Impact of the trapping model on Tritium retention and permeation in DEMO Tungsten/Eurofer First Wall

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Context: Tritium retention and breeding

Fusion reaction in tokamaks: $^{2}\mathrm{D} + {}^{3}\mathbf{T} \rightarrow {}^{4}\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV})$

It needs Tritium which is **Not abundant** on earth

⇒ Tritium needs to be **breeded on site**

Context: Tritium retention and breeding

Fusion reaction in tokamaks: $^{2}\mathrm{D} + {}^{3}\mathrm{T} \rightarrow {}^{4}\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV})$

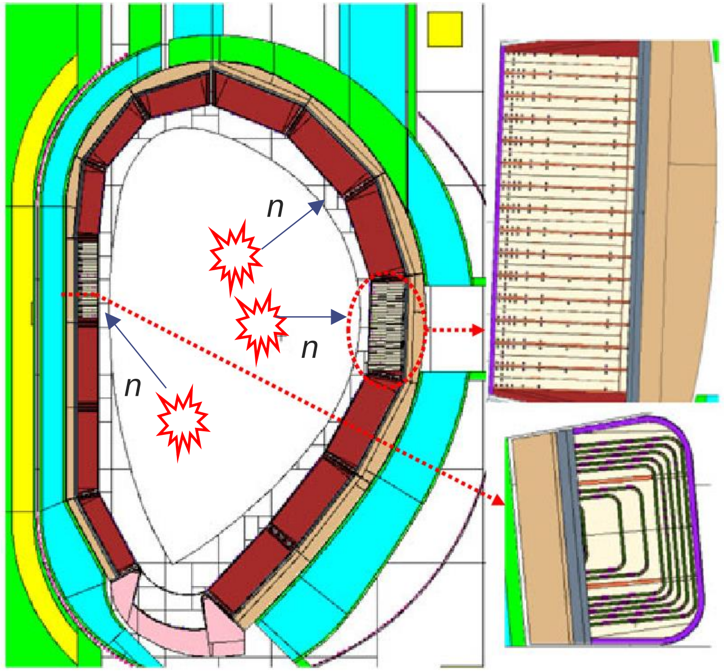
It needs Tritium which is **Not abundant** on earth

