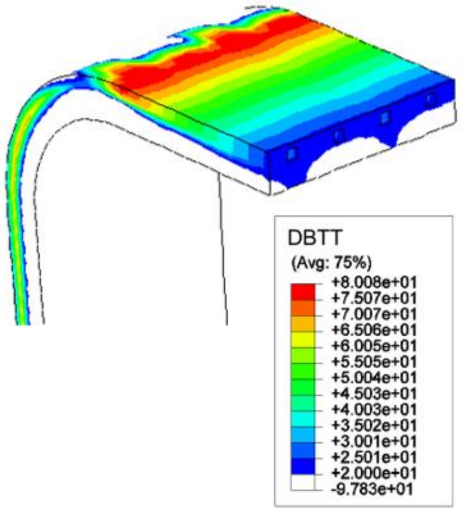
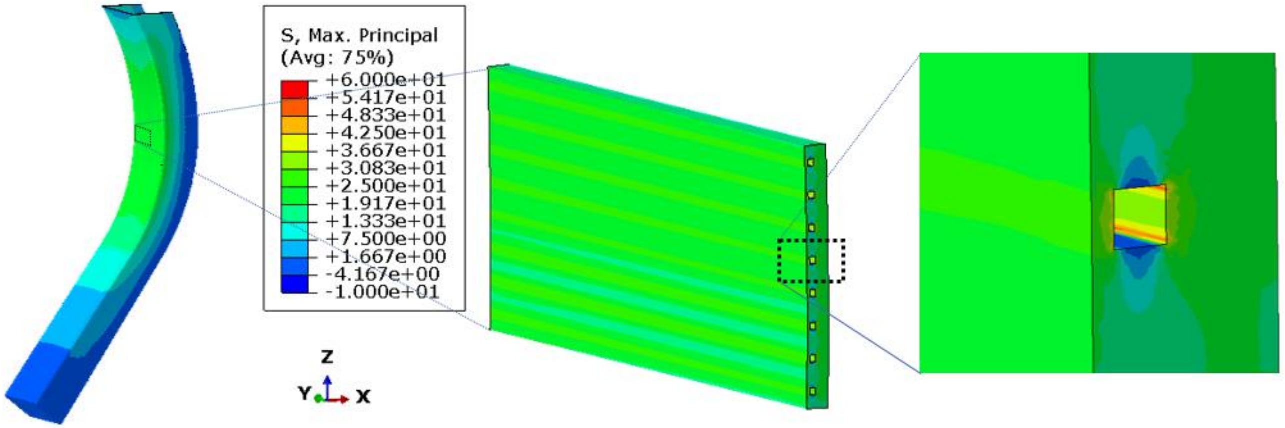
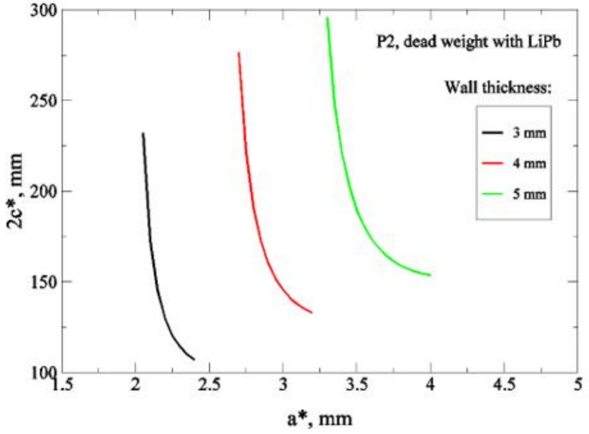
Embrittlement of WCLL Blanket and Its Fracture Mechanical Assessment

Jarir Aktaa, Ermile Gaganidze, Gaetano Bongioví, Pietro Arena, Gandolfo Alessandro Spagnuolo, Giacomo Aiello,
Pierluigi Chiovaro, Christian Bachmann

ISFNT-15, Las Palmas de Gran Canaria, Spain, 10-15 September 2023

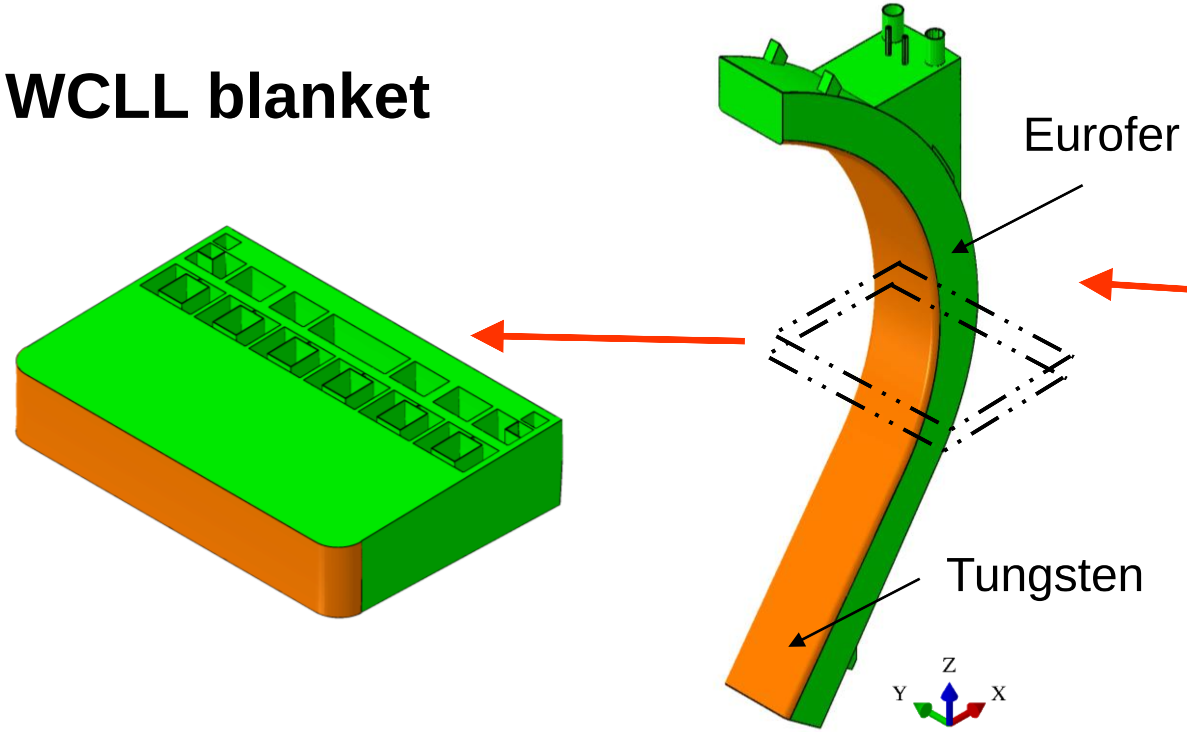


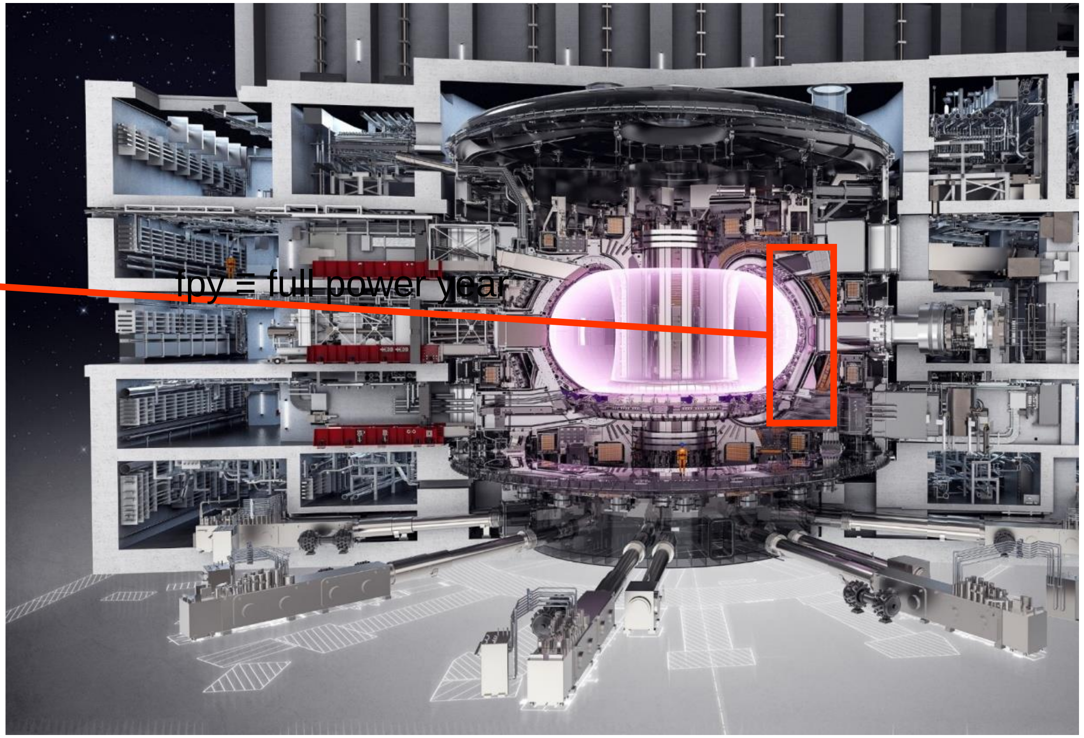




DEMO blanket – extreme loads on structural material

WCLL blanket





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Loads:

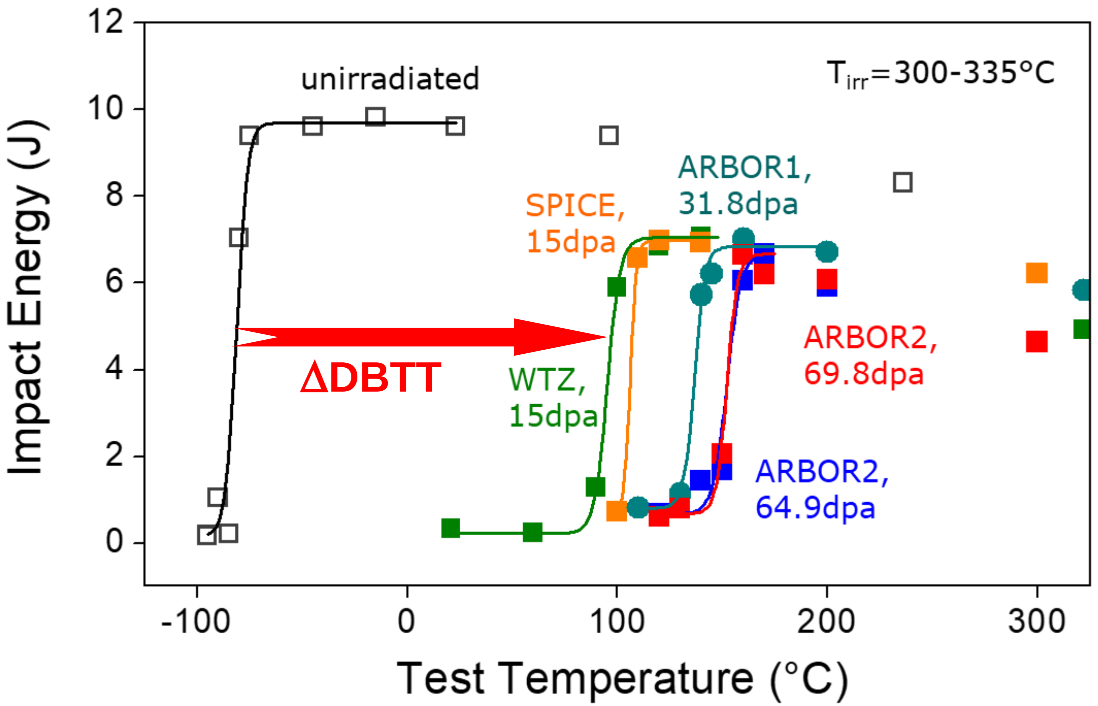
≤ 1.5 MW/m^2
≤ 15 dpa/fpy
≤ 150 appm He/fpy

