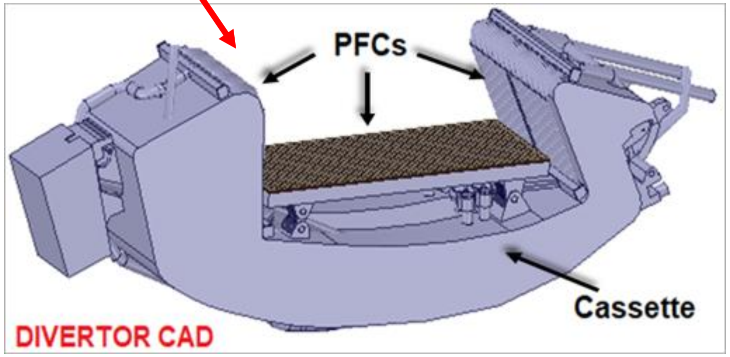
Blanket and Divertor

- Divertor function: removal of plasma power exhaust (20%) and impurity particles (e.g. alfa particles) + neutron shielding of the VV and lower port.

- **Fusion neutrons can gravely affect the divertor operations, due to induced activity, damage, transmutations and swelling on the materials.**

Engineering design of Plasma Facing Components must take into account the neutron irradiation impact!





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Motivation of this study

Neutronics and activation analysis

+

Thermo-structural integrity inelastic assessment (IAP)

→

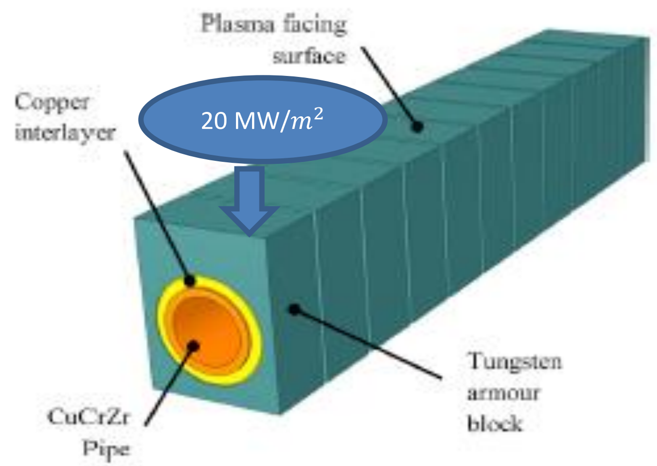
Performance of the DIV PFCs under neutron irradiation:

- Lifetime
- Potential failures
- Critical issues

↑

Data about irradiation effects on plasma facing materials from literature (partly limited)

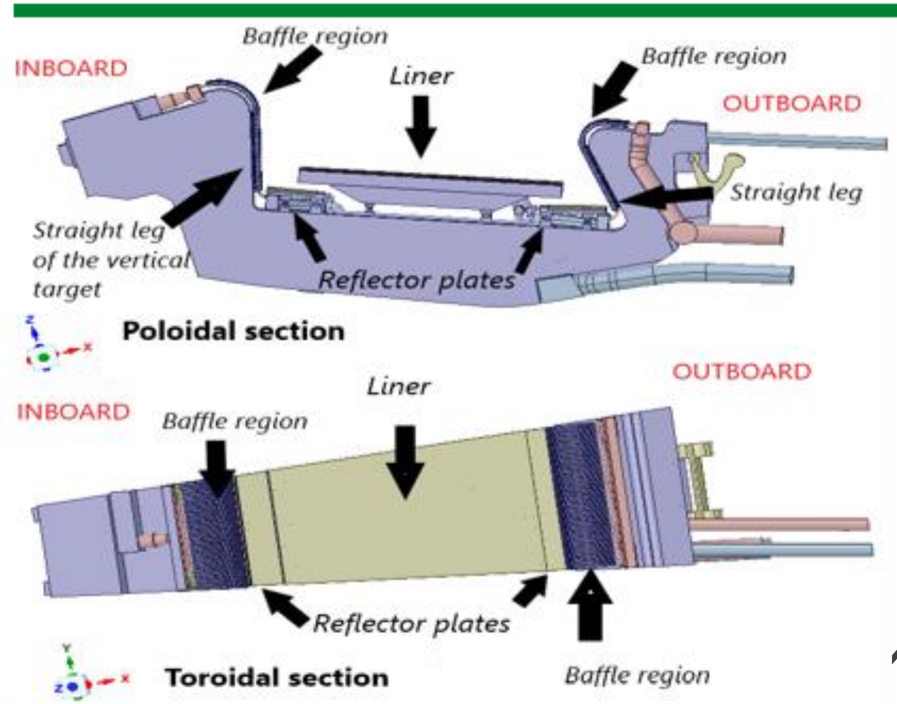
- The divertor PFCs are exposed to very intense thermal load (20 MW/m^2) and high neutron irradiation!



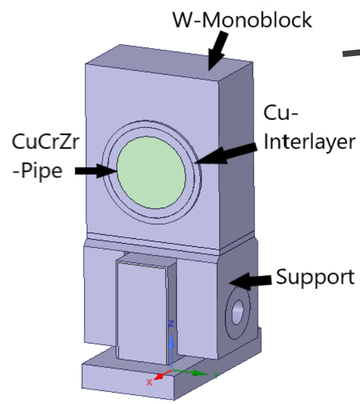
- **Goal of this work:** Showing the impact of neutron irradiation on the PFCs performance, linking a detailed nuclear analysis (first time) with a thermo-structural integrity inelastic assessment.