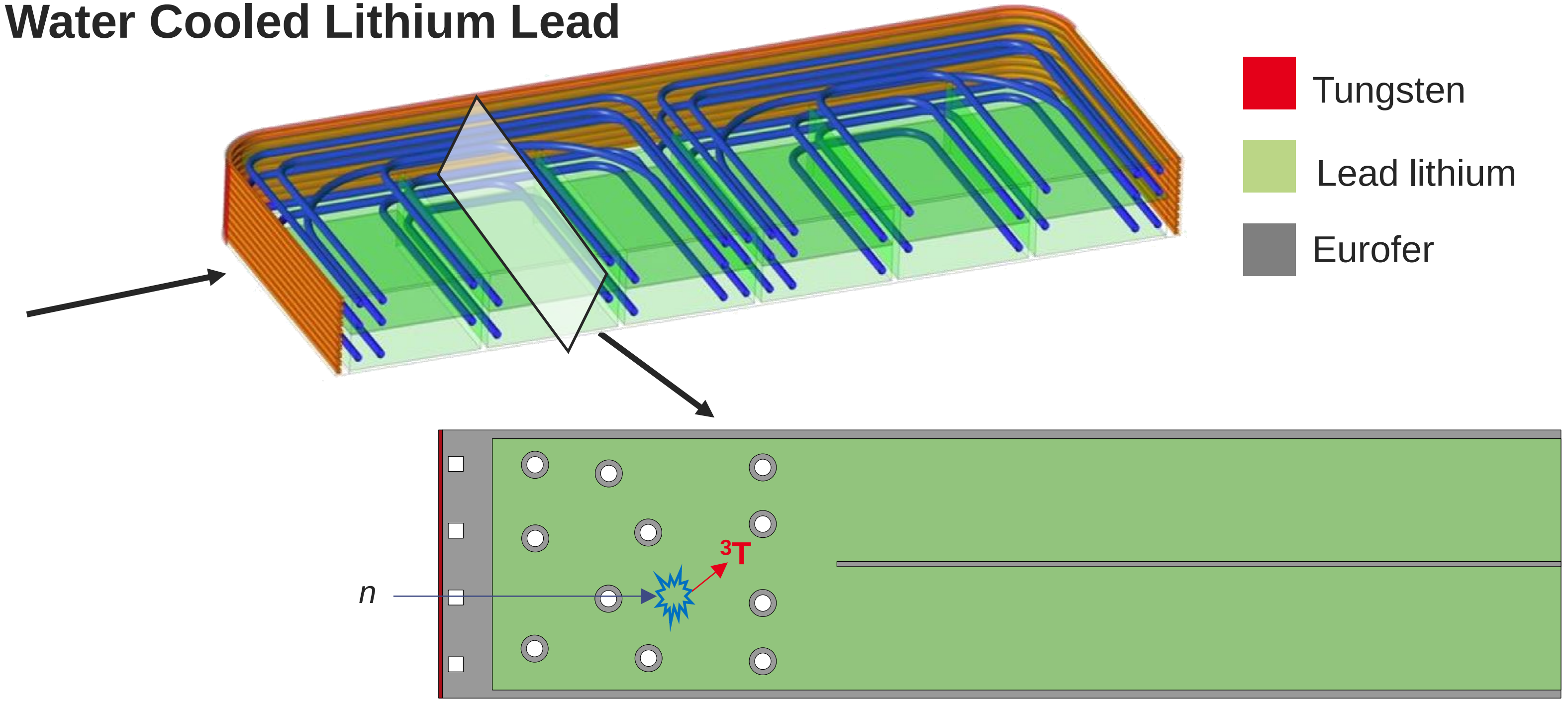
$\Rightarrow$ Tritium needs to be breeded on site **with lithium**

$$n + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{T} + \alpha + 4.8\ \mathrm{MeV}$$

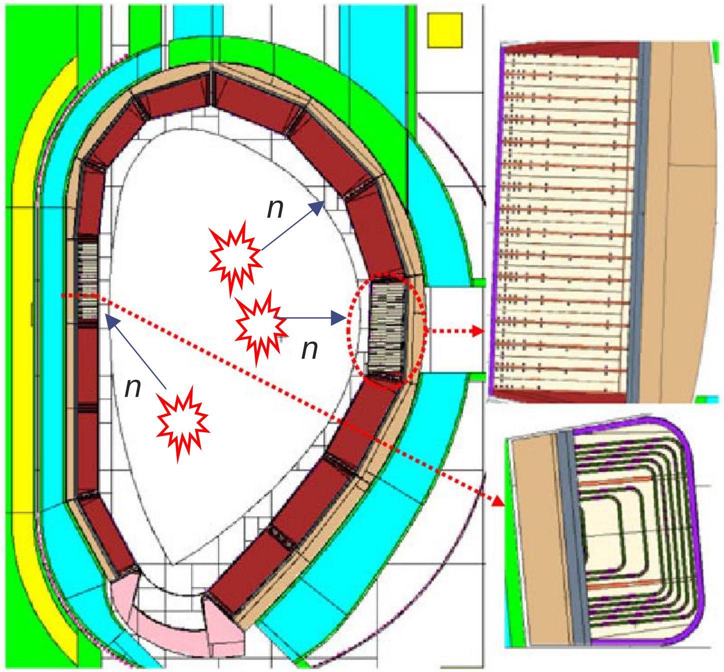
$$n + {}^{7}\mathrm{Li} \rightarrow {}^{3}\mathrm{T} + \alpha + n'$$