→ High thermo-mechanical and neutron irradiation loads

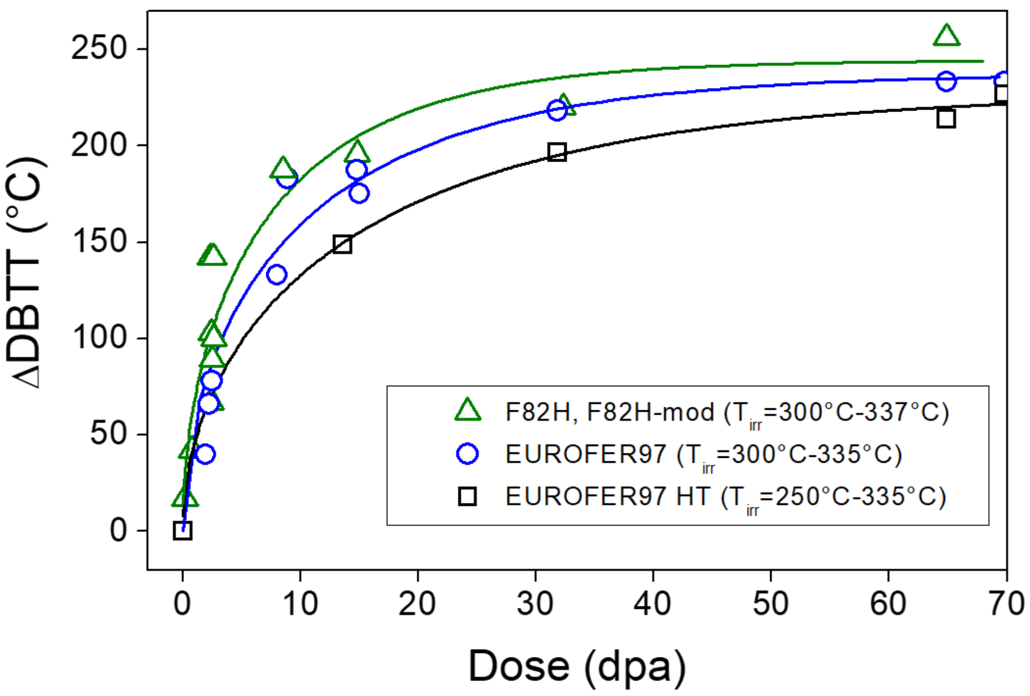
fpy ≡ full power year

Irradiation embrittlement of EUROFER

Due to dpa induced defects



- Shift of ductile-to-brittle transition temperature (**ΔDBTT**)
- Reduction of upper shelf toughness

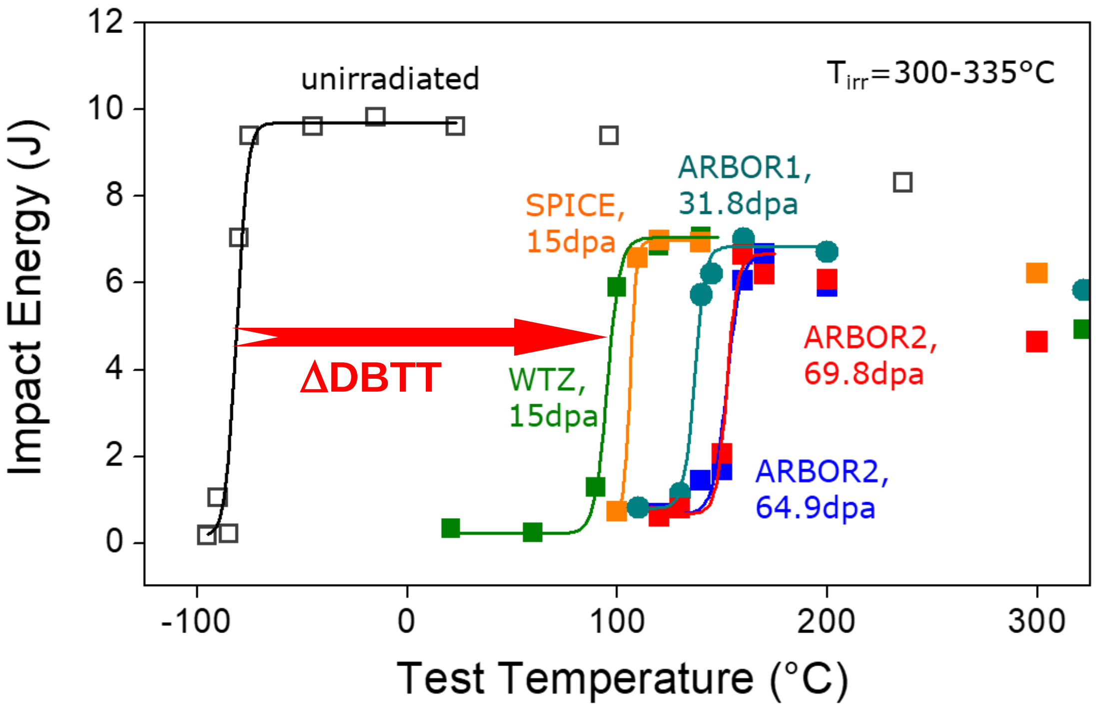


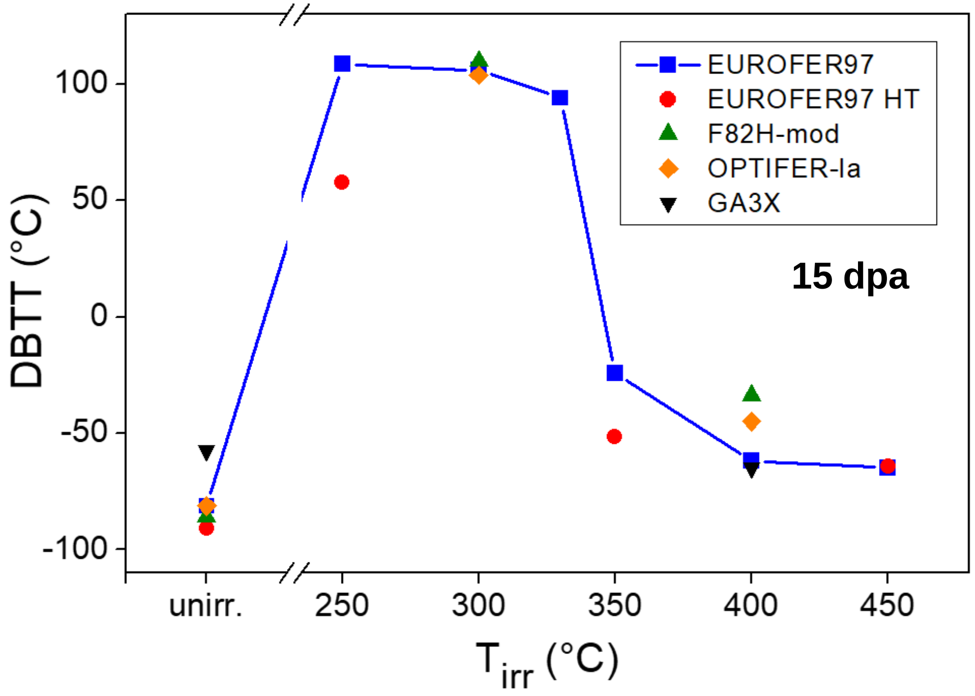
- Steep increase of ΔDBTT at low doses
- Saturation of ΔDBTT towards high doses

E. Gaganidze & J. Aktaa, *Fusion Eng. Des.* , 2013

Irradiation embrittlement of EUROFER

Due to dpa induced defects





- Shift of ductile-to-brittle transition temperature (**ΔDBTT**)
- Reduction of upper shelf toughness

- T_{irr} ≤ 330°C: strong embrittlement
- T_{irr} ≥ 350°C: minor embrittlement

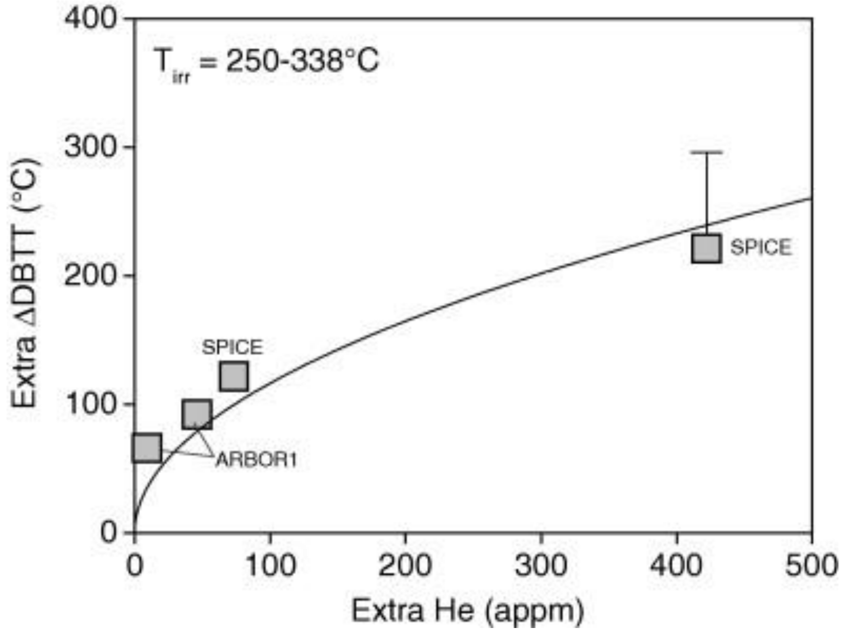
lower application temperature:
T = 350°C

E. Gaganidze & J. Aktaa, *Fusion Eng. Des.* , 2013

Irradiation embrittlement of EUROFER

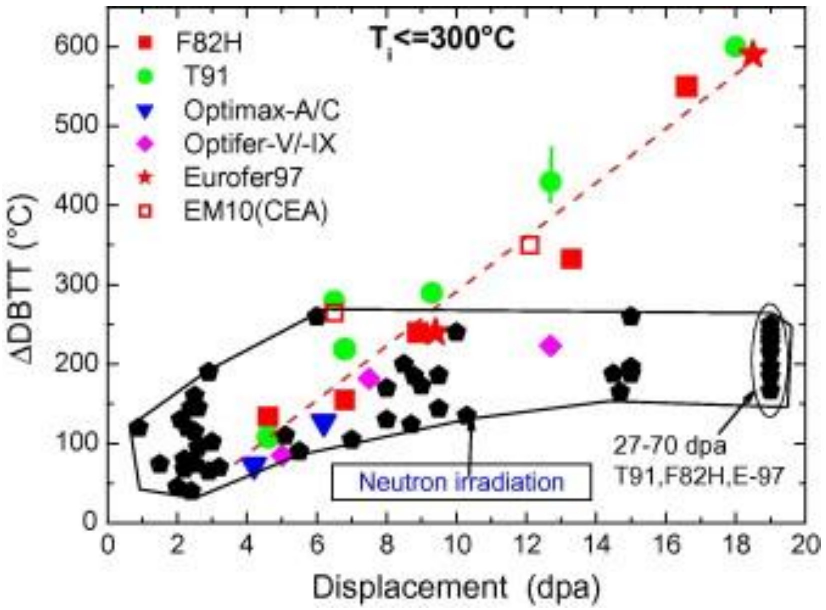
Due to transmuted He clusters/bubbles

- Boron doping experiments



E. Gaganidze et al., *J. Nucl. Mater.* , 2009

- Spallation target experiments



Y. Dai et al., *J. Nucl. Mater.* , 2011

- ➢ Overestimate the extra ΔDBTT due to boron segregations at grain boundaries
- ➢ Comparable extra ΔDBTT at much higher appm He → less conservative than boron doping experiments