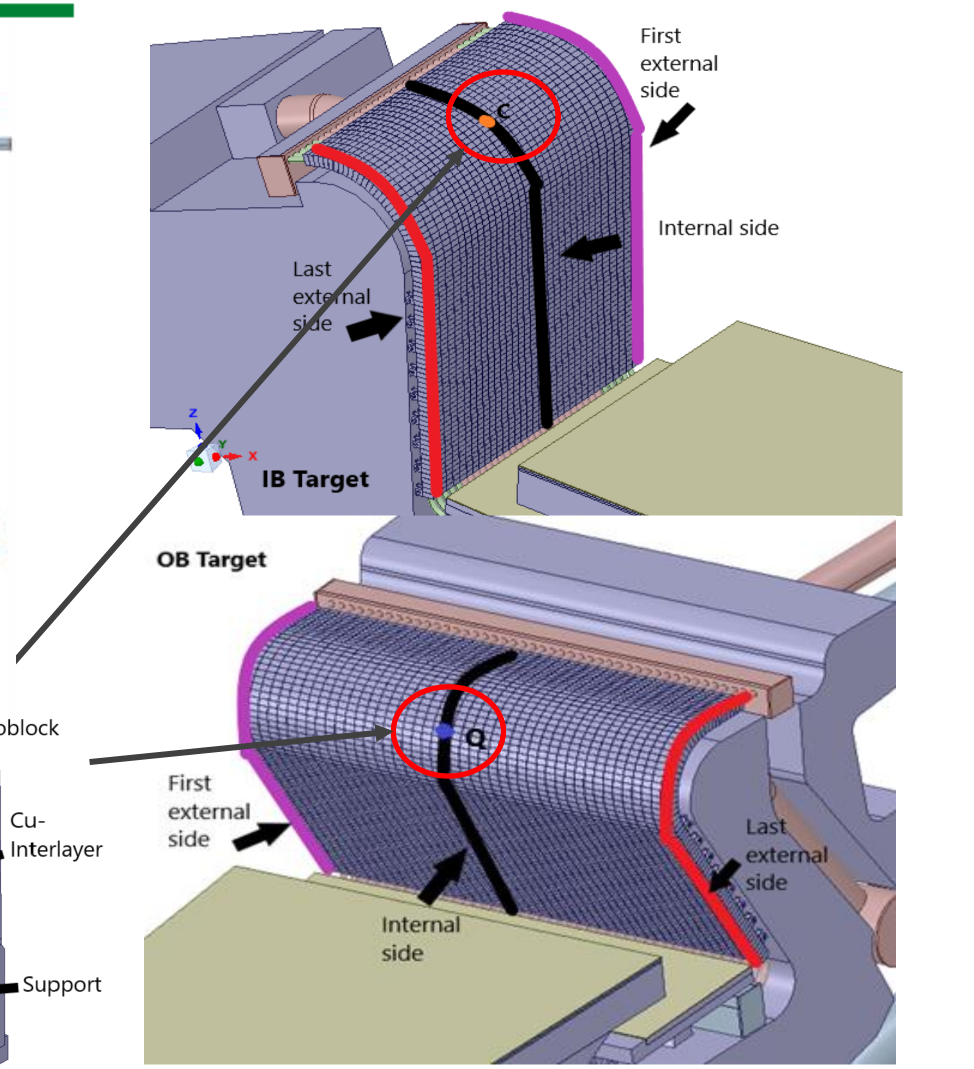
- **Relevance of this work:** Characterization of PFCs thermo-structural performance under neutron irradiation! → Extremely necessary for the Divertor design and never analysed so in depth.

Nuclear analyses: 3D MCNP model and principal results

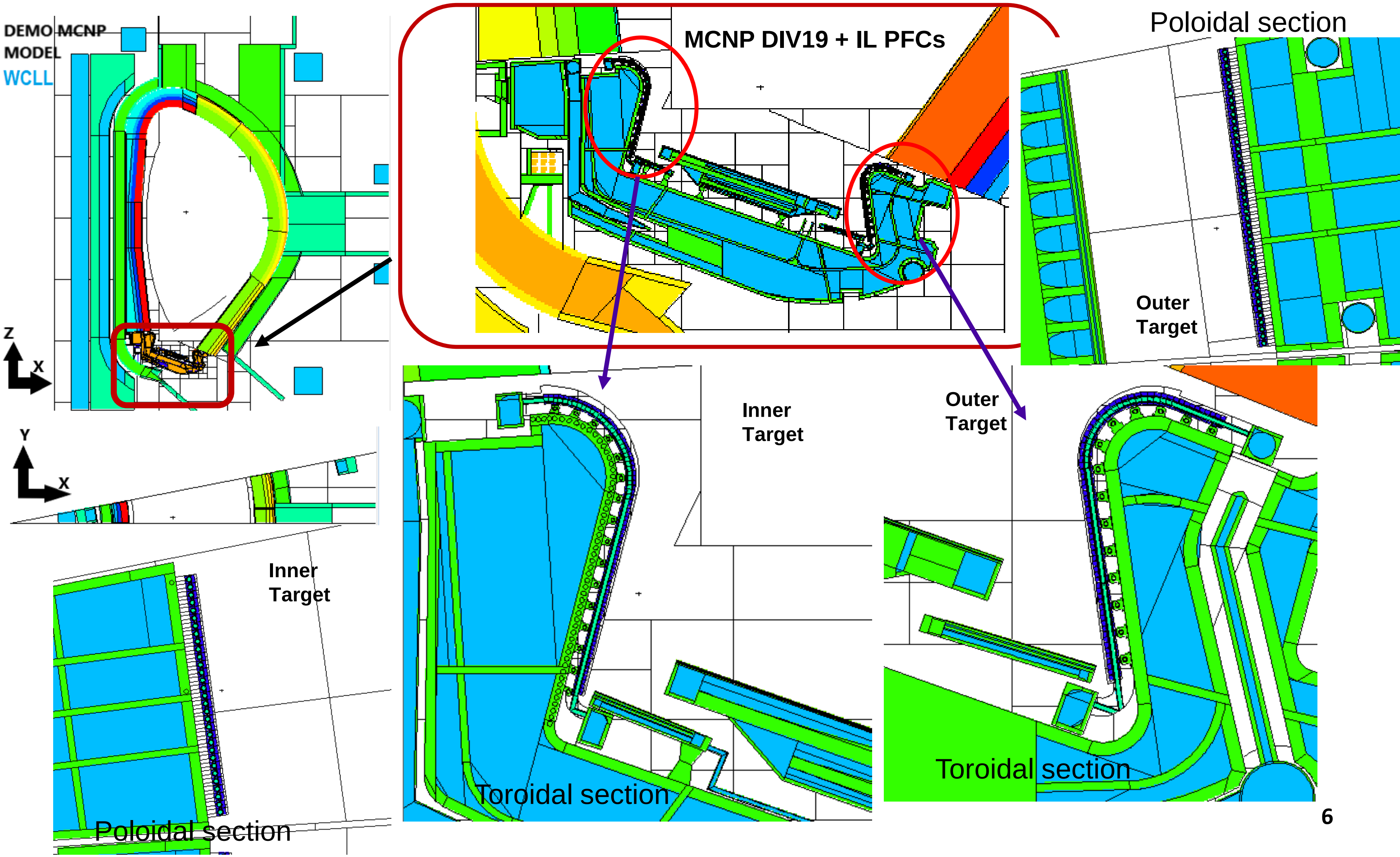


Starting from the latest reference DEMO divertor CAD model, a full detailed neutronics targets 3D representation (based on the ITER-Like PFCs concept) has been reproduced and integrated in the reference DEMO MCNP model.