WCLL concept
Water Cooled Lithium Lead

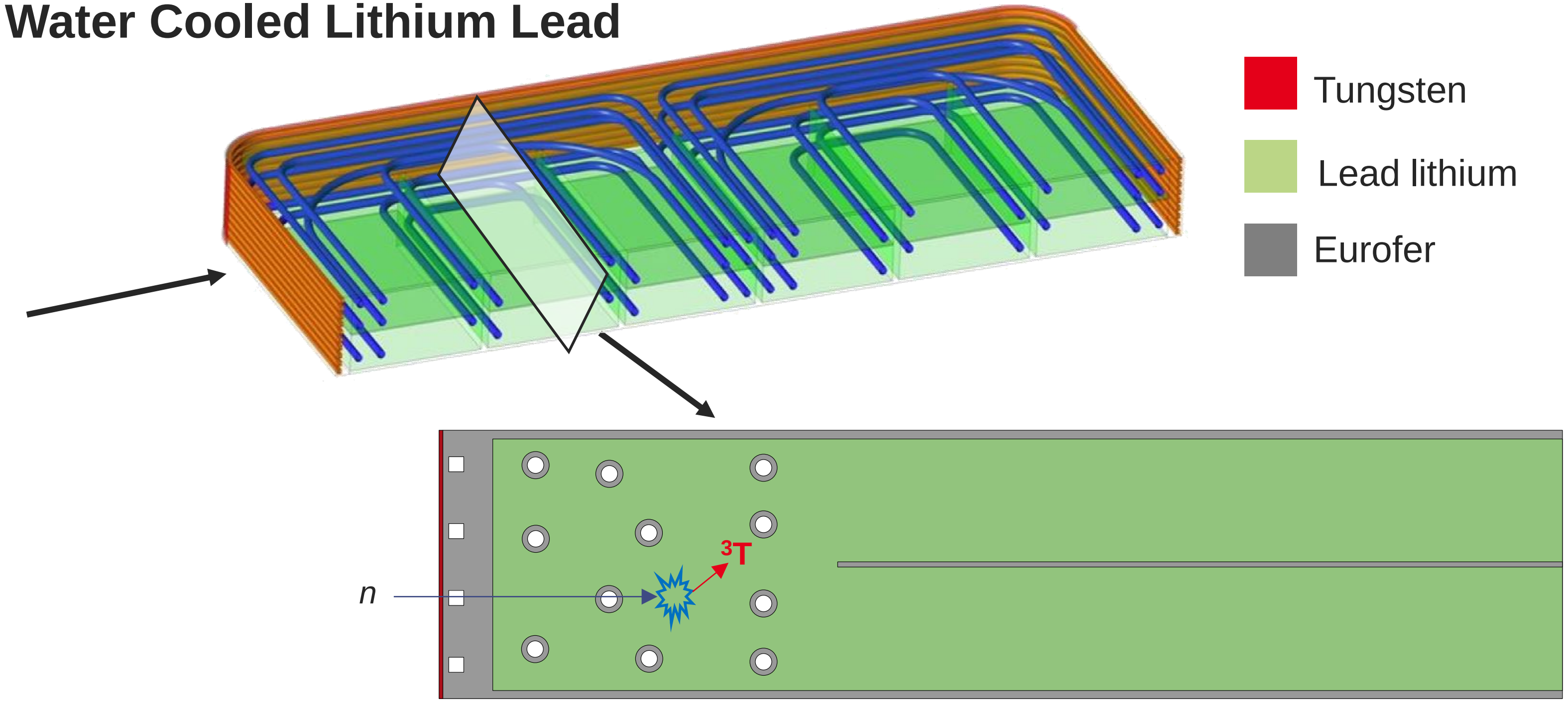




Context: Tritium retention and breeding



WCLL concept
Water Cooled Lithium Lead



Tritium is **Not abundant** and **it is RADIOACTIVE** (β^- emitter max 18 keV)
⇒ **premeation** and **retention** is a **Safety Issue** for fusion reactors: 700 g limit in ITER Vacuum Vessel

Modelling Tritium in Fusion materials is important for predicting Tritium sustainability and safety