E. Gaganidze & J. Aktaa, *Fusion Eng. Des.* , 2013

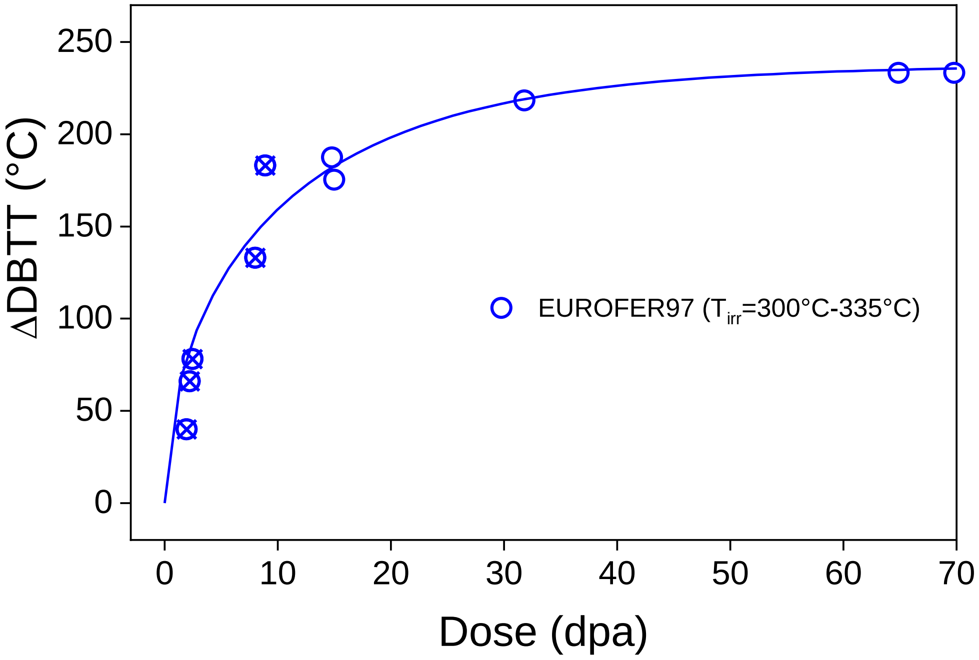
Embrittlement of EUROFER structures

Determination of ΔDBTT at location x and operation duration t_{op}

$$\Delta\mathrm{DBTT}(x) = \Delta\mathrm{DBTT}_{dpa}(x) + \Delta\mathrm{DBTT}_{He}(x)$$

$\Delta\mathrm{DBTT}_{dpa}$:

$$\Delta\mathrm{DBTT}_{dpa}(x) = \Delta\mathrm{DBTT}_{dpa,s}\left(1 - \exp\left(-\frac{\phi(x)}{\phi_0}\right)\right)^{1/2}$$



J. Aktaa et al,, *Nucl. Fusion* , 2023

Embrittlement of EUROFER structures

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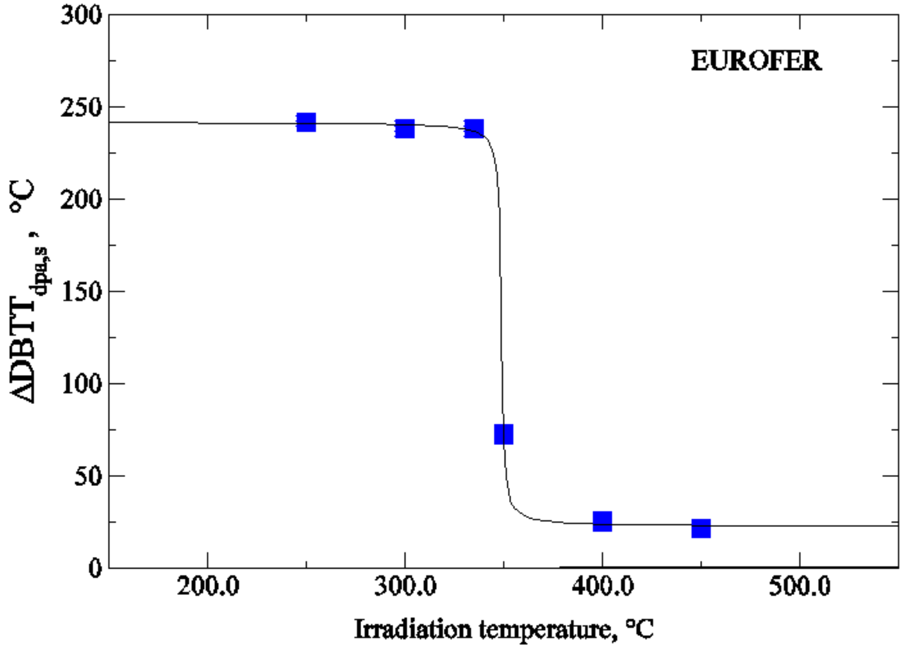
$$\Delta\mathrm{DBTT}_{dpa,s} = 132 - \frac{219.3}{\pi}\arctan(T - 348.85)$$

($\Delta\mathrm{DBTT}_{dpa,s}$ and T in °C)



J. Aktaa et al,, *Nucl. Fusion* , 2023

Embrittlement of EUROFER structures

Determination of ΔDBTT at location x and operation duration t_{op}

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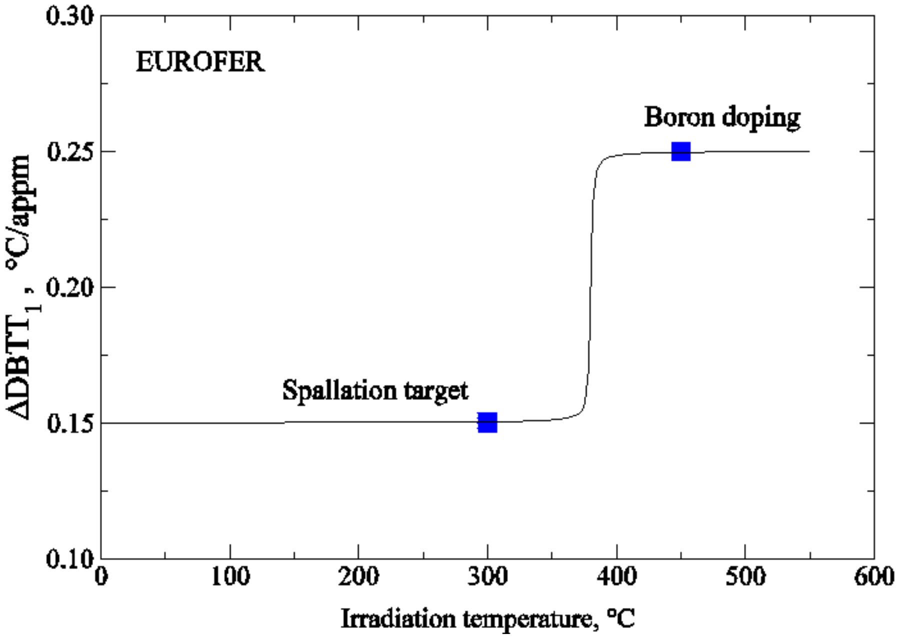

$\Delta\mathrm{DBTT}_{He}$:

$$\Delta\mathrm{DBTT}_{He}(x) = \Delta\mathrm{DBTT}_1\big(T(x)\big)\,\dot{G}_{He}(x)\,t_{op}$$

$$\Delta\mathrm{DBTT}_1 = 0.2 - \frac{0.1}{\pi}\arctan(380 - T)$$

($\Delta\mathrm{DBTT}_1$ in °C /appm He and T in °C)

J. Aktaa et al,, *Nucl. Fusion* , 2023

Embrittlement of EUROFER structures

Determination of ΔDBTT at location x and operation duration t_{op}

$$\Delta\mathrm{DBTT}(x) = \Delta\mathrm{DBTT}_{dpa}(x) + \Delta\mathrm{DBTT}_{He}(x)$$

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($\Delta\mathrm{DBTT}_{dpa,s}$ and T in °C)

$\Delta\mathrm{DBTT}_{He}$:

$$\Delta\mathrm{DBTT}_{He}(x) = \Delta\mathrm{DBTT}_1\big(T(x)\big)\,\dot{G}_{He}(x)\,t_{op}$$

$$\Delta\mathrm{DBTT}_1 = 0.2 - \frac{0.1}{\pi}\arctan(380 - T)$$

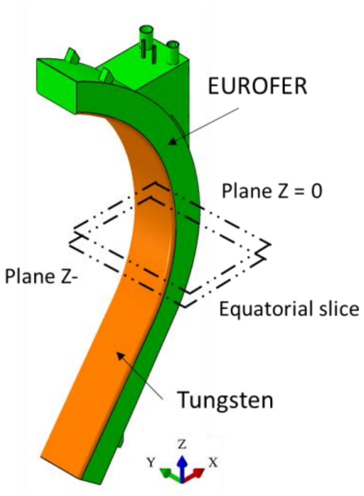
($\Delta\mathrm{DBTT}_1$ in °C /appm He and T in °C)

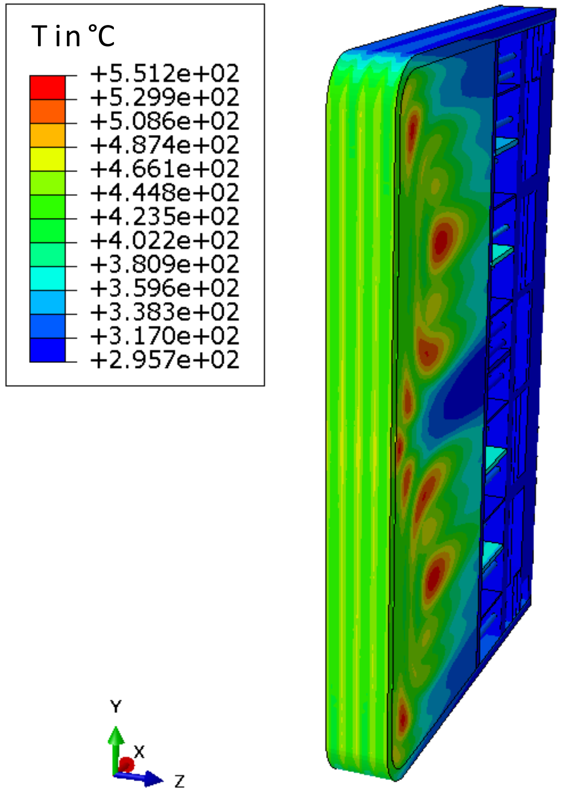
requires temperature $T(x)$**,** irradiation dose (dpa) rate $\dot{\phi}\,(x)$, helium generation rate $\dot{G}_{He}(x)$.