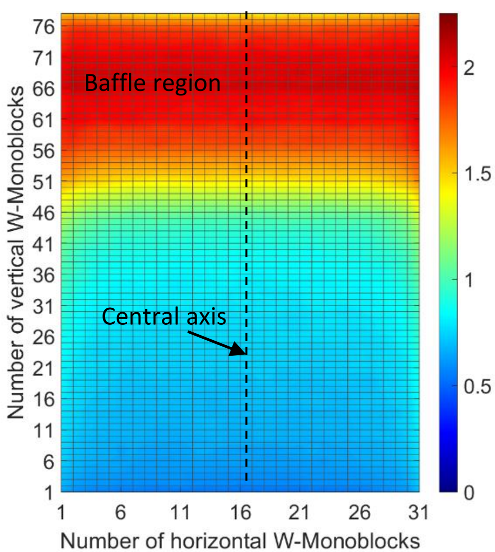


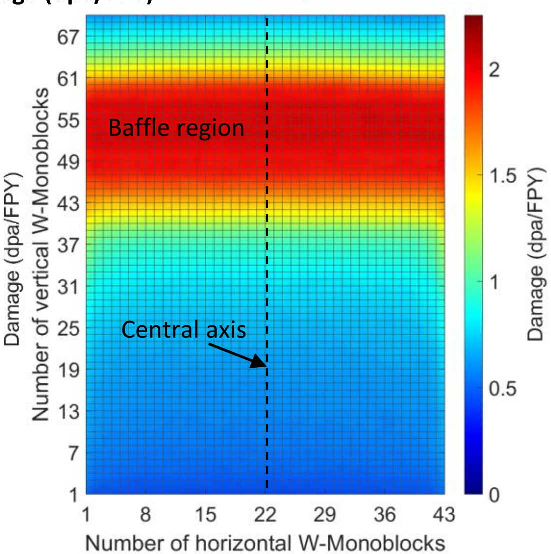
Nuclear analyses: 3D MCNP model and principal results



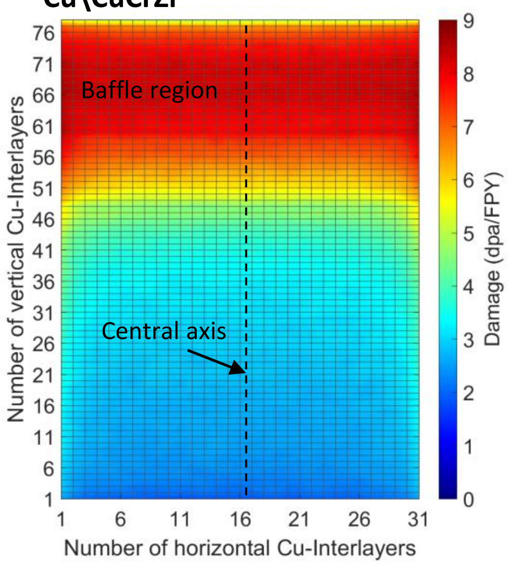
Nuclear analyses: dpa/FPY, He-appm/FPY, W/cm^3

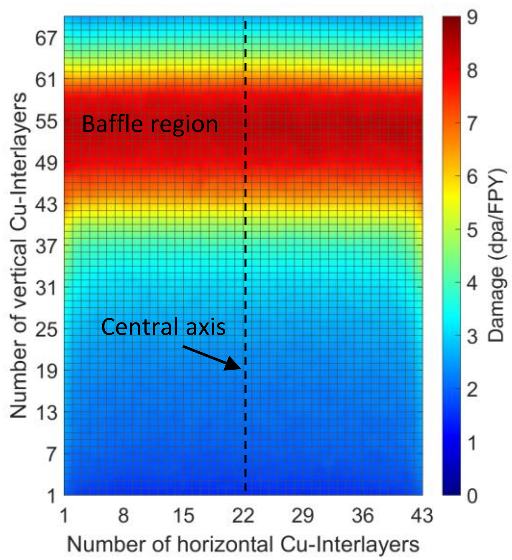
W Inner Target **Nuclear damage (dpa/FPY)** Outer Target





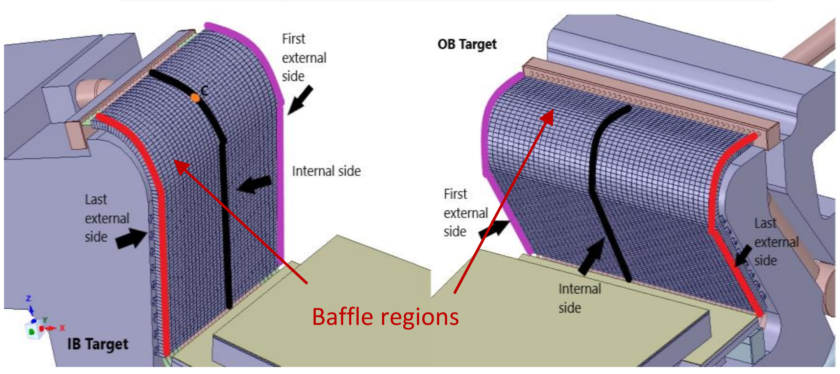
Cu\CuCrZr



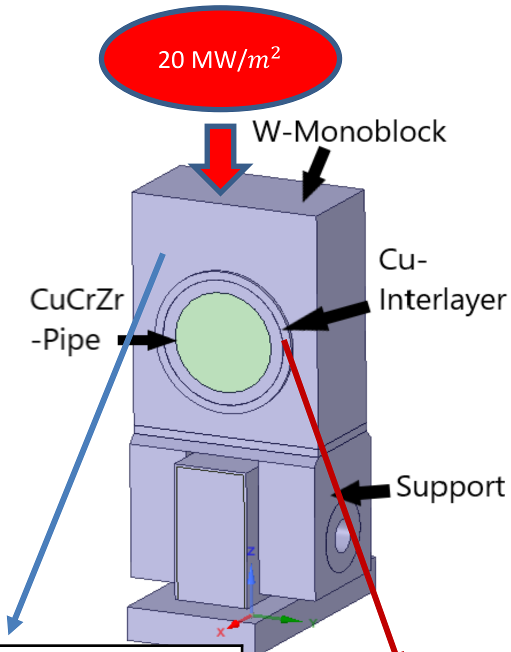


- Nuclear loads spatial distributions for W and Cu/CuCrZr have been calculated.
- Nuclear analyses have been performed with a Water Cooled Lithium Lead Blanket.
- 2D fine meshes show the nuclear loads distributions on the targets.

