Modeling the Response of Tungsten to Fusion reactor Thermal Loading Conditions: T-REX tool

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With the kind help of K.Mergia, G. Pintsuk, J. Mougenot, Y. Charles

Date: 09/11/2022

Start EEG: 01/06/2020

End of EEG: 31/12/2022

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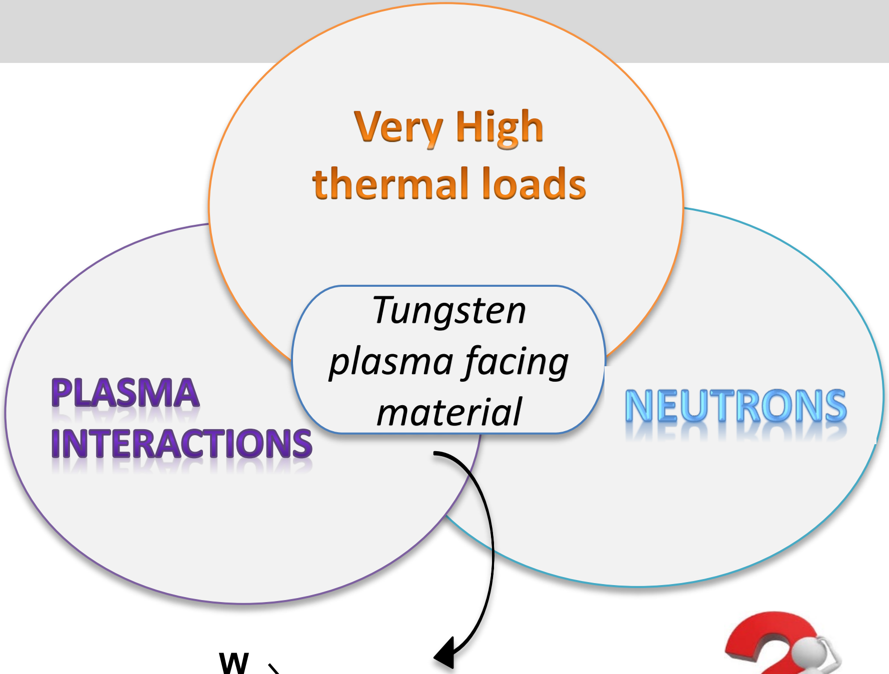
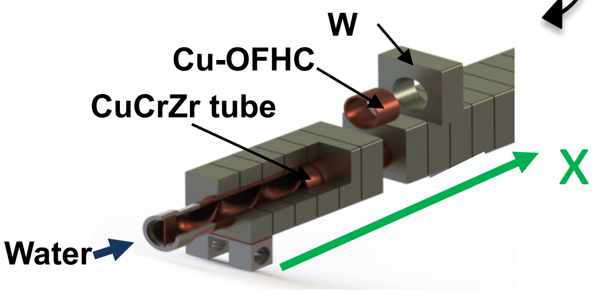
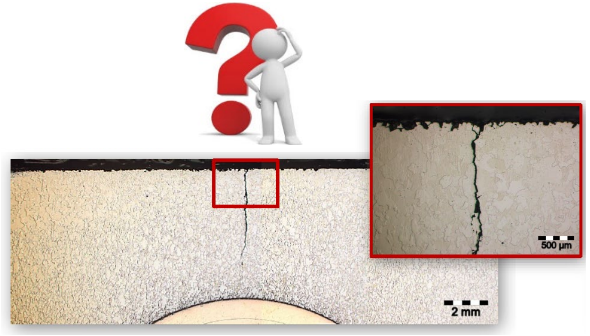
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

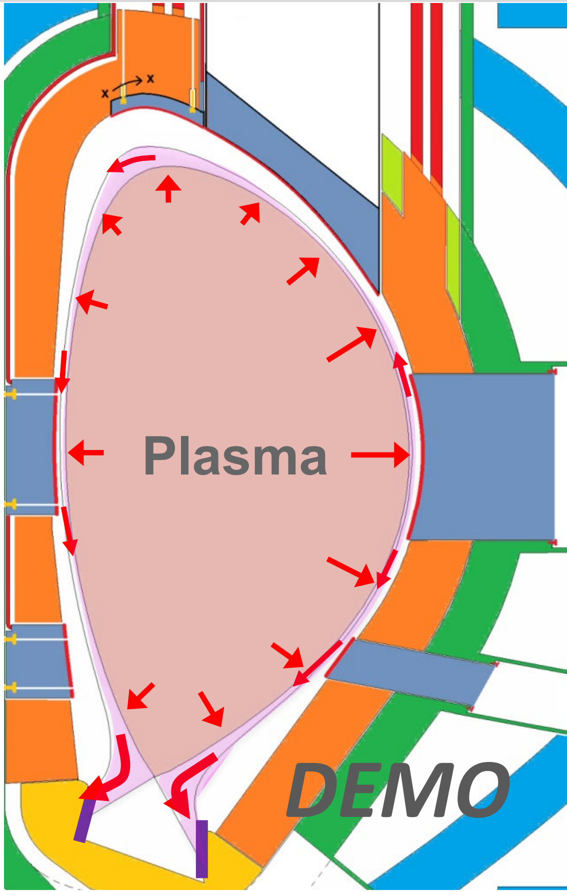
Context





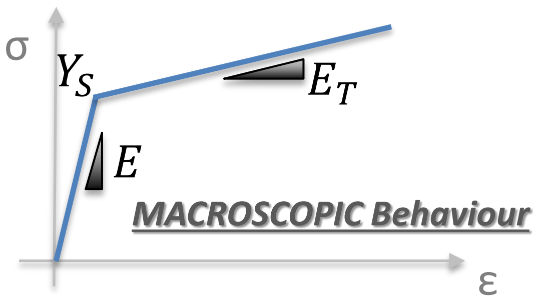


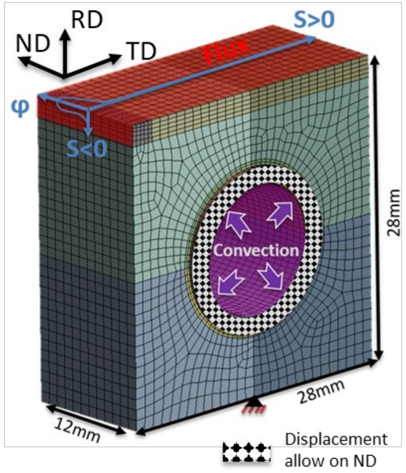
G.Pintsuk et al, FED (2021)



EUROFUSION, WPDIV meeting – June 2019

Provide, for tungsten, a finite element modelling tool able to assess, at the macroscopic scale, relevant stress and strain mechanical fields under tokamak operation conditions to assist component/material design





First phase of the T-REX development

Input:

Thermal / mechanical properties as function of the (i) neutron irradiation, (ii) the temperature, and (iii) the microstructural state

⇨ *Their interactions*

⇨ *Thermally activated phenomena (softening)* **+** ⇨ *Neutron irradiation*

Input:

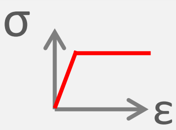
Thermal / mechanical properties as f

(i) neutron irradiation, (ii) the temp

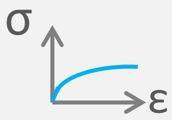
⇨ *Thermally activated phenomena (softening)*

Microstructural evolution changes the tungsten mechanical behavior (softening)