J. Aktaa et al,, *Nucl. Fusion* , 2023

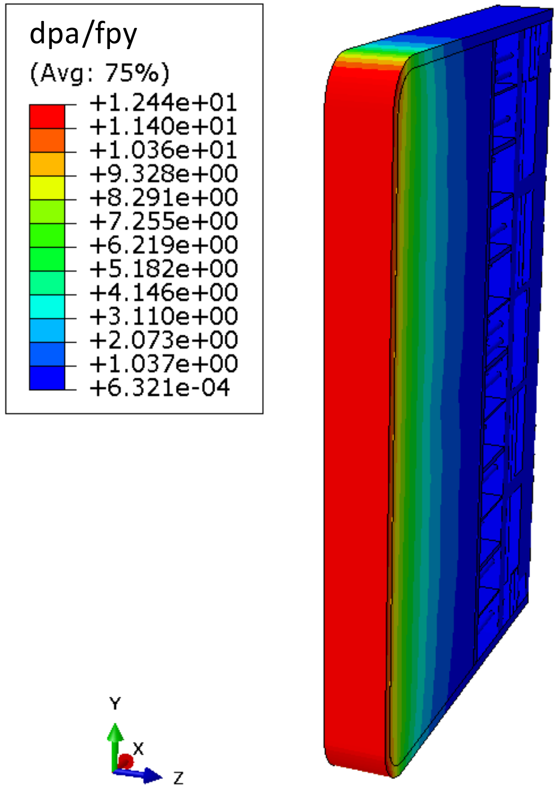
Embrittlement of WCLL blanket

Required input

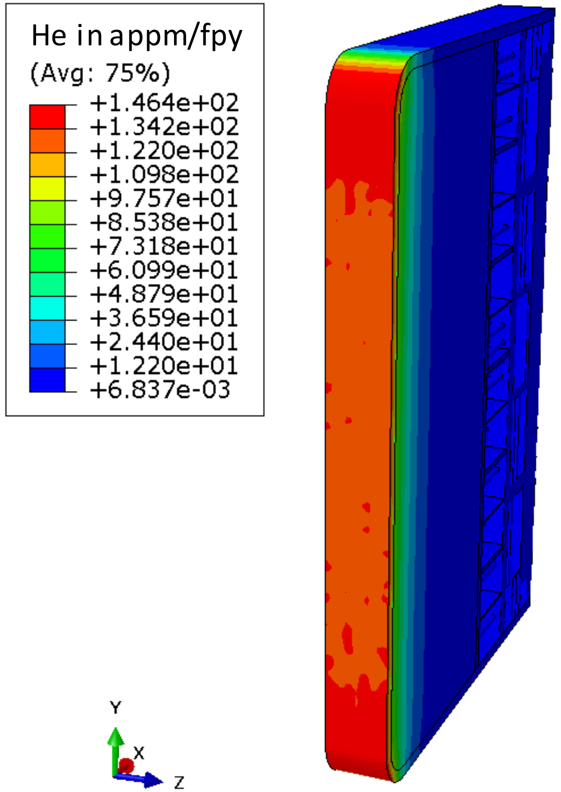




temperature $T(x)$



dpa rate $\dot{\phi}\ (x)$



helium generation rate $\dot{G}_{He}(x)$

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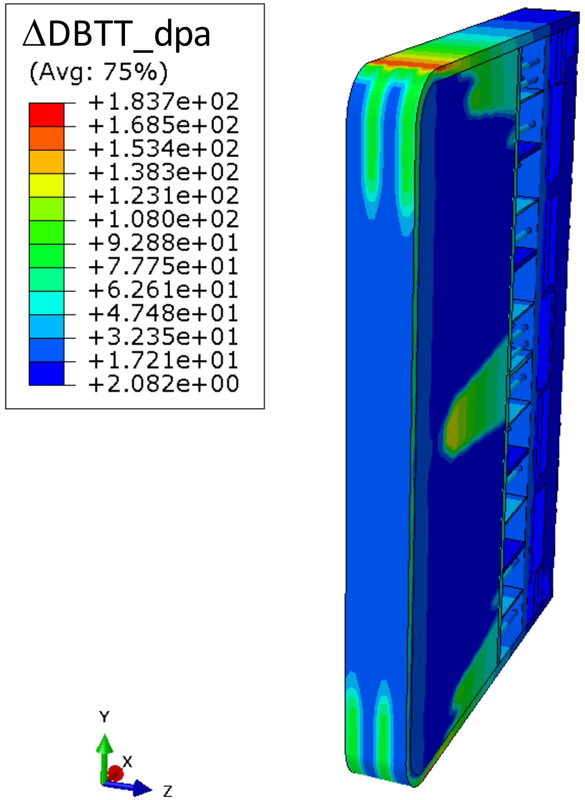
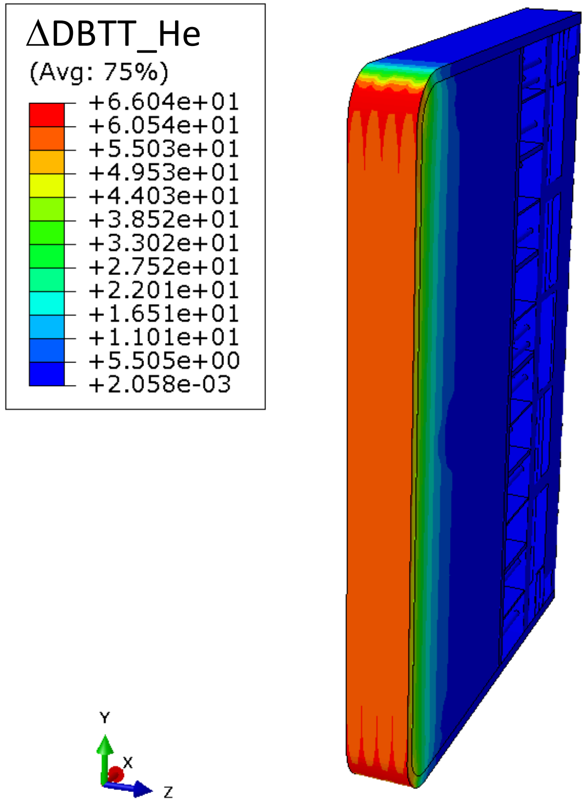
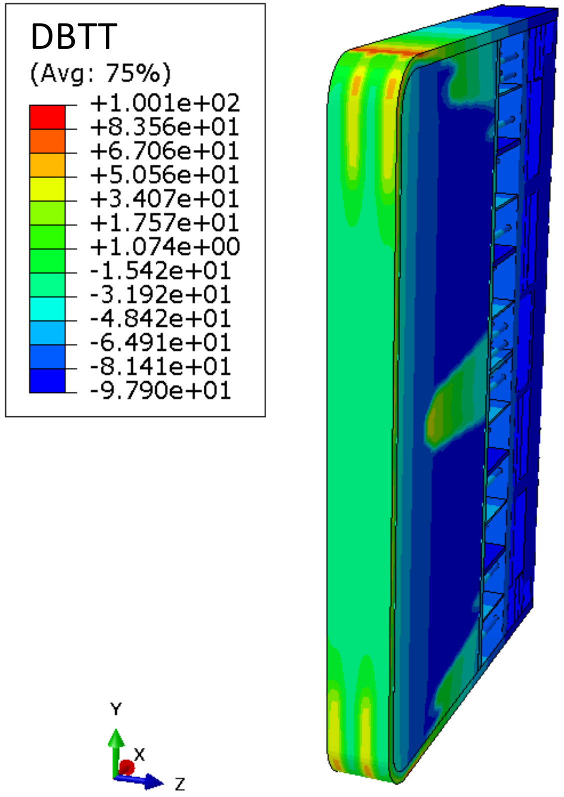
Embrittlement of WCLL blanket

DBTT after 2 fpy operation







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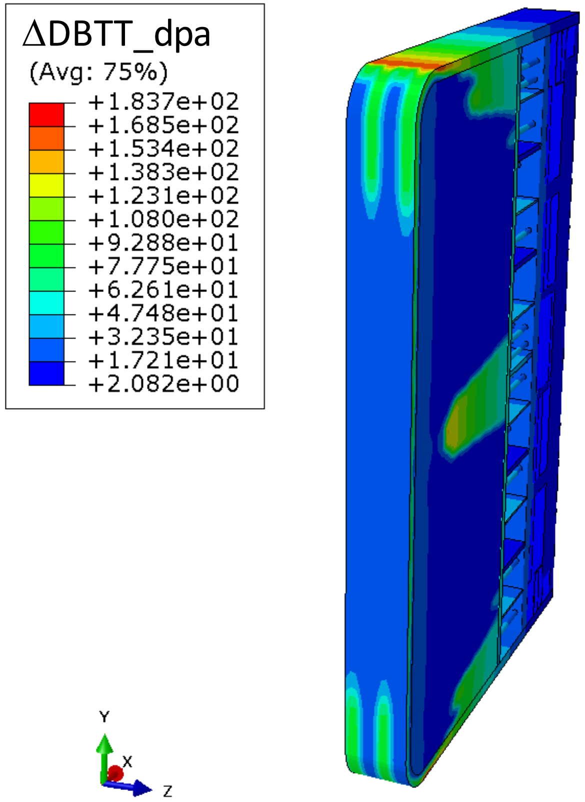
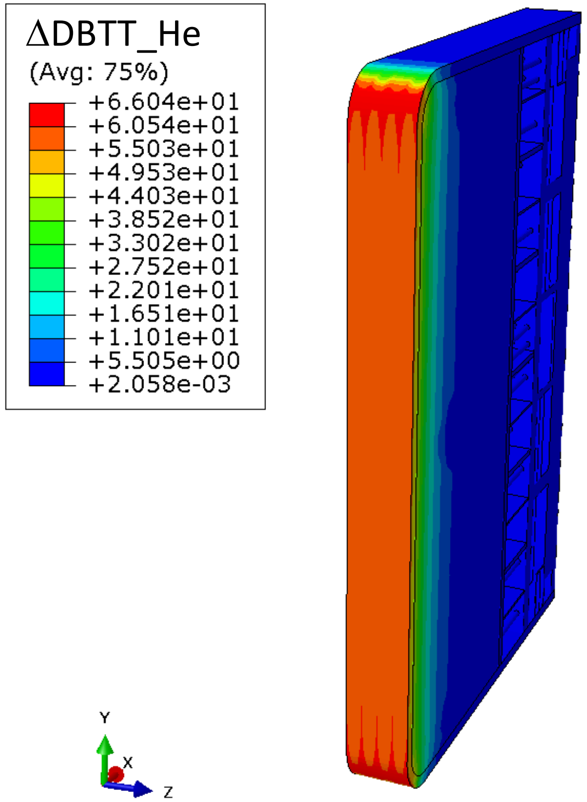
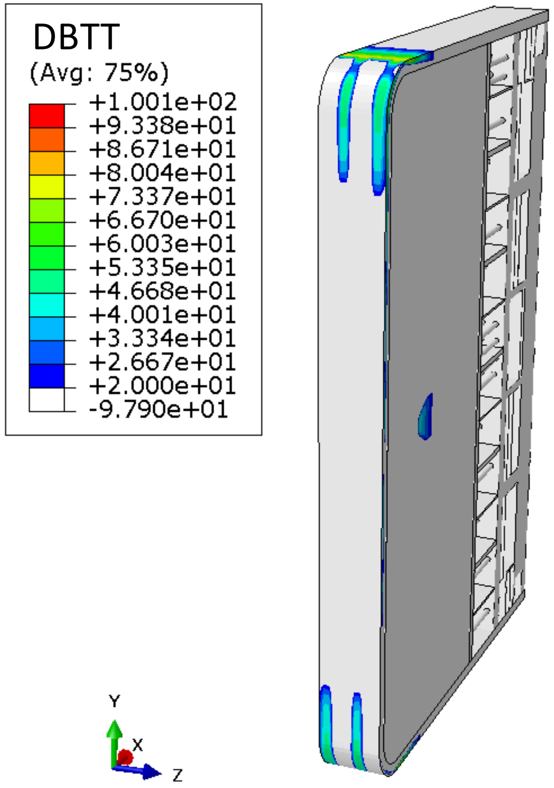
Embrittlement of WCLL blanket