	Number of vertical PFCs	Number of horizontal PFCs
Inner	78	31
Outer	70	43

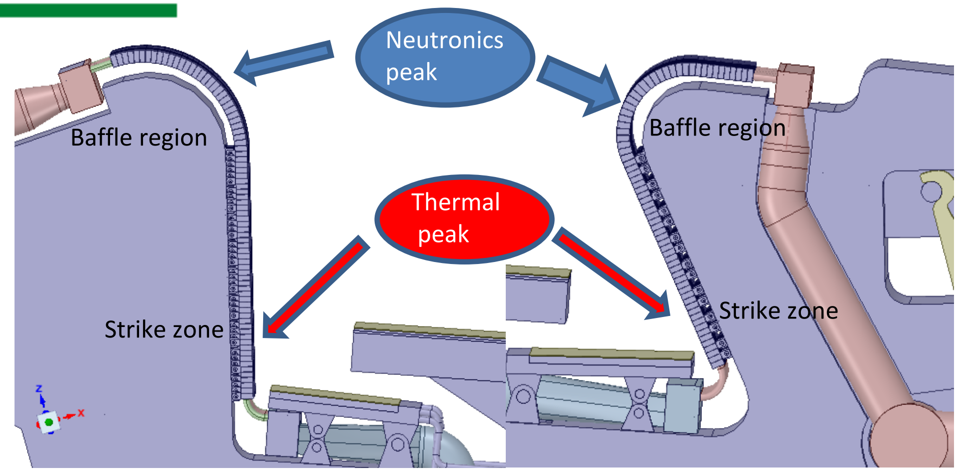


Nuclear analyses: recap of the principal results



W	peak	After 1.5 FPY
W/cm^3	21.40	/
dpa/FPY	2.10	3.2
appm/FPY	1.88	2.8
%at. Re	0.85	/
%at. Os	0.05	/

Cu/CuCrZr	peak	After 1.5 FPY
W/cm^3	8.70	/
dpa/FPY	8.75	13.1
appm/FPY	55.6	84
%at. Ni	0.27	/
%at. Zn	0.12	/



- **Highlights:**

1. The peak values are on the baffle region, generally on the external sides of both the targets.

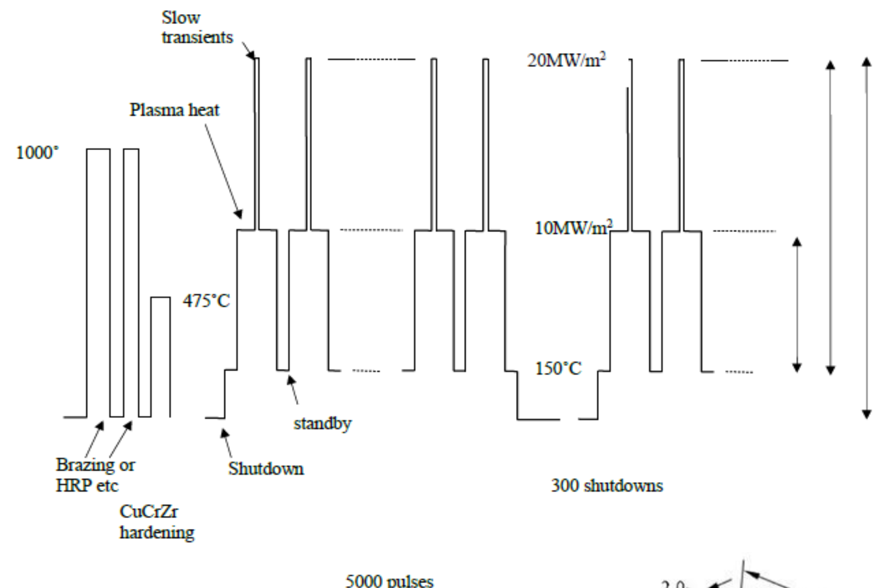
2. Symmetrical behaviour with respect to the target central axis has been observed.

3. Thermal and neutronics peaks are reached in different part of the target. For this study the worst critical condition has been considered, overlapping the two peaks (conservative approach).

Assessment of the PFC performance under irradiation

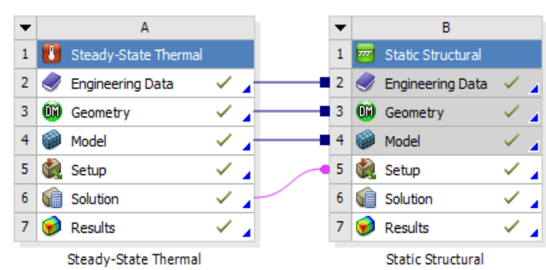
Application of the **Inelastic Analysis Procedure (IAP)**

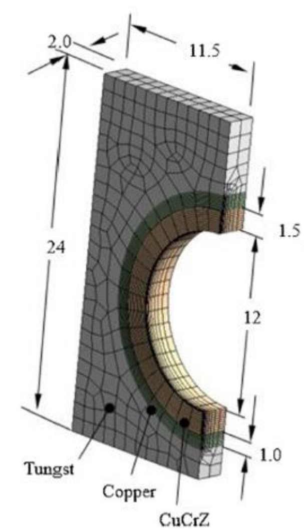
- 5000 normal operation pulses of 2 h duration (10 MW/m^2) + 300 slow transient events of 20 s (20 MW/m^2).
- Coolant conditions: velocity of 16 m/s, pressure of 5 MPa and T=150°C, convective cooling conditions.
- Chaboche material models have been used to define elastoplastic properties for the copper and CuCrZr.
- Tungsten has been defined as an elastic material (for simplicity) since the stress levels appear to remain within the elastic range.