As-Received



Softened



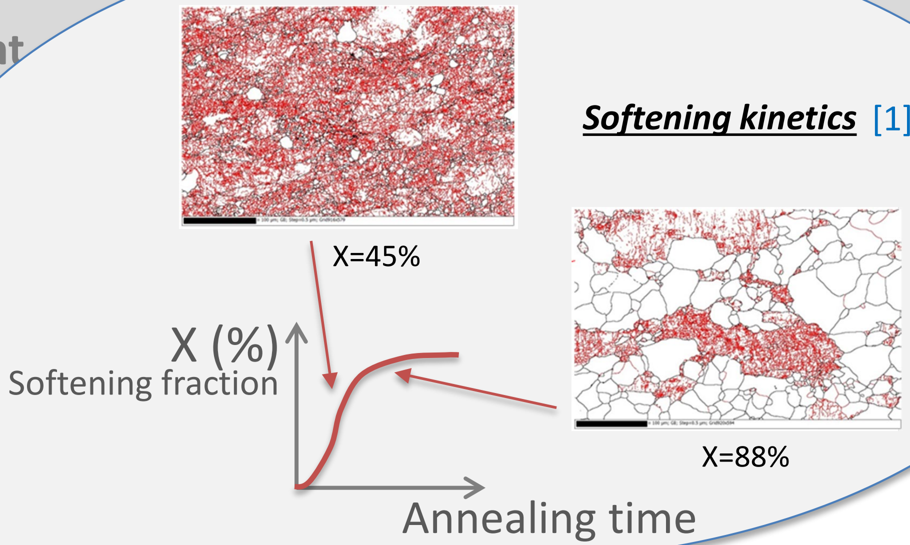
First phase of the T-REX development

Input:

Thermal / mechanical properties as f

(i) neutron irradiation, (ii) the temp

Softening kinetics [1]



⇨ *Thermally activated phenomena (softening)*

[1] M. Richou et al, JNM, 2019

First phase of the T-REX development

Input:

Thermal / mechanical properties as function of the
(i) neutron irradiation, (ii) the temperature, and (iii) the microstructural state

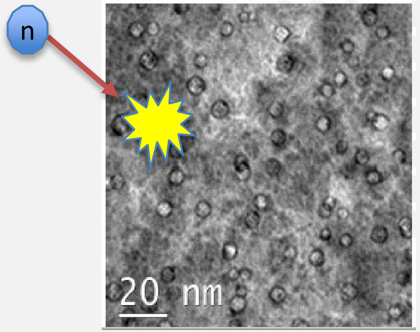
⇨ *Their interactions*

⇨ *Thermally activated phenomena (softening)* **+** ⇨ *Neutron irradiation*

3 dpa after 2 full power years in DEMO [3]

→ Cavities, dislocations networks, solid/gas transmutations, etc…

Cavities in W [2]



[2]Dubinko (2020) EURO fusion midterm [3] Noce et al, FED (2020)

Input:

Thermal / mechanical properties as function of the
(i) neutron irradiation, (ii) the temperature, and (iii) the microstructural state

⇨ *Their interactions*

⇨ *Thermally activated phenomena (softening)* + ⇨ *Neutron irradiation*

Output:

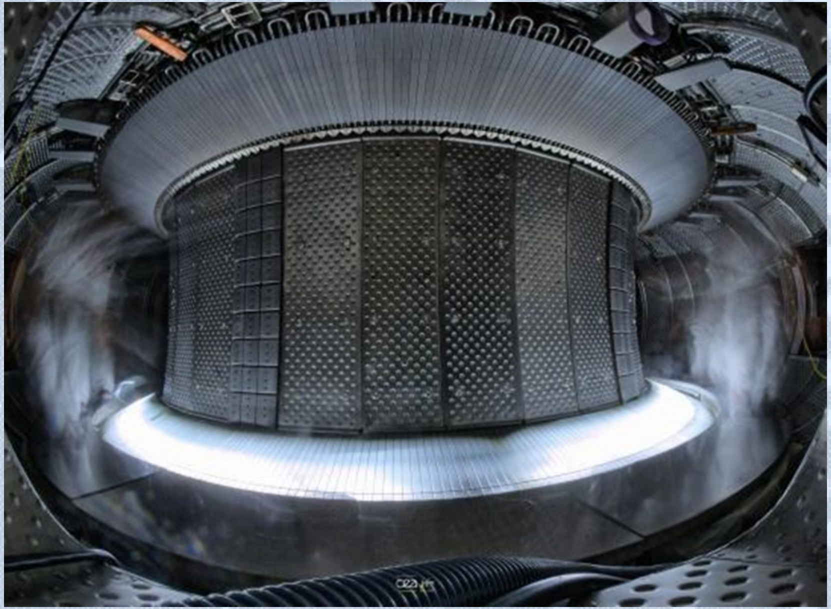
Influence of the neutron irradiation and thermally activated phenomena on the tungsten damage process

1- Thermal modelling T-REX assumptions

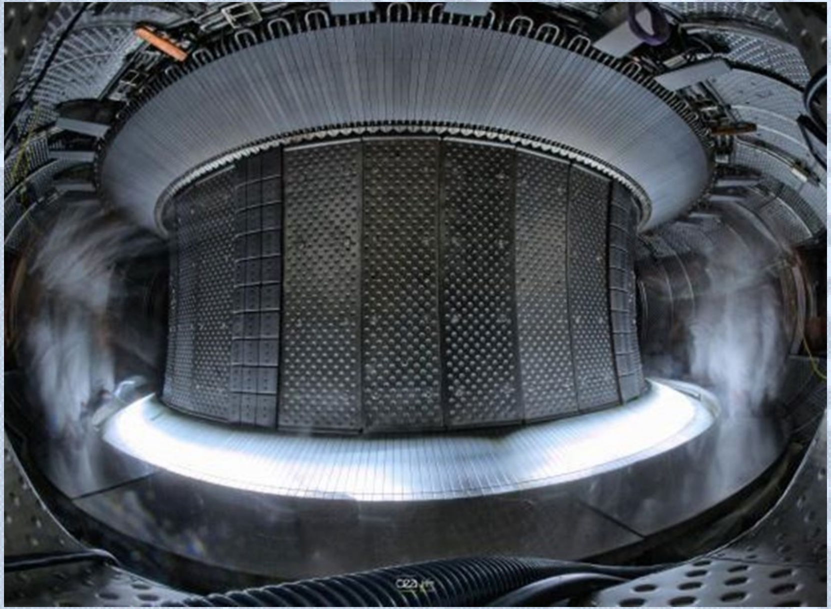
2- Mechanical modelling T-REX assumptions

3- T-REX applications

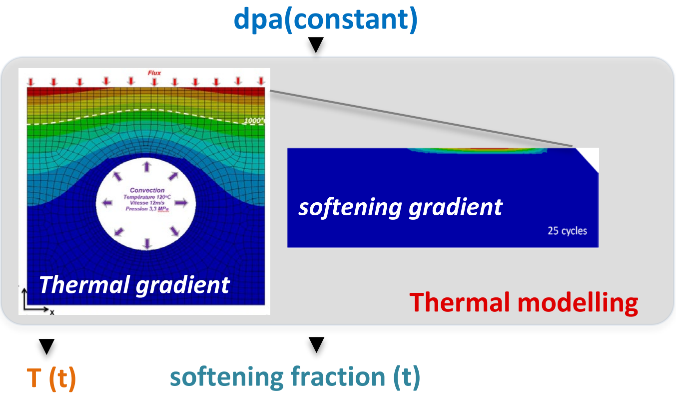
4- Conclusions & perspectives



1- Thermal modelling T-REX assumptions



T-REX assumptions related to the thermal modelling: dpa is assumed as constant



1.T-REX hypothesis:

→ dpa is assumed as constant over the simulation time (dpa rate expected for DEMO: 10^{-6} dpa/s [4]

Order of magnitude:

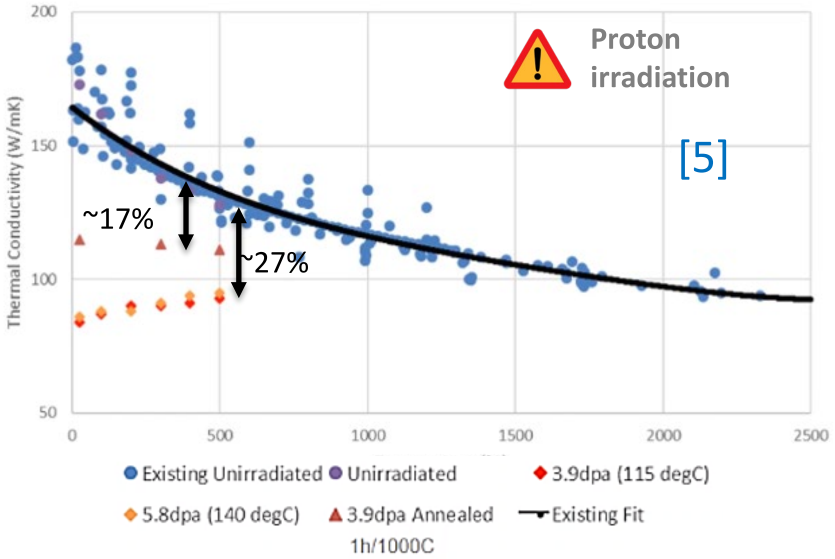
Minute (plasma shock) → 6e-5 dpa

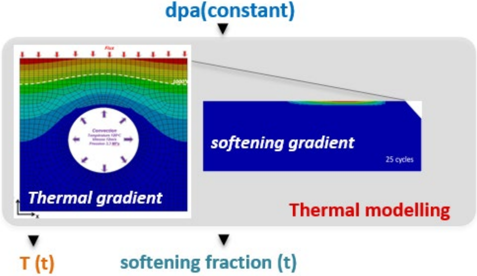
Hour (plasma campaign) → 0,0036 dpa

[4] S. Ishino et al, J. Fus. E. (1989)

T-REX assumptions related to the thermal modelling: decrease of thermal properties due to neutron irradiation

⇨ *Neutron irradiation*





↘ Thermal properties [5]

2.T-REX hypothesis:
→ Proton irradiation data is considered for the modeling to give trends

Further experimental data needed:

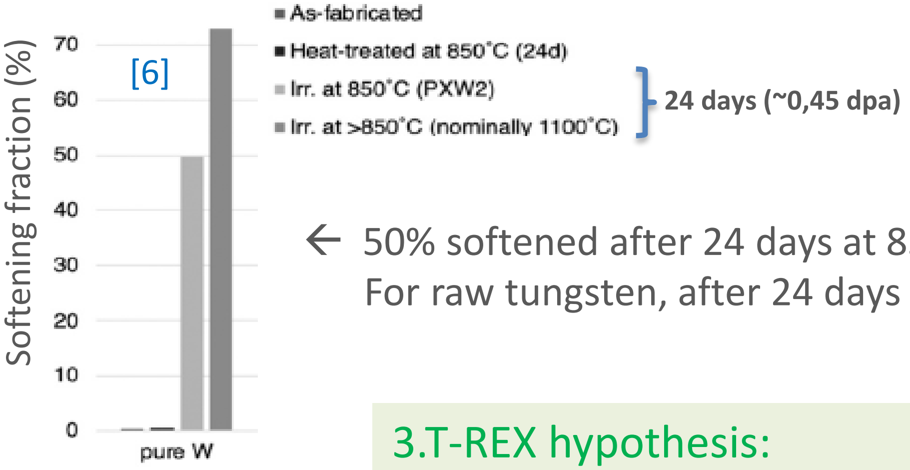
↳ Need to be confirmed under **neutron** irradiation (func. of irradiation temperature & dpa)

[5] E. Gaganidze, 6th DIM meeting, adapted from [Habainy, JNM, 2018]

T-REX assumptions related to the thermal modelling: shift of the tungsten softening kinetics can be considered due to neutron irradiation

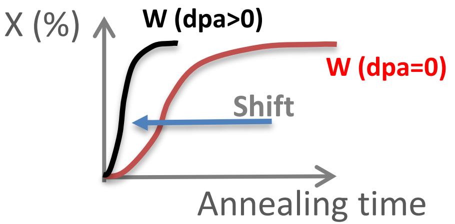
⇨ *Neutron irradiation*

⚠ **Trends need to be consolidate by further experiments**



← 50% softened after 24 days at 850°C (~0.4 dpa)
For raw tungsten, after 24 days at 850°C no softening expected

3.T-REX hypothesis:
→ Possible shift on the softening kinetics

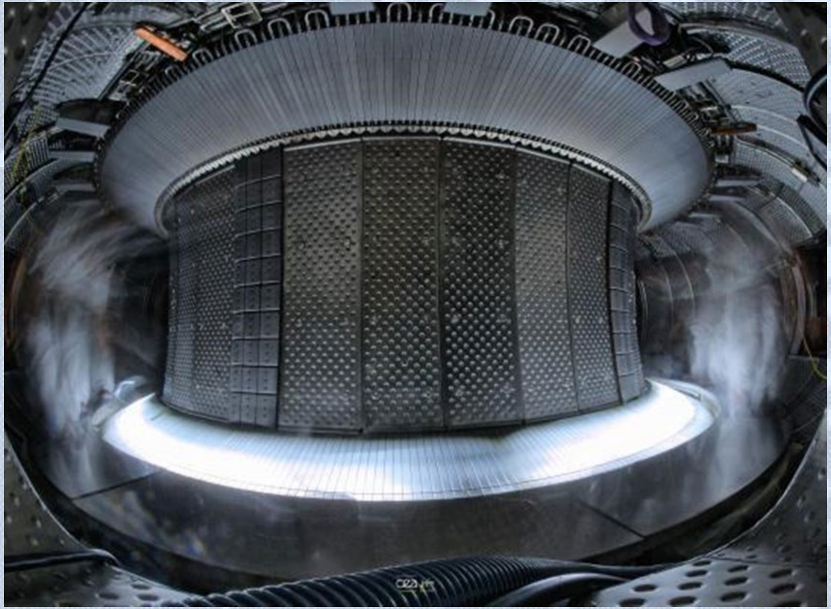


Further experimental data needed for future T-REX implementation:

- Need to be further analyzed

[6] H. Gietl et al, JAC, 2022

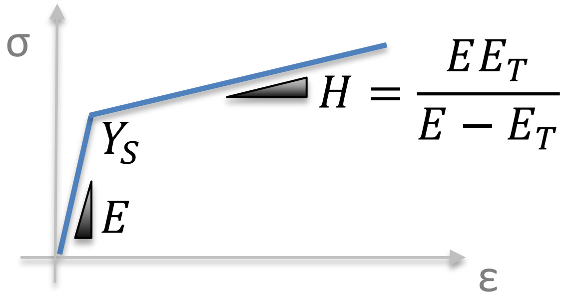
2- Mechanical modellingT-REX assumptions



MACROSCOPIC Behaviour

Elastic-viscoplastic model is considered [7]