DBTT after 2 fpy operation





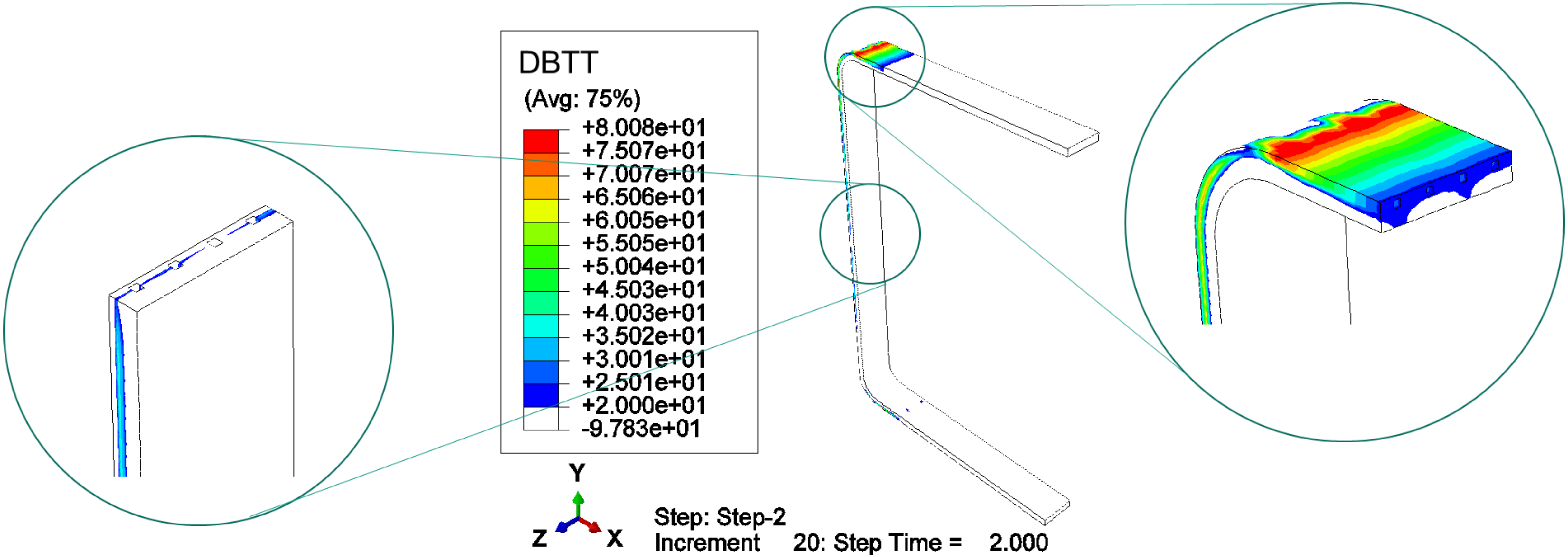


→ Even far below operation temperature **DBTT** is **above RT** at many positions after 2 fpy operation

J. Aktaa et al,, *Nucl. Fusion* , 2023

Embrittlement of WCLL blanket

Critically embrittled zones in FW after 2 fpy (DBTT > RT)



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Non-ductile fracture assessment of WCLL blanket FW

Questions on the risk of brittle/non-ductile fracture of WCLL blanket FW when cooling down to temperatures below the shifted DBTT during shutdown / ramp up and/or maintenance due to

- coolant pressure / re-pressurization of the component
- dead weight and seismic loads when lifting the breeding blanket segment out of the vacuum vessel

To answer these questions a fracture mechanical assessment approach already established in nuclear design codes (KTA, ASME) for embrittled ferritic steel components has been adopted.

Non-ductile fracture assessment of WCLL blanket FW

Fracture mechanical approach (KTA, ASME)

Starting from stress analysis results a surface flaw with the shape of a crack perpendicular to maximum principle stress is postulated. For this flaw the stress intensity factor K_I (t, T) at each instant is determined and evaluated on the base of the reference fracture toughness K_{IR} (T) which is a lower bound of static, dynamic, and crack arrest critical K_I measured as a function of temperature.

For ferritic steels with minimum yield strength of 345 MPa the K_{IR} Values are approximated by the analytical formula:

$$K_{IR} = 29.41 + 1.34 \exp[0.026\,(T - RT_{NDT} + 88.9)]$$

With K_{IR} in $MPa\sqrt{m}$, T in K, and RT_{NDT} as the reference nil ductility temperature determined considering data from Charpy impact and Pellini drop weight testing.

Non-ductile fracture assessment of WCLL blanket FW

Fracture mechanical approach (KTA, ASME)

$\mathrm{RT_{NDT}}$ is the Reference Nil Ductility Temperature determined considering data from Charpy impact and Pellini drop weight testing as

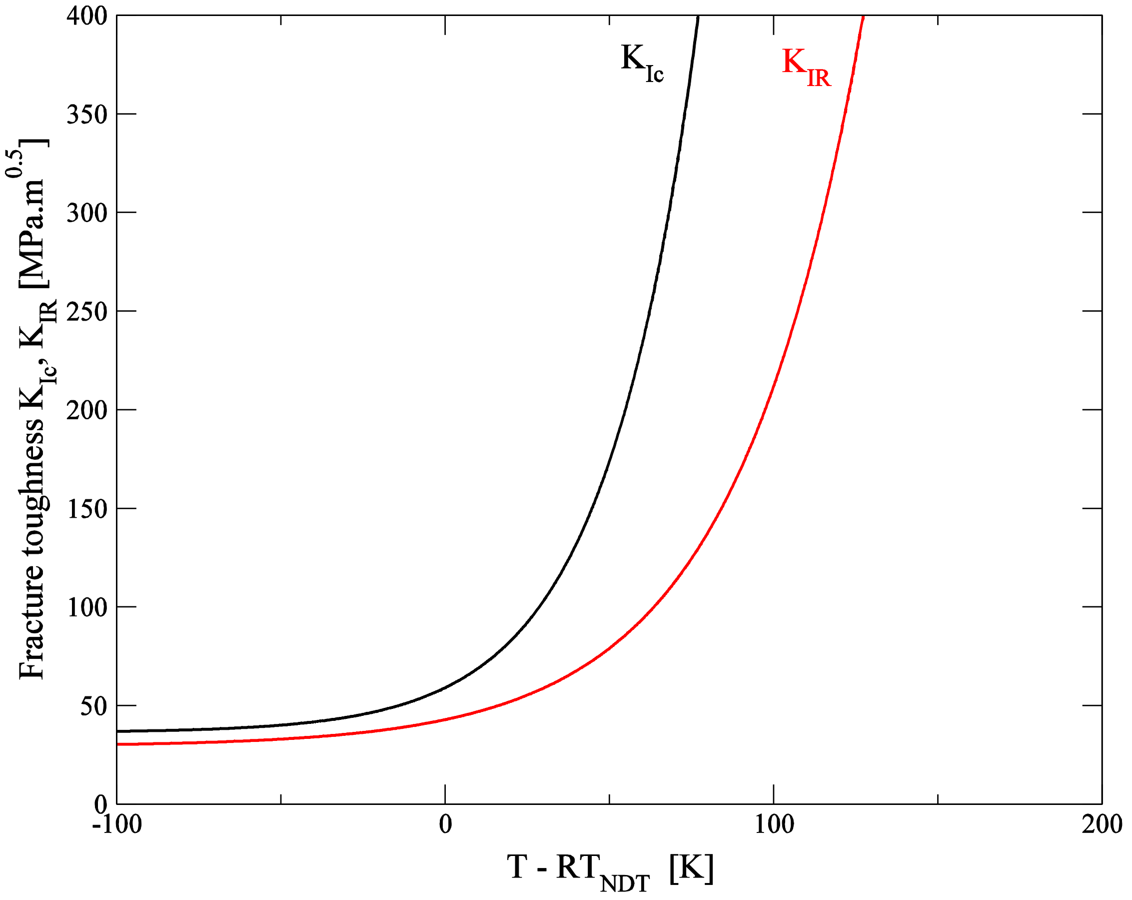
$$\mathrm{RT_{NDT}} = \max\left\{\mathrm{T_{NDT}},\ \mathrm{T_{AV}}(68\,\mathrm{J}) - 33\,\mathrm{K},\ \mathrm{T_{AV}}(0.9\,\mathrm{mm}) - 33\,\mathrm{K}\right\}$$

with

$\mathrm{T_{NDT}}$	Nil Ductility Transition (NDT) temperature which is the highest temperature at which a specimen breaks in drop weight experiment after Pellini,
$\mathrm{T_{AV}}(68\,\mathrm{J})$	temperature at which a Charpy impact energy of at least 68 J on an ISO-V-specimen is measured,
$\mathrm{T_{AV}}(0.9\,\mathrm{mm})$	temperature at which a lateral deformation of at least 0.9 mm on an ISO-V-specimen is observed.

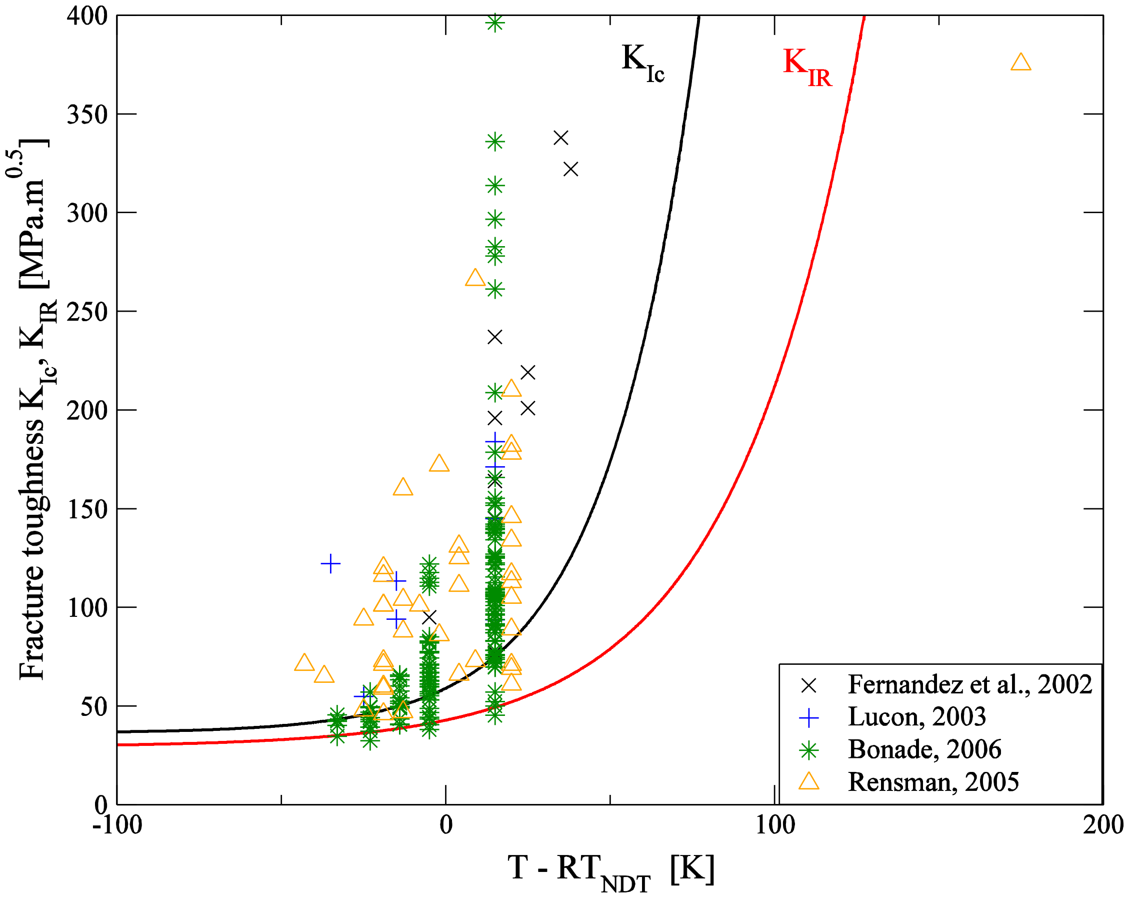
Non-ductile fracture assessment of WCLL blanket FW

Fracture mechanical approach (KTA, ASME)



Non-ductile fracture assessment of WCLL blanket FW

Fracture mechanical approach (KTA, ASME)



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Non-ductile fracture assessment of WCLL blanket FW

Fracture mechanical approach (ASME, KTA)

Embrittlement, e.g. induced by irradiation, is considered by proper increase of the reference nil ductility temperature:

$$K_{IR} = 29.41 + 1.34 \exp\left[0.026\left(T - RT_{NDT} - \Delta T_{41} + 88.9\right)\right]$$

ΔT_{41} $\equiv$ Temperature shift of the Charpy impact energy of 41 J due to irradiation

ΔT_{41} $=$ $\Delta DBTT$ (assumption to be verified by fracture toughness data of irradiated EUROFER!)