Critical failure phenomena under irradiation:

1) Exceeding the maximum temperature (CuCrZr)
2) Exhaustion of ductility (Cu, CuCrZr)
3) Low cycle fatigue (Cu, CuCrZr)
4) Exceeding the maximum Ultimate Strength (W)





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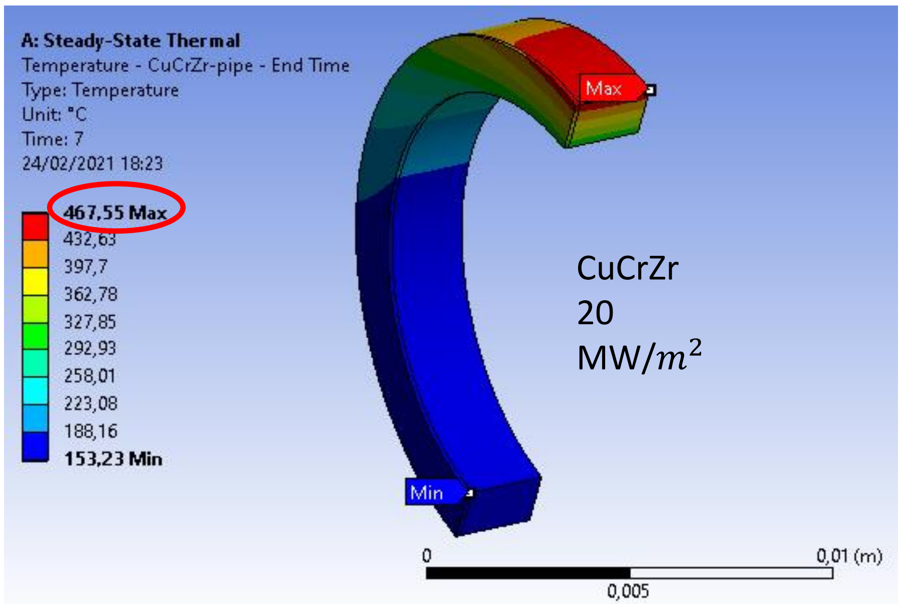
Main data source of material's properties variation

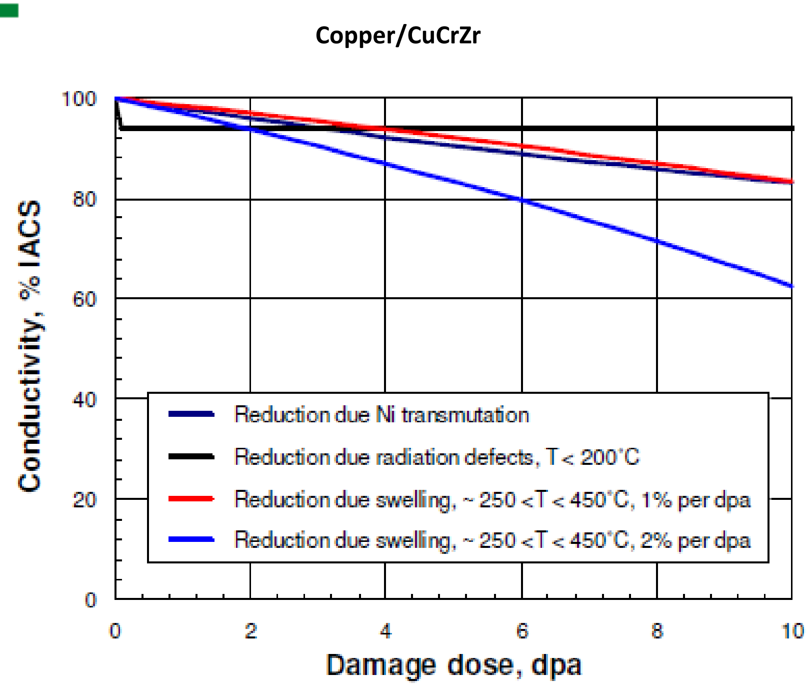
	Material	Main source
Thermal Conductivity	CuCrZr	Fabritsiev, Journal of Nuclear Materials 233-237 (1996) 5266533/ITER SDC-IC Appendix A
	Cu	Fabritsiev, Journal of Nuclear Materials 233-237 (1996) 5266533/ITER SDC-IC Appendix A
	W	Habainy, Journal of Nuclear Materials 514 (2019) 189-195/M. Fuijitsuka et al., Journal of Nuclear Materials 283-287 (2000) 1148-1151
Swelling	CuCrZr	Singe B H, Journal of nuclear materials 191-194 (1992) 1172-1176
	Cu	Zinkle, Journal of Nuclear Materials 329–333 (2004) 938–941
	W	Bykov, Sov. At. Energy 32 (1972) 365-366,
Stress-strain (monotonic)	CuCrZr	P. Fenici, Journal of Nuclear Materials 212-215 (1994) 399-403
	Cu	Fabritsiev, Journal of Nuclear Materials 324 (2004) 23–32
rupture strain	CuCrZr	ITER SDC-IC Appendix A
	Cu	Fabritsiev, Plasma devises and Operations 1997 Vol 5 pp133-141
fracture toughness	CuCrZr	Tahtinen, Nuclear Materials 258-263 (1998) 1010-1014/ITER SDC-IC Appendix A
	Cu	-
Fatigue	CuCrZr	Li, Fusion Science and Technology, 2003, 44, p. 186-190.
	Cu	ITER SDC-IC Appendix A
	W	-
Strength	W	Gorynin, Journal of Nuclear materials 1919-194 (1992) 421-425/Zinkle, Nuclear Fusion Supll Atomic And Plasma-Material Interaction Data For Fusion

Exceeding the maximum temperature (CuCrZr)

$$T_{max} < T_{limit} \rightarrow \mathbf{468°C > 450°C}$$



CuCrZr
20
MW/m^2



$$\frac{\Delta\rho}{\rho_{unirr}} = \frac{\Delta\rho_{rd}}{\rho_{unirr}} + \frac{\Delta\rho_{tr}}{\rho_{unirr}} + \frac{\Delta\rho_{sw}}{\rho_{unirr}}$$

Radiation damage: 7%

Transmutation: 20%

Swelling: negligible

13 dpa

Irradiation effects on thermal conductivity (λ) can be assessed from electrical resistivity changes (ρ) by means of Wiedemann-Franz law:

$$\frac{\lambda_{irr}}{\lambda_{unirr}} = \frac{1}{1 + \frac{\Delta\rho}{\rho_{unirr}}}$$