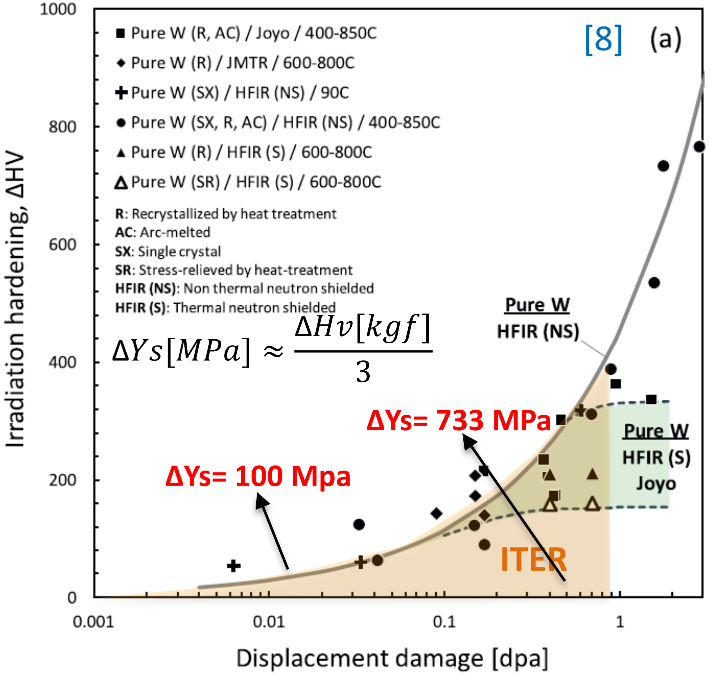
↳ assuming linear kinematic hardening

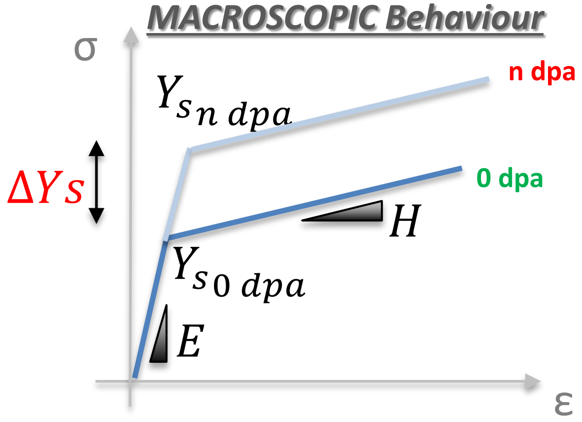


[7] A. Durif et al, IJF, 2021

T-REX mechanical model consider tungsten neutron embrittlement

⇨ *Neutron irradiation*



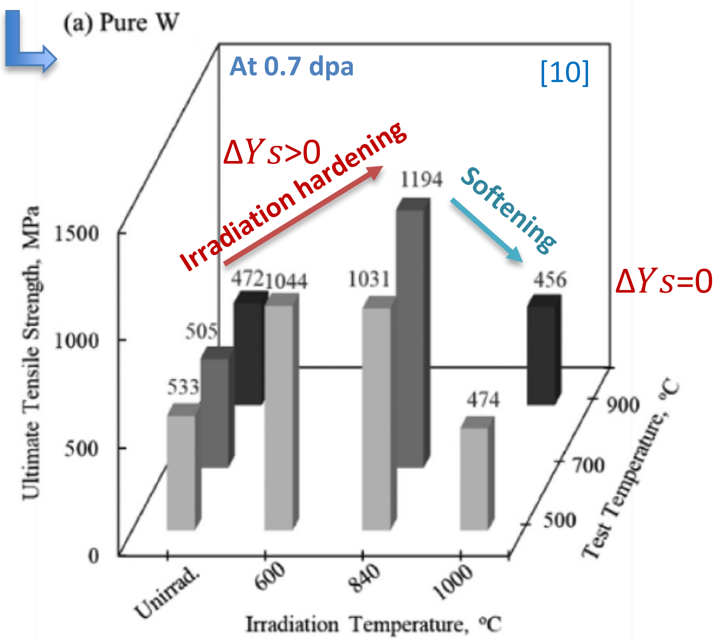


4.T-REX hypothesis:

→ Evolution law given by [9] is considered to set ΔYs (embrittlement) for irradiated tungsten

[8] S. Nogami et al, JNM, 2021 [9] Terentyev, IJRMHM, 2021

Assumption related to ΔYs :



Softening under neutron irradiation leads to reduce the irradiation-enhanced embrittlement of tungsten

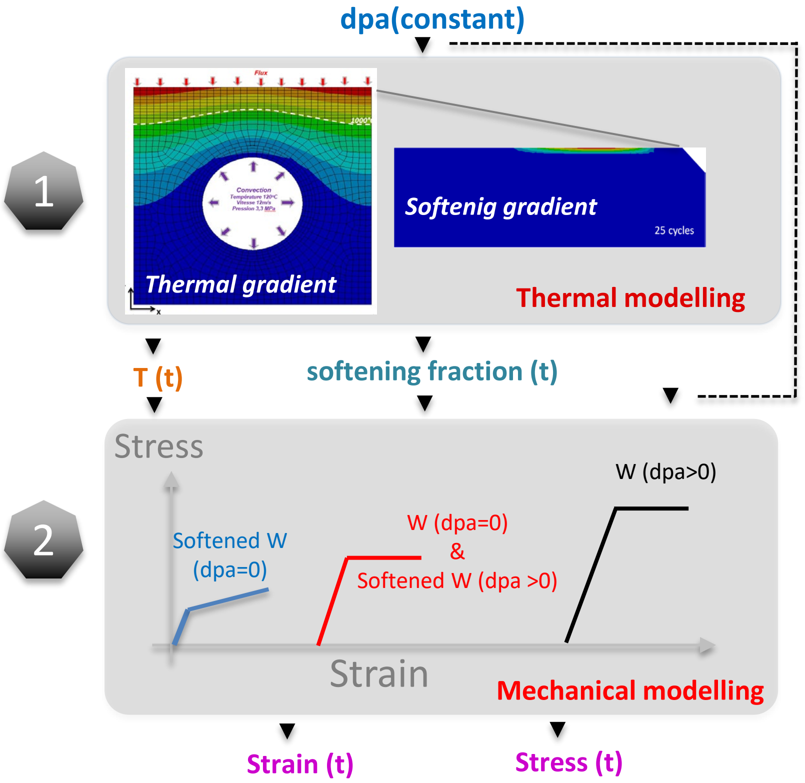
6.T-REX hypothesis:
ΔYs=0 MPa for softened neutron irradiated tungsten

Further experimental data needed:

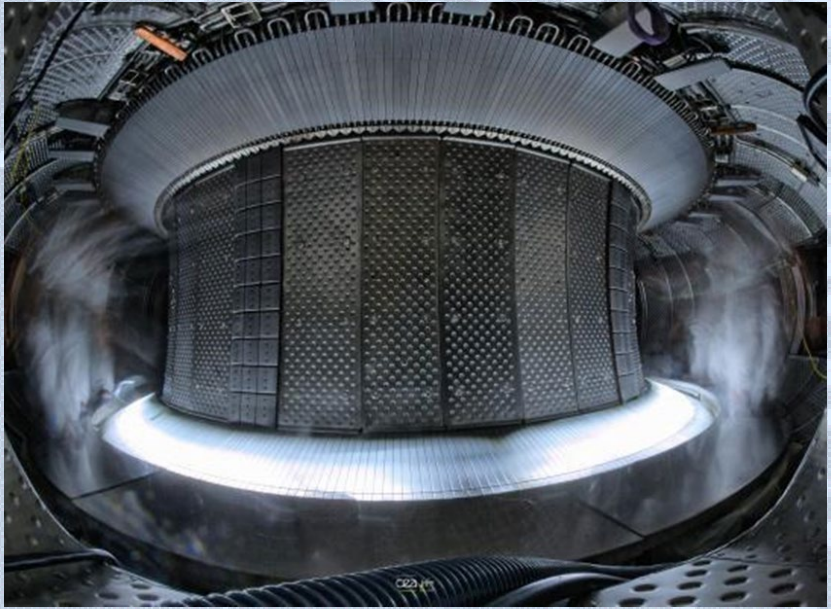
- Need to be further analyzed

[10] T. Miyazawa, JNM, 2020

Current state of the T-REX tool (Nov. 2022)



3- T-REX applications



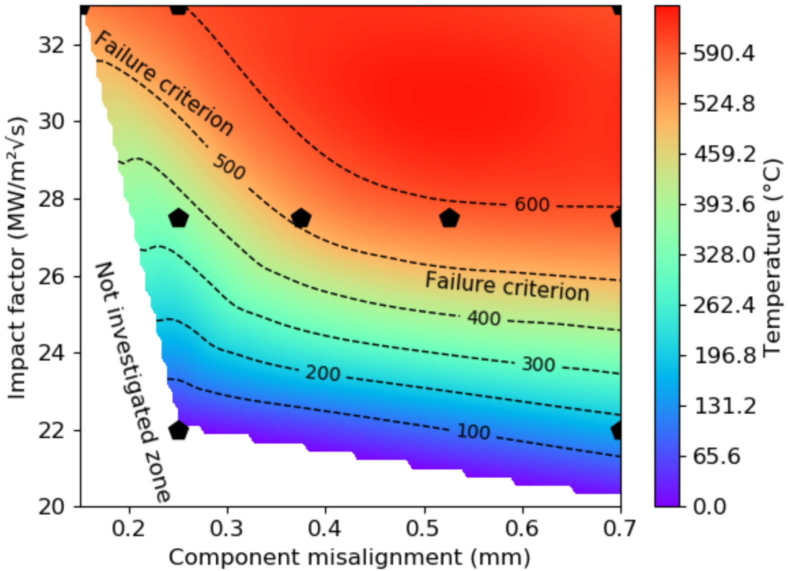
Study related to WEST & ITER:

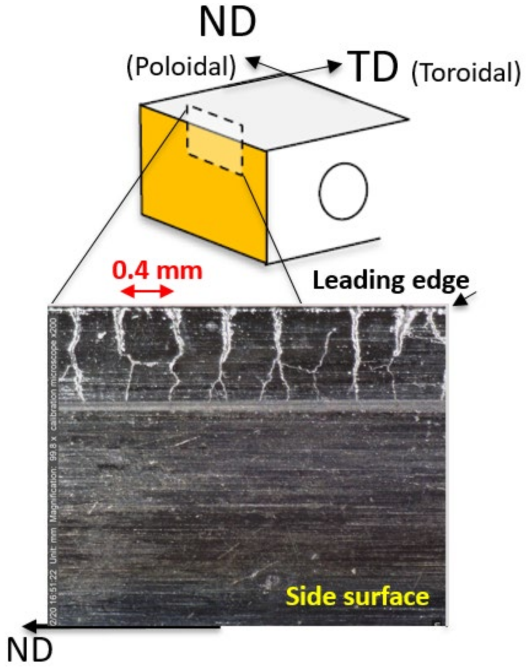
⇨ Their interactions

⇨ Thermally activated phenomena (softening) + ⇨ Neutron irradiation

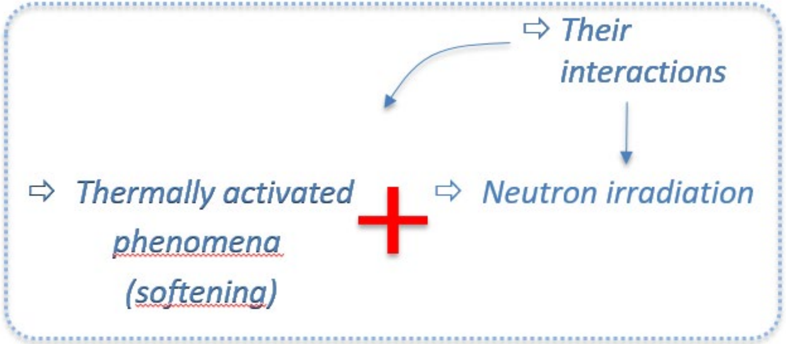
Interpret the tungsten monoblock leading edge cracking observed during the WEST phase I operation [11] [12]

Main results:
Leading edge cracking could occur under fast transient (disruption)





[11] A. Durif *et al* 2022 *Phys. Scr.* 97 074004
[12] A. Durif *et al* 2022 FED [Submitted]



Study related to ITER & DEMO

Study the influence of the neutron irradiation on the monoblock tungsten damage process change (from 0 to 0.3 dpa) [13]

Main results:
Monoblock geometry can be optimized to delay crack opening (optimize the lifetime)

[13] A. Durif *et al*, *J. Nuc. Mat. 569 (2022) 153906*

5- Conclusions & perspectives

Conclusions & perspectives (I/2)

T-REX model takes into account the influence of both isolated and combined heat flux/neutron loading on thermal and mechanical properties change of tungsten to **improve the estimation of stress and strain mechanical fields** ⇒ **Assist Material & Component design**

Conclusions & perspectives (I/2)

T-REX model takes into account the influence of both isolated and combined heat flux/neutron loading on thermal and mechanical properties change of tungsten to **improve the estimation of stress and strain mechanical fields** → **Assist Material & Component design**

T-REX assumptions:

- Elastic-viscoplastic behaviour for tungsten, irradiated tungsten, softened tungsten (WORK NEEDED)
- dpa assumes as constant over the time of the finite elements modelling simulation
- dpa impact leads to:
  - a decrease of thermal conductivity (WORK NEEDED)
  - a shift of Yield Stress (independent temperature parameter) expected after softening (WORK NEEDED)
  - a shift of the tungsten softening kinetics (WORK NEEDED)

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Thank for your attention

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Laboratoire de Tribologie et Dynamique des Systèmes

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UMR 5307

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Acknowledgments

- Thanks to the all T-REX partners

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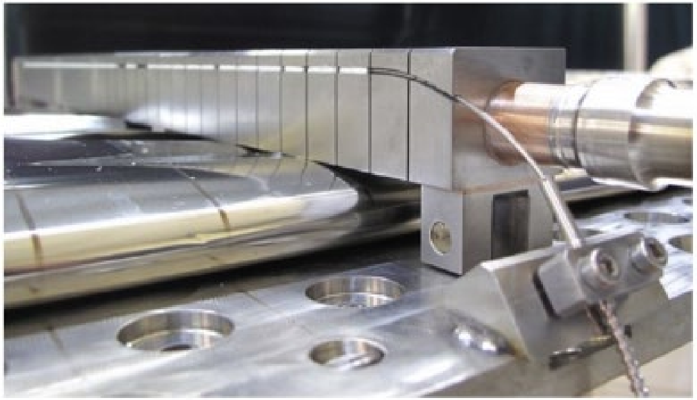
⇨ ~~Their interactions~~

⇨ *Thermally activated phenomena (softening)* + ⇨ ~~*Neutron irradiation*~~

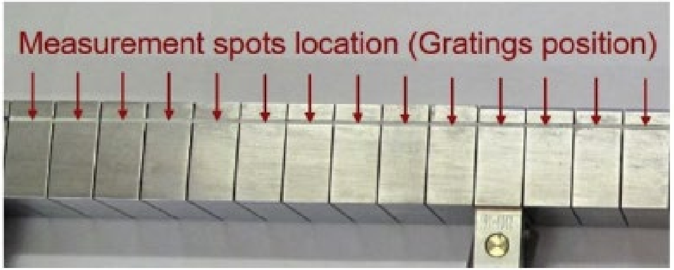
Model validation (2023):

Qualitative high heat flux campaigns in HADES to study the number of cycles to failure

Quantitative strain estimation via HADES and embedded FBG in PFCs (FIBRA-MECA project)



[13]



➡ **Structural Health Monitoring**

[13] N. Chanet et al, FED, 2021

Elastic-viscoplastic constitutive equations:

↳ assuming linear kinematic hardening

MACROSCOPIC SCALE

Elastic-viscoplastic model:

$$\bar{\bar{\varepsilon}}^{tot} - \bar{\bar{\varepsilon}}^{th} = \bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}^{e} + \bar{\bar{\varepsilon}}^{p} \quad (1)$$

$$\bar{\bar{\sigma}} = \bar{\bar{\bar{\bar{C}}}} : \bar{\bar{\varepsilon}}^{e} \quad (2)$$

$$f(\bar{\bar{\sigma}}, \bar{\bar{\chi}}) = J(\bar{\bar{S}} - \bar{\bar{\chi}}) - Y_s \quad (3)$$

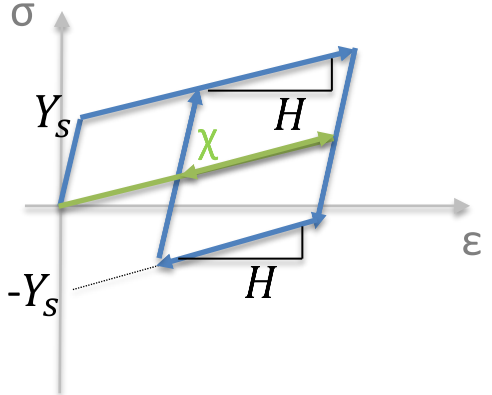
$$\dot{\bar{\bar{\varepsilon}}}^{p} = \frac{3}{2}\dot{p}\frac{\bar{\bar{S}} - \bar{\bar{\chi}}}{J(\bar{\bar{S}} - \bar{\bar{\chi}})} \quad (4)$$

$$\bar{\bar{\chi}} = \frac{2}{3} H\, \bar{\bar{\varepsilon}}^{p} \quad with \quad H = \frac{E E_T}{E - E_T} \quad (5)$$

$$\dot{p} = \left\langle \frac{J(\bar{\bar{S}} - \bar{\bar{\chi}}) - Y_s}{K} \right\rangle^{n} \quad (6)$$

Elastic behaviour if $f \leq 0, \dot{p} = 0$.