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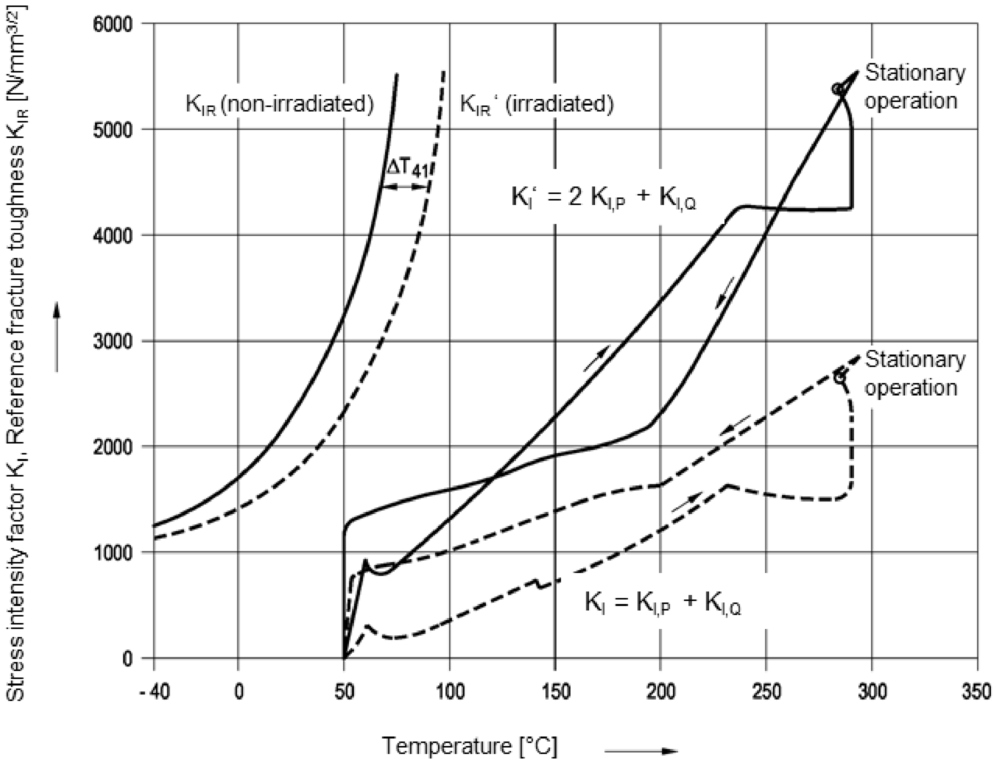
Non-ductile fracture assessment of WCLL blanket FW

Fracture mechanical approach (ASME, KTA)

The assessment is performed by

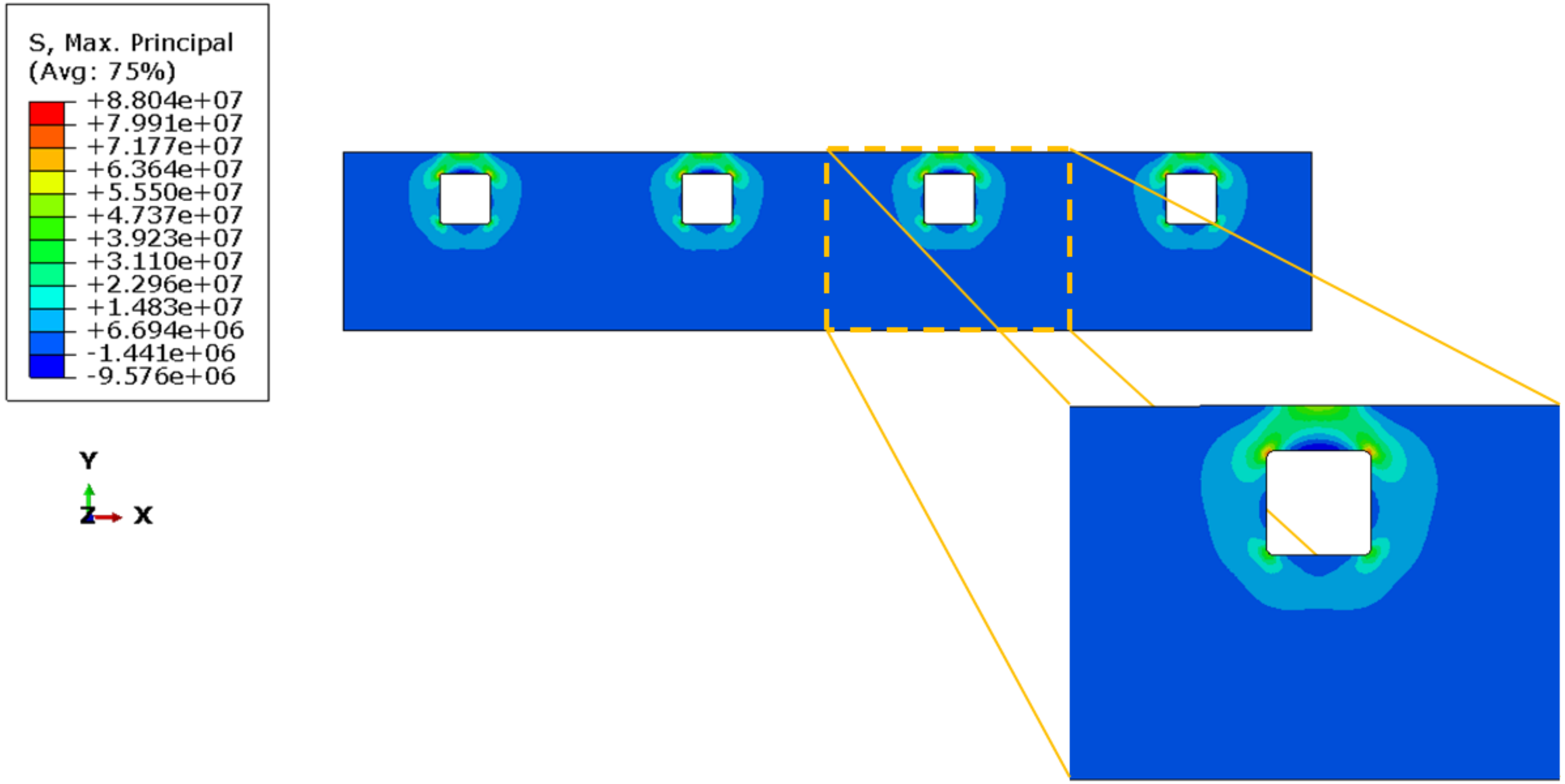
- calculating for the postulated surface crack (for loading levels A and B: 0.25 of the wall thickness in depth and 1.5 of the wall thickness in length) $K_{I,P}$ and $K_{I,Q}$, the stress intensity factors resulting from primary and secondary stresses, respectively,
- applying a safety factor of 2 on $K_{I,P}$
- and ensuring that the sum $2K_{I,P} + K_{I,Q}$ is always below K_{IR} particularly during start-up and shut-down



Non-ductile fracture assessment of WCLL blanket FW

Re-pressurization of breeding blanket – stresses (in Pa)

- FE simulation using ABAQUS
- 2D FE model with generalized plane strain elements
- Load: 155 bar coolant pressure
- Temperature: RT



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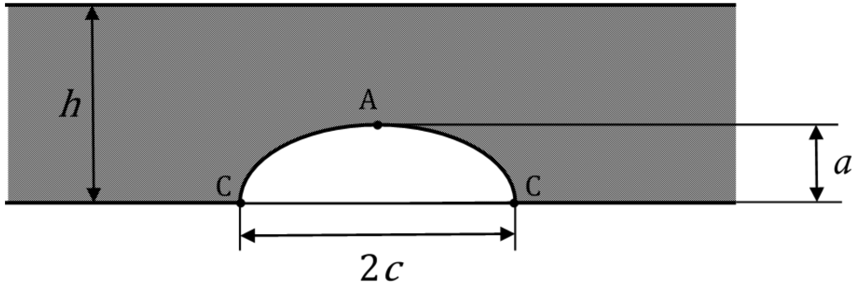
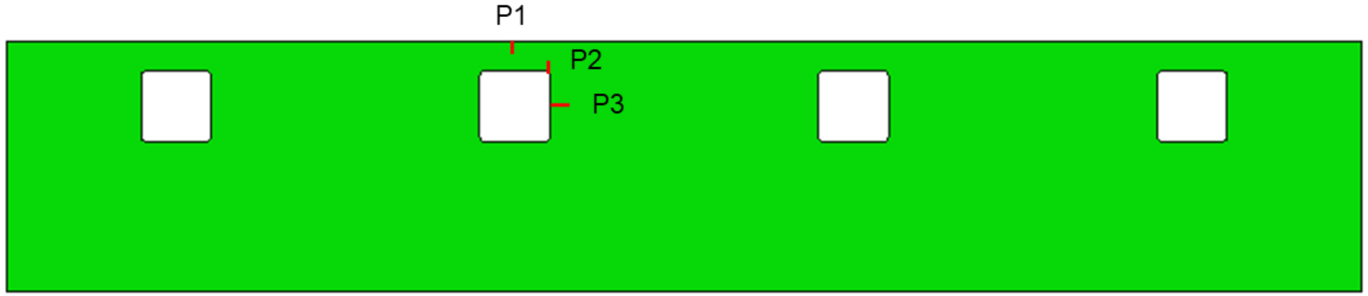
Non-ductile fracture assessment of WCLL blanket FW

Re-pressurization of breeding blanket – postulated cracks and results

Semi-elliptical surface crack at P1, P2 and P3 with crack plane perpendicular to FE model plane



$a = 0.25\ h,\ 2c = 1.5\ h$



Position	$K_I^{\ A}$ $[\mathrm{MPa}\sqrt{m}]$	$K_I^{\ C}$ $[\mathrm{MPa}\sqrt{m}]$	K_{IR} $[\mathrm{MPa}\sqrt{m}]$	Margin [%]
P1	2.196	1.652	33.617	765
P2	2.93	2.59	33.617	574
P3	1.227	1.012	33.617	1370

→ Coolant pressure is not sufficiently high to cause non-ductile failure of the FW after 2 fpy operation