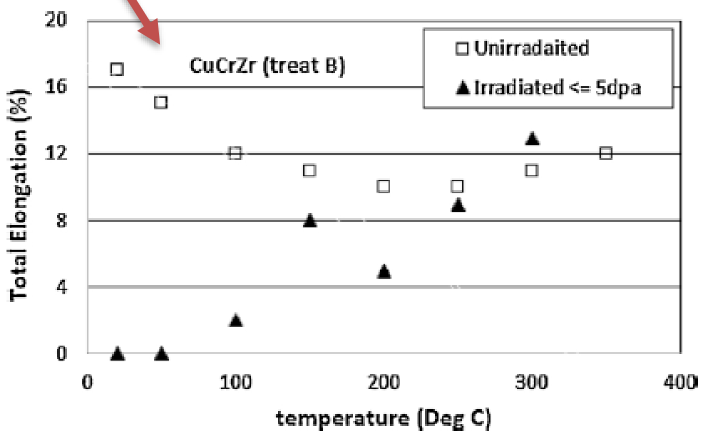
80%

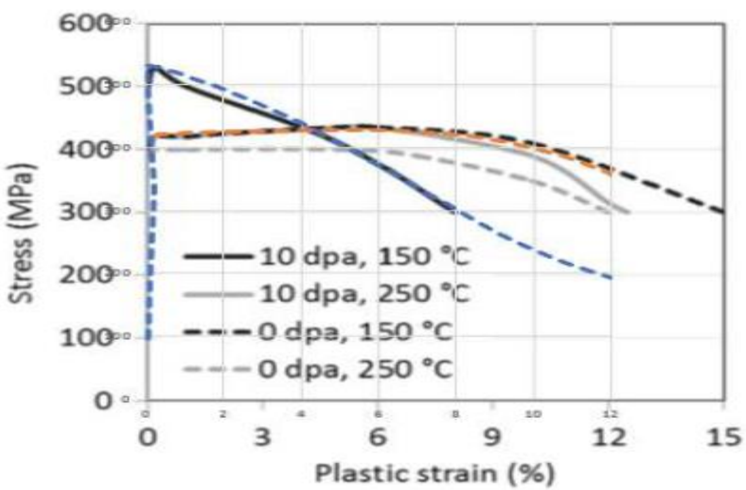
Thermal conductivity degradation due to irradiation causes an increase of the T field of ~ 10%, thus exceeding the limit to avoid thermal creep!

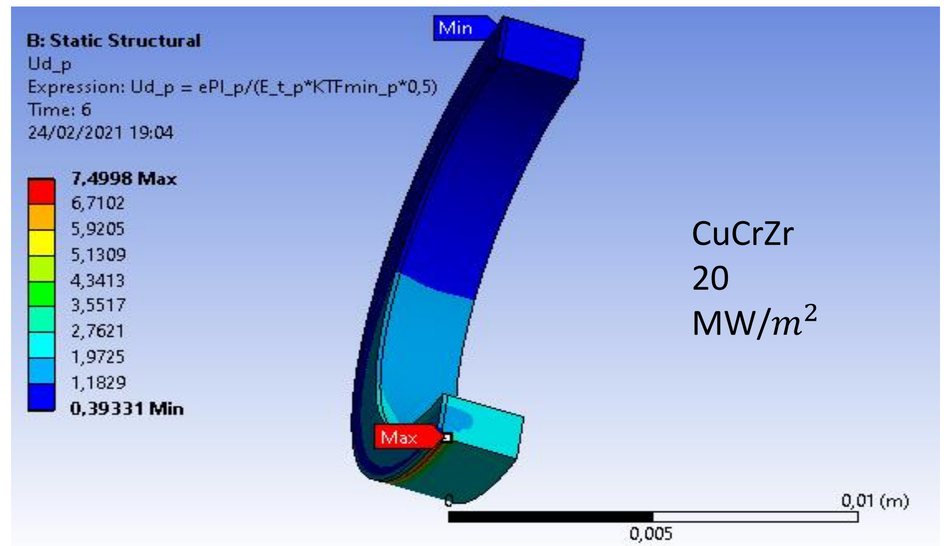
Exhaustion of ductility (CuCrZr)

$$\varepsilon_{pl} < \varepsilon_{LU} \cdot K_{TF} \cdot 0.5 \rightarrow U_d = \frac{\varepsilon_{pl}}{\varepsilon_{LU} \cdot K_{TF} \cdot 0.5} < 1$$

- ε_{pl} is the calculated local equivalent plastic strain.
- ε_{LU} is the uniaxial strain at rupture material limit.
- K_{TF} is the triaxiality factor, defined by the following expression: $K_{TF} = \min(1, \exp(-(\frac{\alpha_{SL}}{1+m}) \cdot (\left\{\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_{eq}}\right\} - \frac{1}{3}))$