MACROSCOPIC Behavior



Y_S, E and E_T ~ f (T)

E_T ~ 0 for tungsten

$\bar{\bar{\varepsilon}}^{tot}$: total strain tensor / $\bar{\bar{\varepsilon}}^{th}$: Thermal strain tensor / $\bar{\bar{\varepsilon}}^{e}$: elastic strain tensor / $\bar{\bar{\varepsilon}}^{p}$ Plastic strain tensor / $\bar{\bar{\sigma}}$: Stress tensor / $\bar{\bar{\bar{\bar{C}}}}$: elastic stiffness / $f(\bar{\bar{\sigma}}, \bar{\bar{\chi}})$: plastic criteria / $\bar{\bar{\chi}}$: kinematic hardening / σ^y: Yield stress / $\bar{\bar{S}}$: deviatoric stress tensor / p: accumulated equivalent plastic strain / n, K & H: material parameters

[5] A. Durif et al, IJF, 2021

T-REX: Concentration profil of D

Trapping / Transport modelling

3

Analytical solutions (performed as post-treatment) taking into account the estimated dislocation density (nb of traps, n_i)

▼

…

▼

C_t^{eq}

(D concentration)

With:

$\frac{1}{\nu_i(T)}$ the characterisitic detrapping time

$\frac{1}{\nu_m(T).cm}$ the characteristic trapping time

ϕ the incident heat flux

$D(T)$ the diffusion coefficient

$K(T)$ a thermo dependent parameter

ni an output of the T-REX simulations

Based on equations presented in [R.Delaporte-Mathurin, 2020] and [E. Hodille et al, 2017]

$$c_{t,i}^{eq} = R_{trap,i}(T, c_m) \cdot n_i$$

$$R_{trap,i} = \frac{1}{1 + \frac{\nu_i(T)}{\nu_m(T) \cdot c_m}}.$$

$$c_{max} = \frac{\varphi_{imp} \cdot R_p}{D(T_{surface})}$$

T-REX: Concentration profil of D

Trapping / Transport modelling

3

Analytical solutions (performed as post-treatment) taking into account the estimated dislocation density (nb of traps, $\underline{n_i}$)

▼

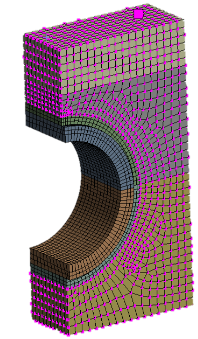
N_i (p,*) (*dpa neglected as first approach)

(densité de disclocation)

▼

C_t^{eq}

(D concentration)



How estimate Nt as function of p?

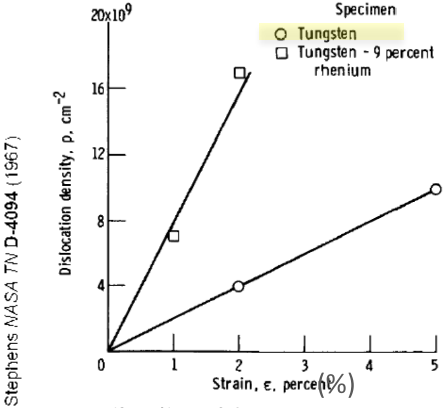
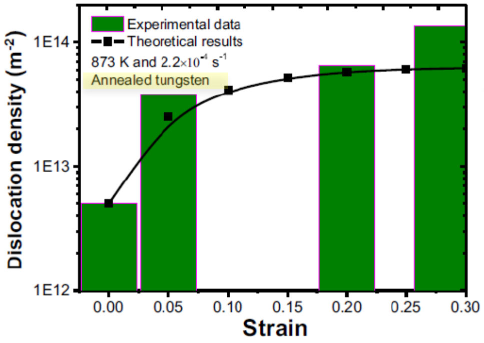


Figure 10. - Variation of dislocation density with strain for unalloyed tungsten and tungsten - 9 percent rhenium.

D. Terentyev et al. / J. Mech. Phys. Solids 85 (2015) 1–15



Same trends for W and softened W

$$n_i = p * 3.10^{12} + 5.10^{12}$$

Assumption:

→ plastic strain = strain (elastic strain is neglected)

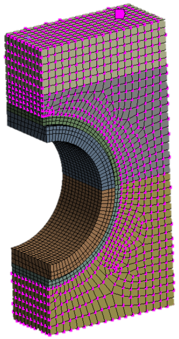
Trapping / Transport modelling

3

Analytical solutions (performed as post-treatment) taking into account the estimated dislocation density (traps, $\underline{n_i}$)

N_i (p, dpa)

(densité de disclocation)



For W:

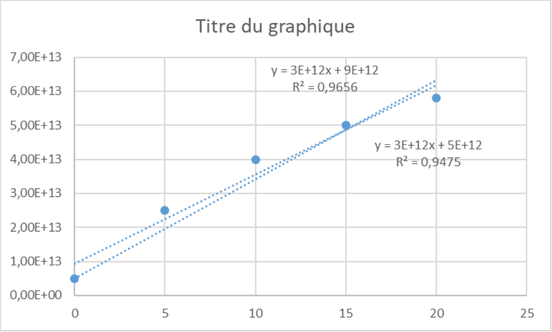
$$n_{i\ init\_W} = 4.10^{13}/m^2$$ [papier CM]

$$n_i = n_{i\ init\_W} + p * 3.10^{12}$$

For fully softened W:

$$n_{i\ init\_Wrx} = 5.10^{12}/m^2$$ [Terentyev]

$$N_i = n_{i\ init\_Wrx} + (p(t) - p(t_{X=50\%})) * 3.10^{12}$$



If the softening process is ongoing:

If X<50% → cf W

If X>50% → cf fully softened W

Irradiation campaigns to be organized in FP9

	Brief description	Irradiation period	PIE planned
LOT D	5 different ITER-conform **tungsten** grades, 400-800-1200C, 0.2 – 0.5 dpa for HHF	Q4 2020 – Q3 2021, completed	Tensile tests at 600C are performed, rest is pending decision on new ALMT grade
LOT E	**Steels** E97-2; 3 optimized E97 grades for LT, 2.5 dpa, 300C for SDQ	Q4 2021 – Q3 2022, running	Charpy at KIT, tensile at SCK CEN
LOT KJ	**W-CuCrZr joints** (fabricated by FAST), 0.5 dpa, 150-350C for HHF	Q1 2022 – Q3 2022, running	Tensile, hardness, SEM
LOT A2	**Steels** E97-3, 3 dpa, 300-350-450-550C. Fracture toughness samples for TBM qualification for TBM	Q2 2022 – Q2 2023, loading to reactor	Fracture toughness, hardness
LOT SDQ	**Steel** E97-3; 6 optimized E97 grades for LT, 2.5 dpa, 300C for SDQ	Q2 2022 – Q1 2023, manufacturing	Charpy at KIT, tensile, hardness at SCK CEN
	Tungsten. Validation of design rules for brittle and transition region fracture 400/600 and 1000/1200C at 0.2 and 1 dpa, DCC-IC	Q3 2022 – Q2 2023, design	Bending tests, fracture toughness
	Tungsten. Tensile properties & DBTT of W advanced grades under shielded irradiation (Gd), 400-800-1200C, 1 dpa, for HHF	Q3 2022 – Q2 2023, design	Tensile tests, hardness
	Tungsten. High temperature irradiation (recrystallization and limit for irradiation damage recovery), 0.2 dpa 1200-1600C, for HHF	Q3 2022 – Q1 2023, design	Bending/tensile tests
	CuCrZr & Steel. Low-T irradiation for DIV (E97-3, CuCrZr), Tirr=50-150-250C (350 and 450 for CuCrZr) to cover the gaps, 1 – 3 – 6 dpa.	Q2 2022 – Q1 2024, design	Tensile, fracture toughness, LCF
	Low-T irradiation for IREMEV (**E97, W, CuCrZr**), Tirr=50 and 300C for 0.1-1 dpa	Q3 2022 – Q1 2023, design	TEM study, in-situ annealing and in-situ deformation, PAS/hardness
	Irradiation of advanced Cu-materials (**Wf and W yarns**) materials, irradiation of sole W-fibers/yarns. Tirr= 400 – 800 – 1200C to be combined with other W irradiation. For DIV and HHF.	Exact design and sample geometry still to be defined.	Tensile or bending tests, objective is to define DBTT shift