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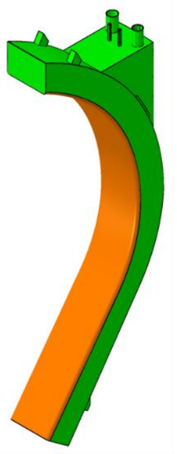
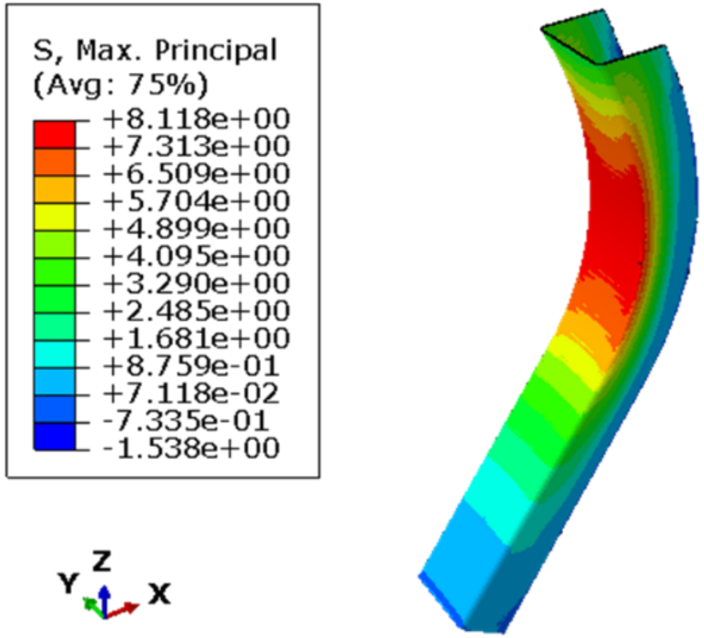
Non-ductile fracture assessment of WCLL blanket FW

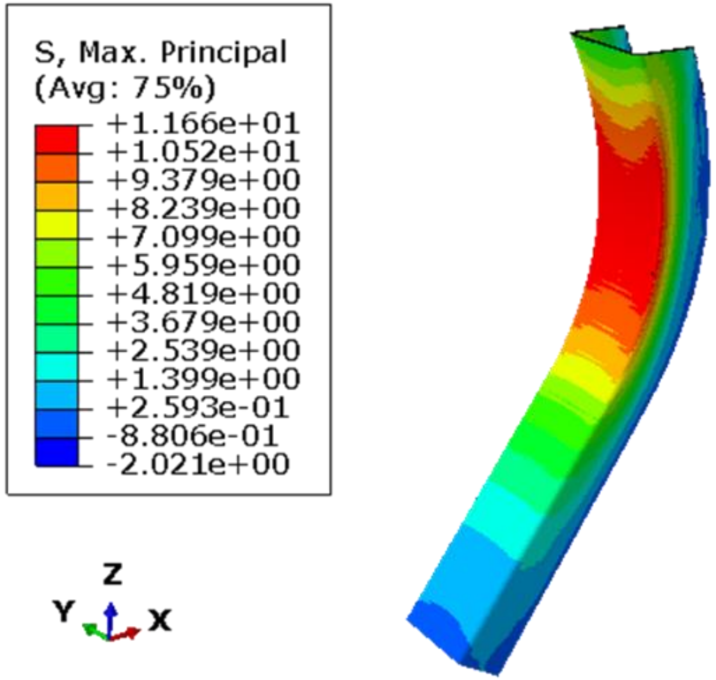
Lifting the WCLL blanket segment – stresses (in MPa)



3D FE model of BB segment with no detailed features, e.g. FW cooling channels



Dead weight (no LiPb)



Dead weight (no LiPb) + seismic acceleration

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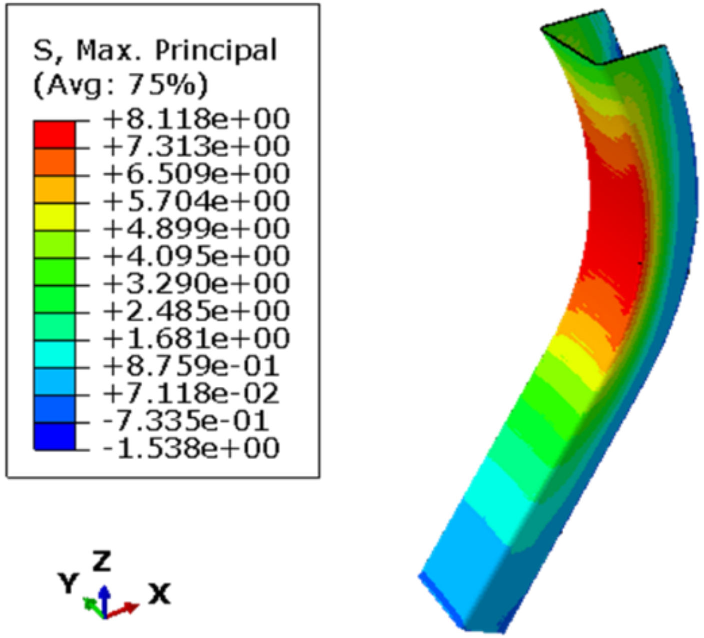
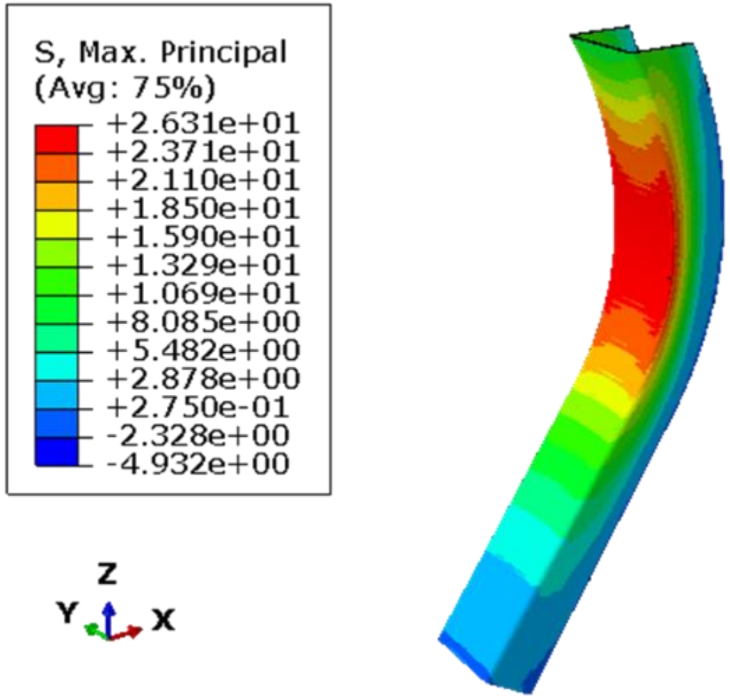
Non-ductile fracture assessment of WCLL blanket FW

Lifting the WCLL blanket segment – stresses (in MPa)

3D FE model of BB segment with no detailed features, e.g. FW cooling channels



Dead weight (no LiPb)



Dead weight (with LiPb)

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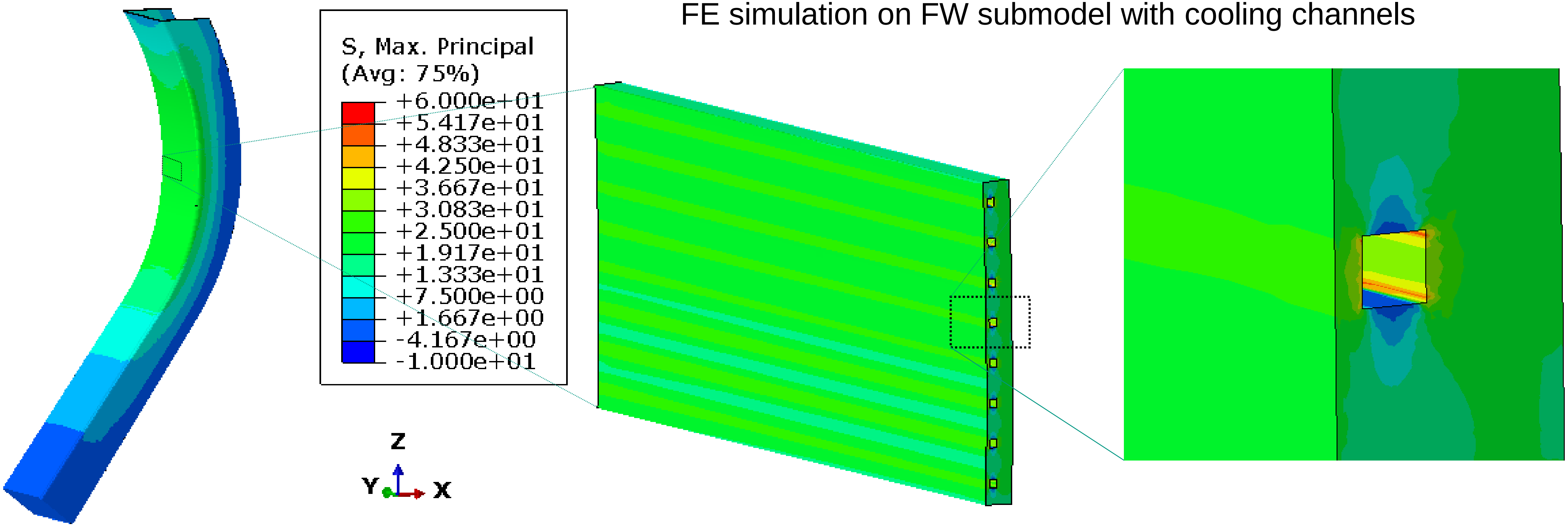
Non-ductile fracture assessment of WCLL blanket FW

Lifting the WCLL blanket segment – stresses (in MPa)

FE simulation on FW submodel with cooling channels



Dead weight (with LiPb)

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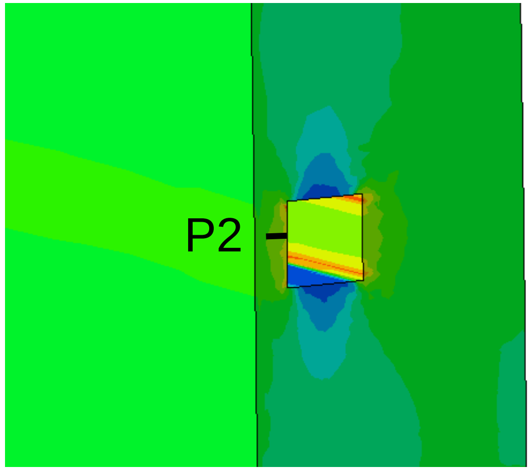
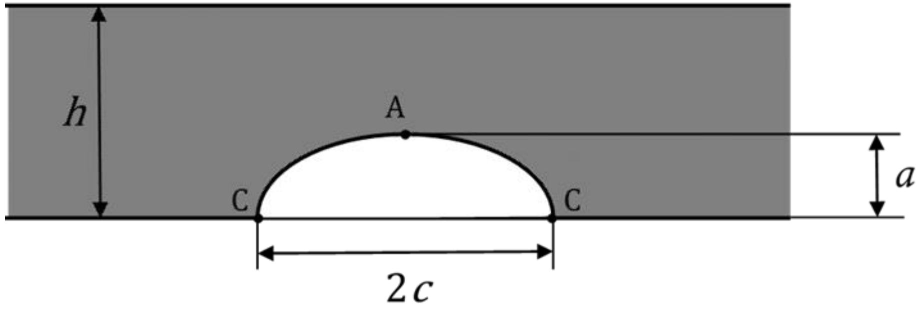
Non-ductile fracture assessment of WCLL blanket FW