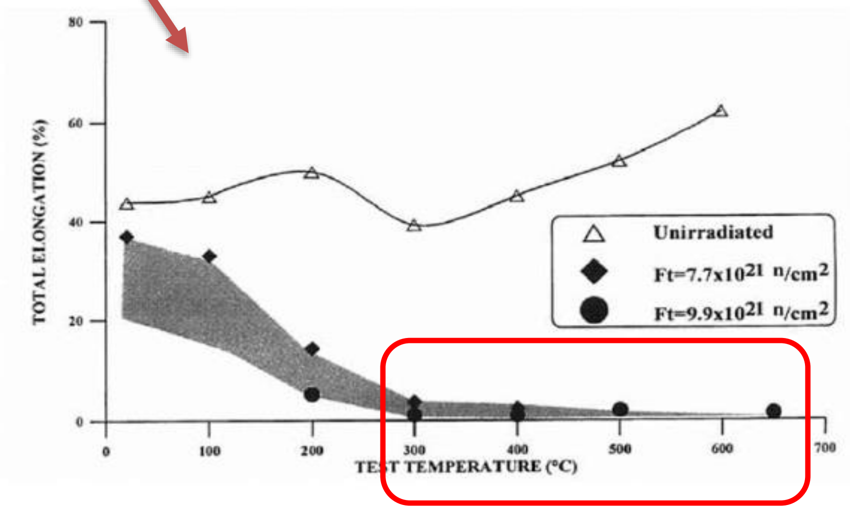


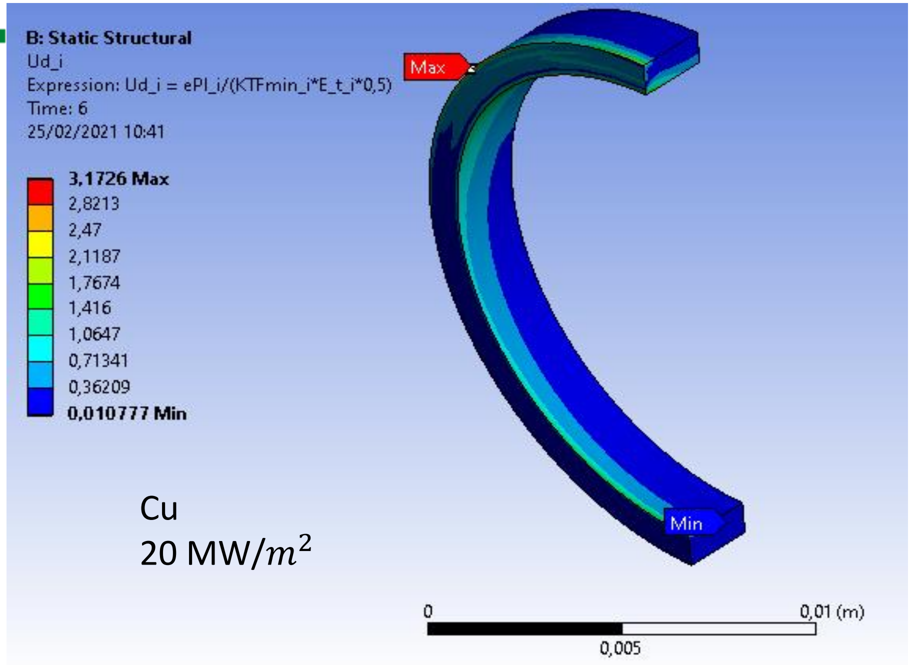


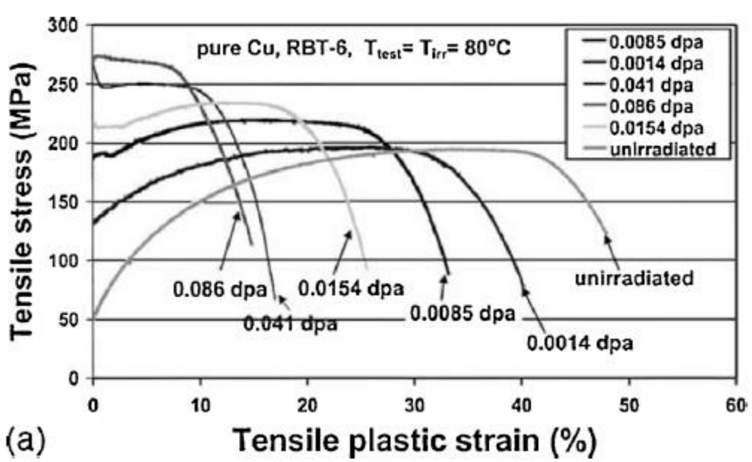
- The maximum plastic strain is more than 7 times that limit at rupture.
- In the unirradiated case (20 MW/m^2) it amounts to 0.5, highlighting a consistent loss of ductility for CuCrZr, especially where temperature is lower.

Exhaustion of ductility (Copper)

$$\varepsilon_{pl} < \varepsilon_{LU} \cdot K_{TF} \cdot 0.5 \rightarrow U_d = \frac{\varepsilon_{pl}}{\varepsilon_{LU} \cdot K_{TF} \cdot 0.5} < 1$$



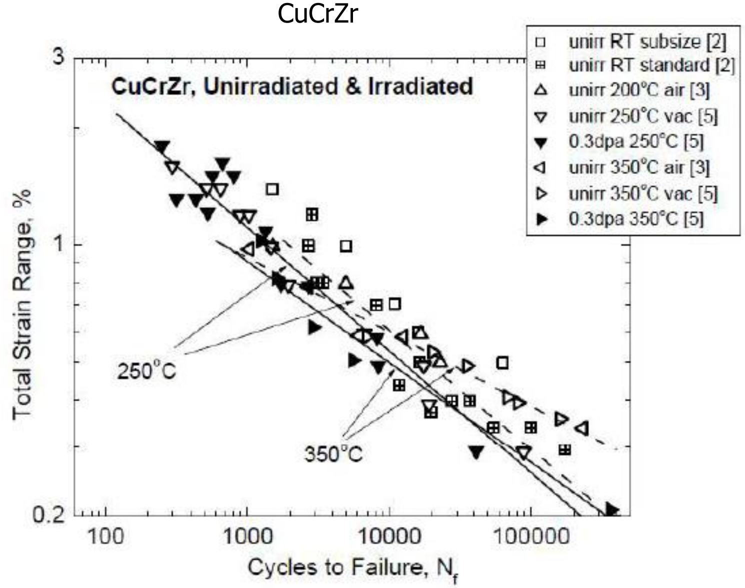




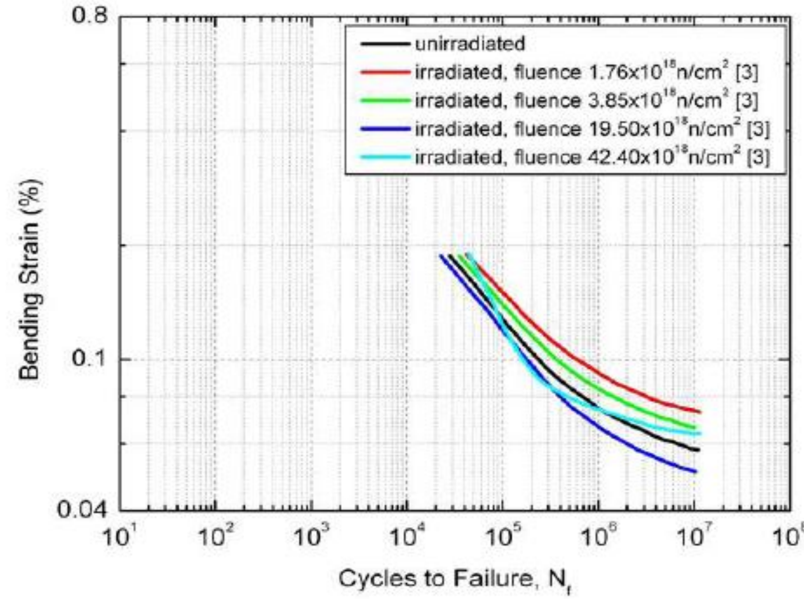
- The maximum plastic strain is more than 3 times that limit at rupture.
- In the unirradiated case (20 MW/m^2) it amounts to 0.15, highlighting a significant loss of ductility also for copper.
- He produced in copper appears to be the main cause of this significant embrittlement, resulting in an intense loss of ductility, especially at high temperature.