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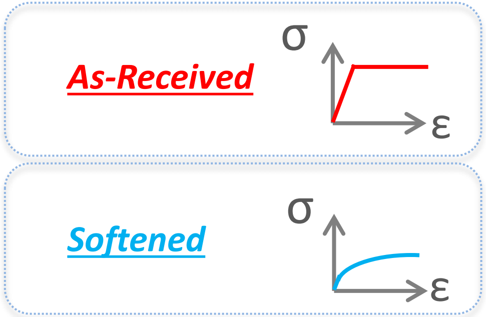
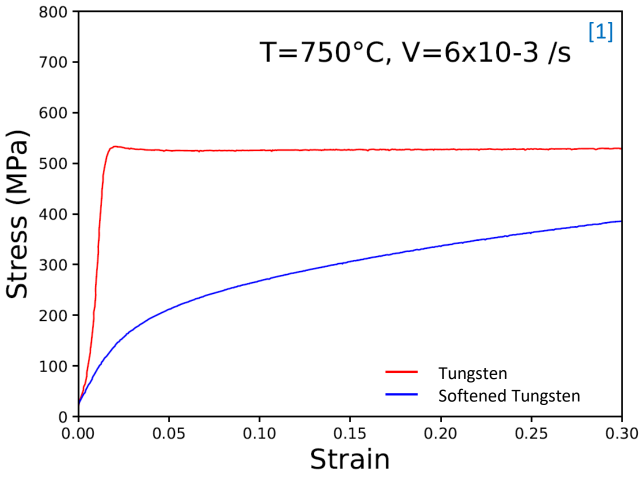
⇨ *Thermally activated phenomena*





↘ Yield stress [1]

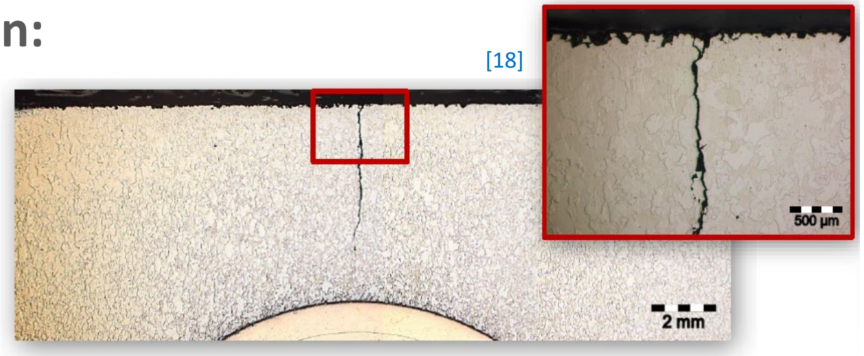
↗ Ductility [2]

Softened = restored / recrystallized

[1] A. Durif et al, FED, 2019
[2] A. Durif et al, IJF, 2021

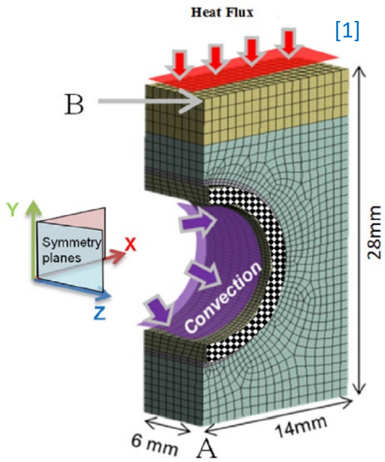
Focus on the accumulation of plastic strain:

[18]



- Under thermal cycles (15 - 20 MW/m²) the tungsten damage process is governed by plasticity →

[1]

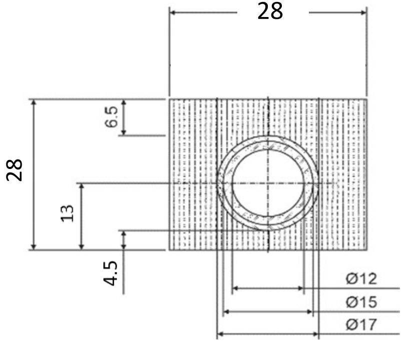


Focus on the evolution of the equivalent plastic strain increment per cycle (Δp) at maximum expected (point B)

[18] G.Pintsuk et al, FED (2021)
[1] A. Durif et al, FED, 2019

ITER divertor target geometry and boundary conditions

Geometry



Convection param.

120°C,
3.3 MPa,
12 m/s

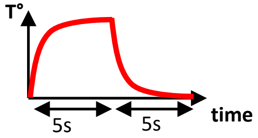
ΔY_s (dpa)

100 MPa (0.01 dpa)
400 MPa (0.1 dpa)
733 MPa (0.3 dpa)

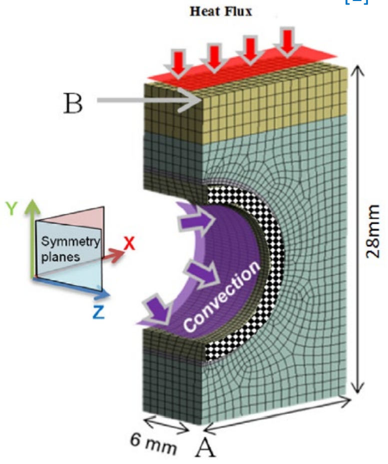
Boundary conditions

Intensity:
15 & 20 MW/m²

Thermal cycle

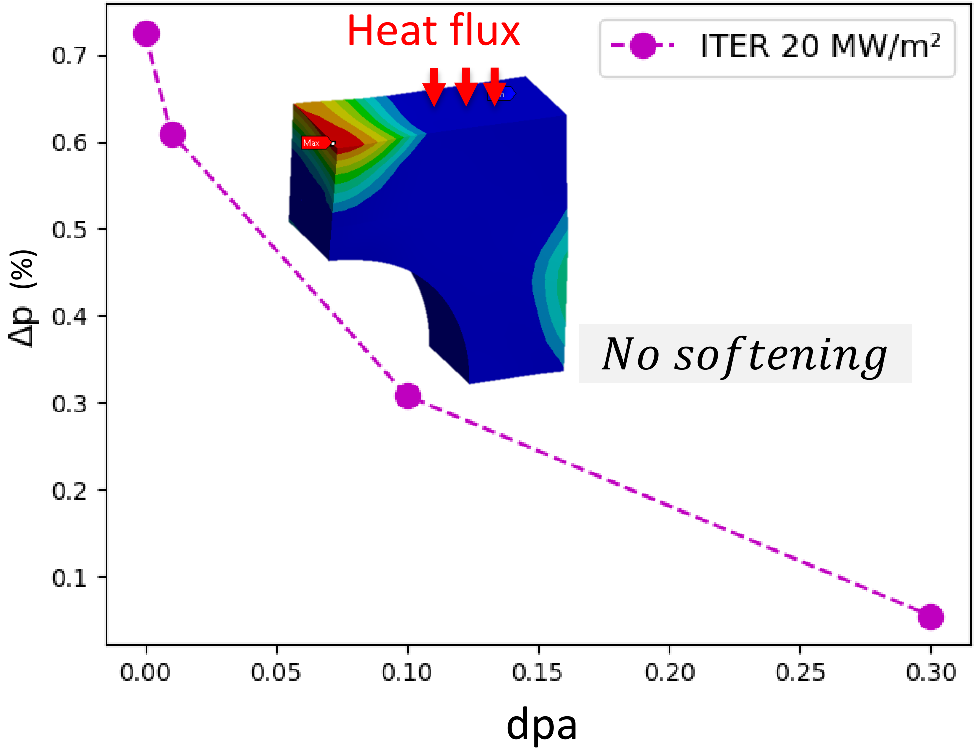


[1]