Lifting the WCLL blanket segment – postulated crack and results





$$h = 3\ \text{mm} \Rightarrow\ a = 0.75\ \text{mm},\ 2c = 4.5\ \text{mm}$$

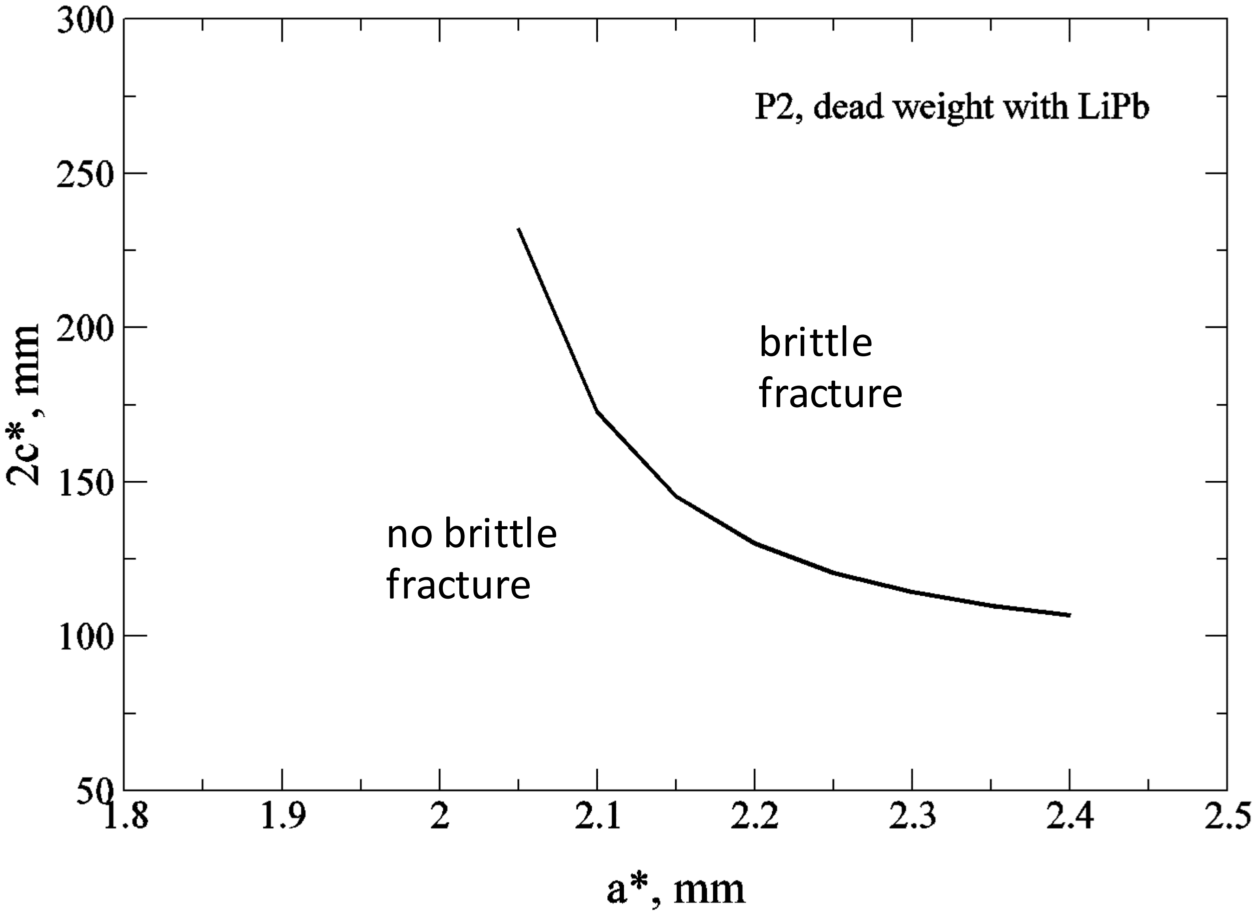
J. Aktaa et al,, *Nucl. Fusion* , 2023

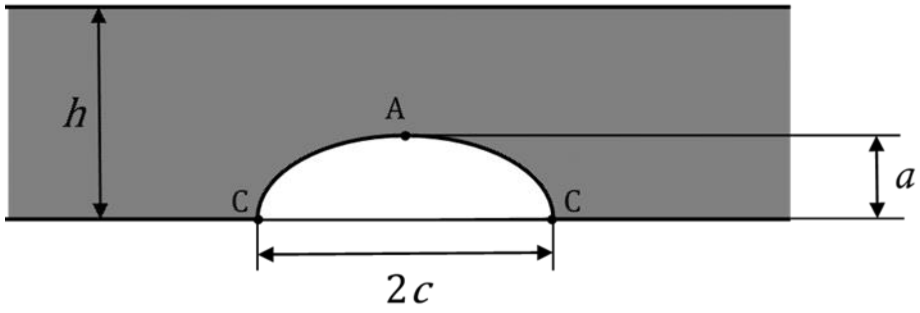
Load case	$K_I{}^A$ $[\mathrm{MPa}\sqrt{m}]$	$K_I{}^C$ $[\mathrm{MPa}\sqrt{m}]$	K_{IR} $[\mathrm{MPa}\sqrt{m}]$	Margin [%]
no LiPb	0.623	0.422	33.617	2699
no LiPb, seismic	0.885	0.620	33.617	1899
LiPb	1.910	1.338	33.617	880

→ Loads when lifting the BB are not sufficiently high to cause non-ductile failure of the FW after 2 fpy operation

Non-ductile fracture assessment of WCLL blanket FW

Lifting the WCLL blanket segment – critical crack sizes



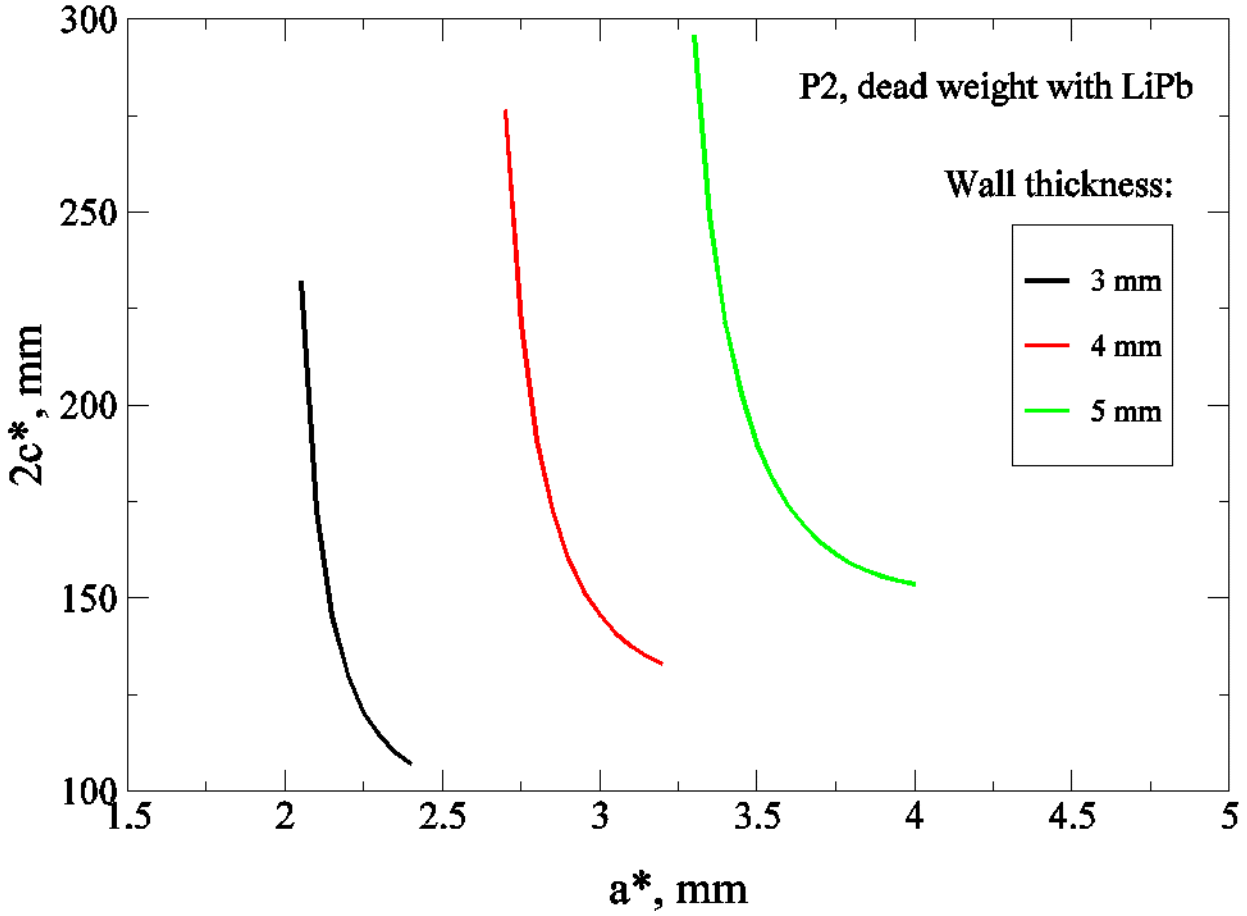


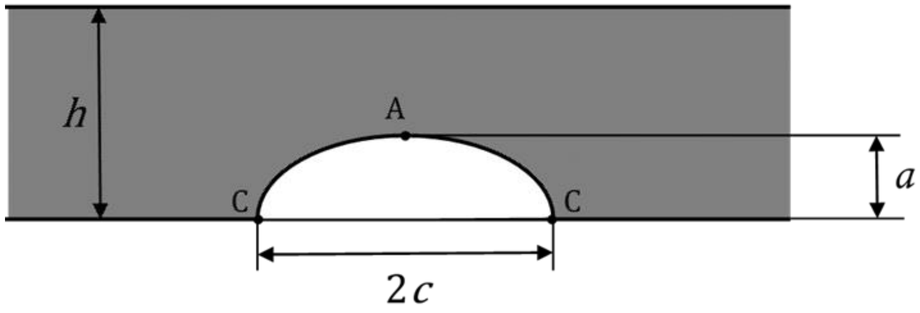
Assumption: No limit by other criteria!

J. Aktaa et al,, *Nucl. Fusion* , 2023

Non-ductile fracture assessment of WCLL blanket FW

Lifting the WCLL blanket segment – critical crack sizes





Assumption: No limit by other criteria!

J. Aktaa et al,, *Nucl. Fusion* , 2023

Summary

- A suitable, not overly conservative procedure to evaluate and quantify embrittlement of EUROFER structures was derived based on nowadays knowledge on the embrittlement behaviour of EUROFER under neutron irradiation considering dpa and transmuted helium effects.
- Embrittlement of WCLL BB was investigated quantifying the locally resolved DBTT shift and identifying the 3D spread of critically embrittled zones, in particular those with DBTT shifted to temperatures above room temperature.
- To assess the risk of brittle/non-ductile fracture of the critically embrittled zones a fracture mechanical approach established in existing nuclear design codes for embrittled ferritic structures was adapted to the embrittled EUROFER structures.
- According to the criteria of the approach adopted for non-ductile fracture assessment coolant pressure as well as the loads when lifting of the BB segment were not found high enough to cause fracture in the FW. The calculated comfortable margin to the criteria resulted in relatively high maximum tolerable crack sizes.
- The determined maximum tolerable crack sizes however need to be confirmed prior maintenance, e.g. by inspecting the FW before initial installation and assessing the extension of detected flaws during operation by a dedicated fatigue crack growth (FCG) analysis.

Acknowledgment

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Thanks for your attention!