Outline

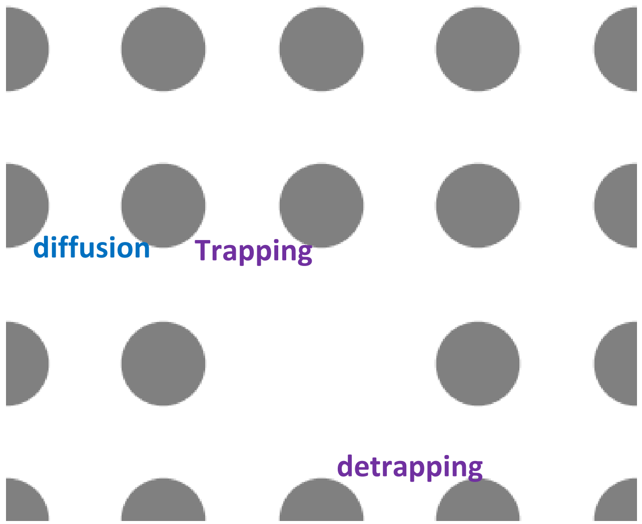
1. **Model presentation**
   - Tritium transport in materials: governing equations
   - Geometry of the WCLL First Wall
   - Model parametrizations for W and Eurofer
2. **Results**
   - Inputs of the simulations
   - Tritium spatial distribution
   - Tritium inventory and permeation
3. **Conclusions and perspectives**

Tritium transport in materials: governing equations

c_m (m^{-3}): Interstitial Tritium

$c_{\mathrm{t},i}$ (m^{-3}): trapped Tritium in type trap i

n_i (m^{-3}): trap of type i



H/D diffusion-trapping model in the Bulk

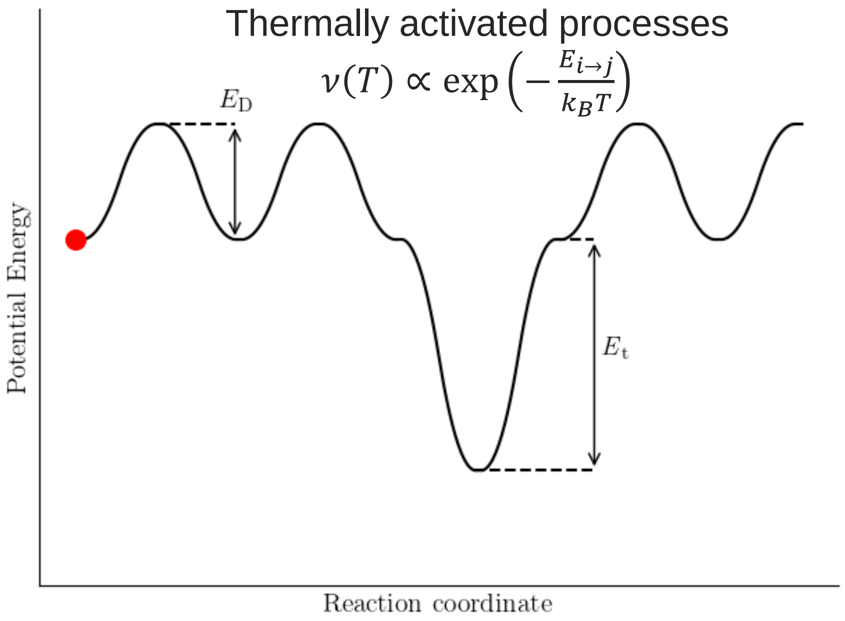
$$\frac{\partial c_\mathrm{m}}{\partial t} = \frac{\partial}{\partial x}\left(D(T)\frac{\partial c_\mathrm{m}}{\partial x}\right) - \sum_i \frac{\partial c_{\mathrm{t},i}}{\partial t} + S(x)$$

$$\frac{\partial c_\mathrm{t}}{\partial t} = \nu_\mathrm{t}(T) c_\mathrm{m}\left(n_i - c_{\mathrm{t},i}\right) - \nu_\mathrm{dt}(T) c_\mathrm{t} - A_i c_{\mathrm{t},i}$$

$$\frac{\partial n_i}{\partial t} = \Phi K\left[1 - \frac{n_i}{n_{\mathrm{max},\Phi}}\right] - A n_i$$