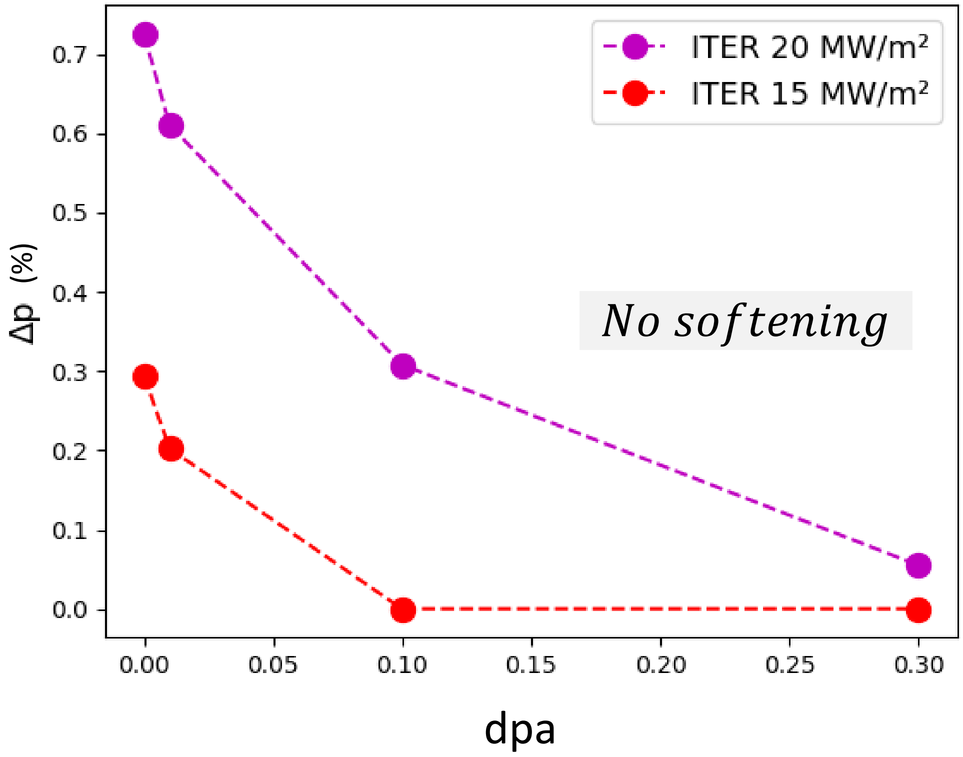
[1] A. Durif et al, FED, 2019

Influence of dpa on Δp (plastic strain increment per cycle)



- Δp decreases with dpa
- As Δp~ 0 at 0.3 dpa , damage process could be not governed by plasticity

Influence of incident heat flux intensity on Δp



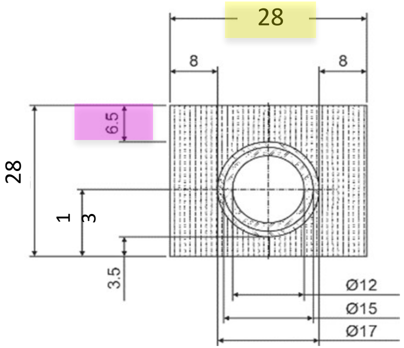
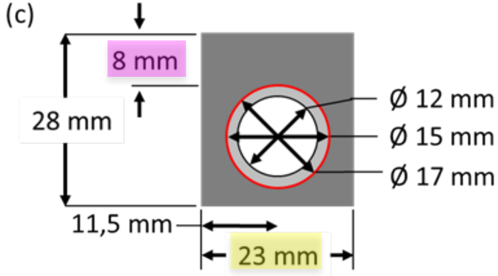
- As expected, if heat flux ↘ then Δp ↘

↳

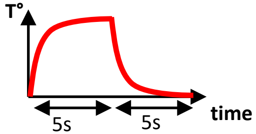
- At 15 MW/m^2 :

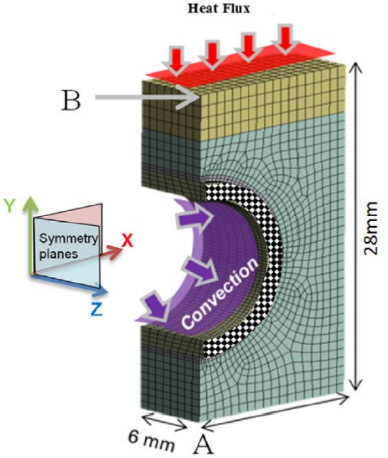
As Δp~ 0 at 0.1 dpa, damage process could be not governed by plasticity

ITER / DEMO divertor target geometries and boundary conditions

	Geometry	Convection param.	ΔYs (dpa)	Boundary conditions
ITER		120°C, 3.3 MPa, 12 m/s	100 MPa (0.01 dpa) 400 Mpa (0.1 dpa) 733 Mpa (0.3 dpa)	**Intensity: 15 & 20 MW/m^2**
DEMO		130°C, 4MPa, 16m/s		

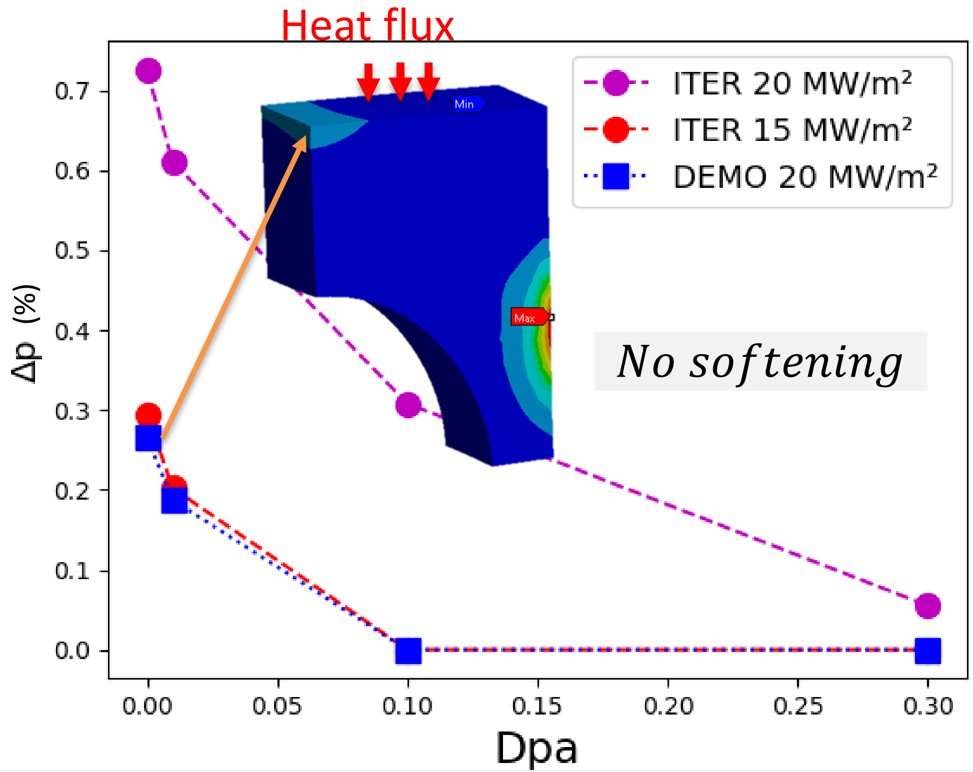
Thermal cycle





[1] A. Durif et al, FED, 2019

Influence of geometry on Δp



- Geometry changes lead to ↘ Δp

→ Δp (DEMO@20MW/m²) ≈ Δp (ITER@15MW/m²)

- For another geometry, Δp Max is obtained on the side face of the monoblock

→ relative damage process have to be investigated (experimentally or numerically)