Fatigue (Copper and CuCrZr)

CuCrZr



Copper



Fatigue limit curves in the irradiated and unirradiated conditions show a similar trend both for Cu and CuCrZr (low dpa!)

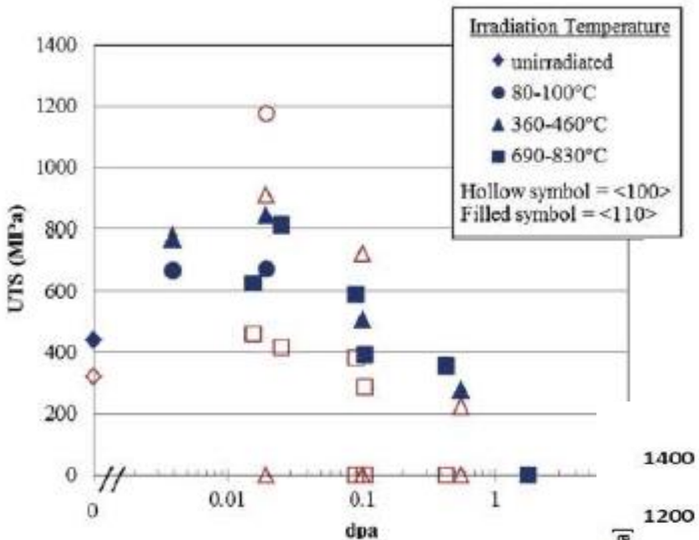
- Neutron irradiation leads to a reduction of 20-50% of the admissible operating cycles than the unirradiated case!

Operating admissible cycles	Unirr (10 MW/m^2) – 5000 cycles	Irr (10 MW/m^2) – 5000 cycles	Unirr (20 MW/m^2) – 300 cycles	Irr (20 MW/m^2) – 300 cycles
CuCrZr	2800	2300 (-20%)	150	80 (-45%)
Cu	130	50 (-50%)	20	10 (-50%)

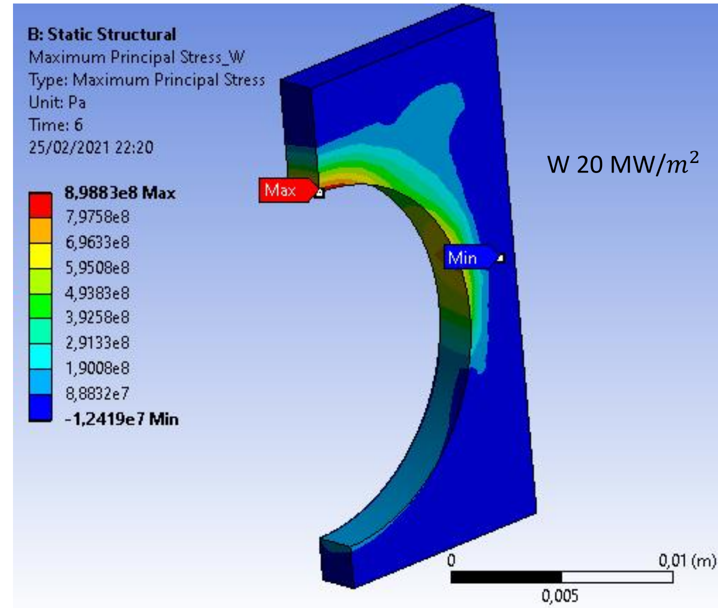
Exceeding the maximum Ultimate Strength (W)

Rankine stress criterion:

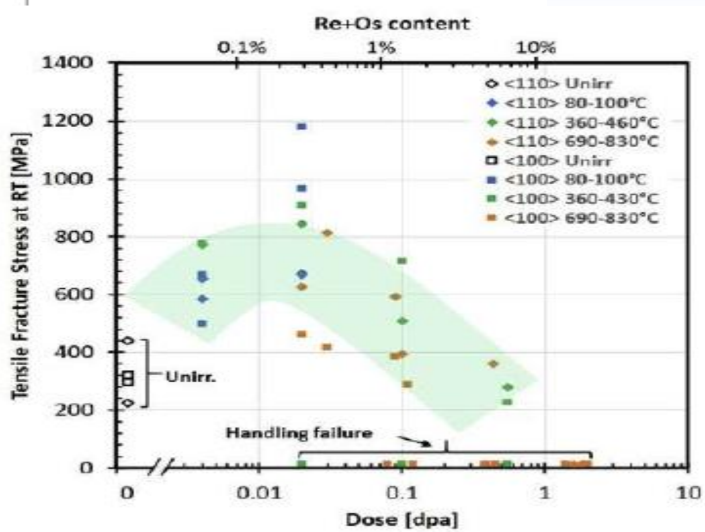
$$\sigma_1 < 0.2 \cdot \sigma_{UTS}$$



Irradiation test data on W suggest very fragile material properties for damage dose > 1 dpa and with a Re+Os contents > 1%, highlighting UTS well below 200 MPa.



Considering that the total amount of Re+Os transmuted from tungsten is ~ 1%, and the peak damage expected is 3 dpa, an UTS value in the irradiated conditions, of **100 MPa**, has been chosen.



$\sigma_{1max} = 900\ MPa$
$> 20\ MPa\ (0.2 \cdot 100\ MPa)$!

The maximum principal stress is 45 times greater than the ultimate strength limit!

Conclusions

- Neutronics analysis has been joined with a thermo-structural integrity assessment under irradiation, following the IAP methodology.

- Critical failure phenomena under irradiation:

- ❑ **Exceeding the maximum temperature** (+10% than the unirradiated case) for CuCrZr with the risk of incurring in thermal creep.
- ❑ **Loss of ductility for Cu and CuCrZr:** the maximum plastic strain is more than 3 and 7 times that limit at rupture, respectively in the peak thermal condition.
- ❑ **Fatigue (Cu, CuCrZr):** neutron irradiation causes a reduction of 20-50% of the operating cycles for Cu/CuCrZr than the unirradiated conditions.
- ❑ **Exceeding the maximum Ultimate Strength (W):** the maximum principal stress is 45 times greater than the ultimate strength limit, considering the peak thermal load.

⇓

Fracture of copper interlayer, thermal isolation of the tungsten from the pipe leading to overheating and early failure, cracks of W armour, early fatigue cracks of Cu/CuCrZr and potential coolant leaks may occur.

- ❑ Lack of data about neutron irradiation effects → Necessary other experimental tests!

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THANKS FOR THE ATTENTION