Creation by neutron

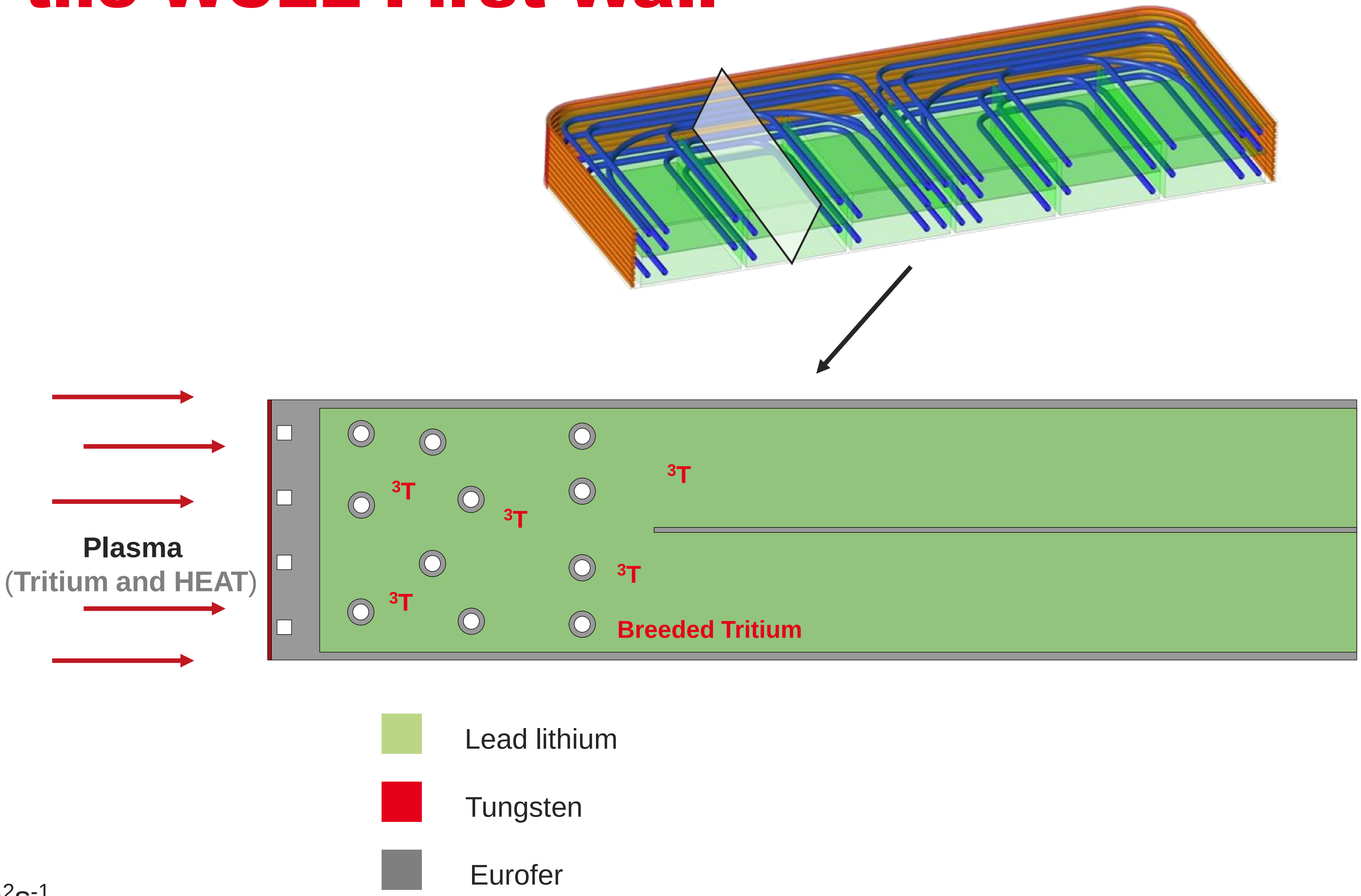
Annealing



Implemented in the **Open Source Code FESTIM** Dark et al, NF (2024)

Delaporte-Mathurin et al, IJHE (2024)

Geometry of the WCLL First Wall

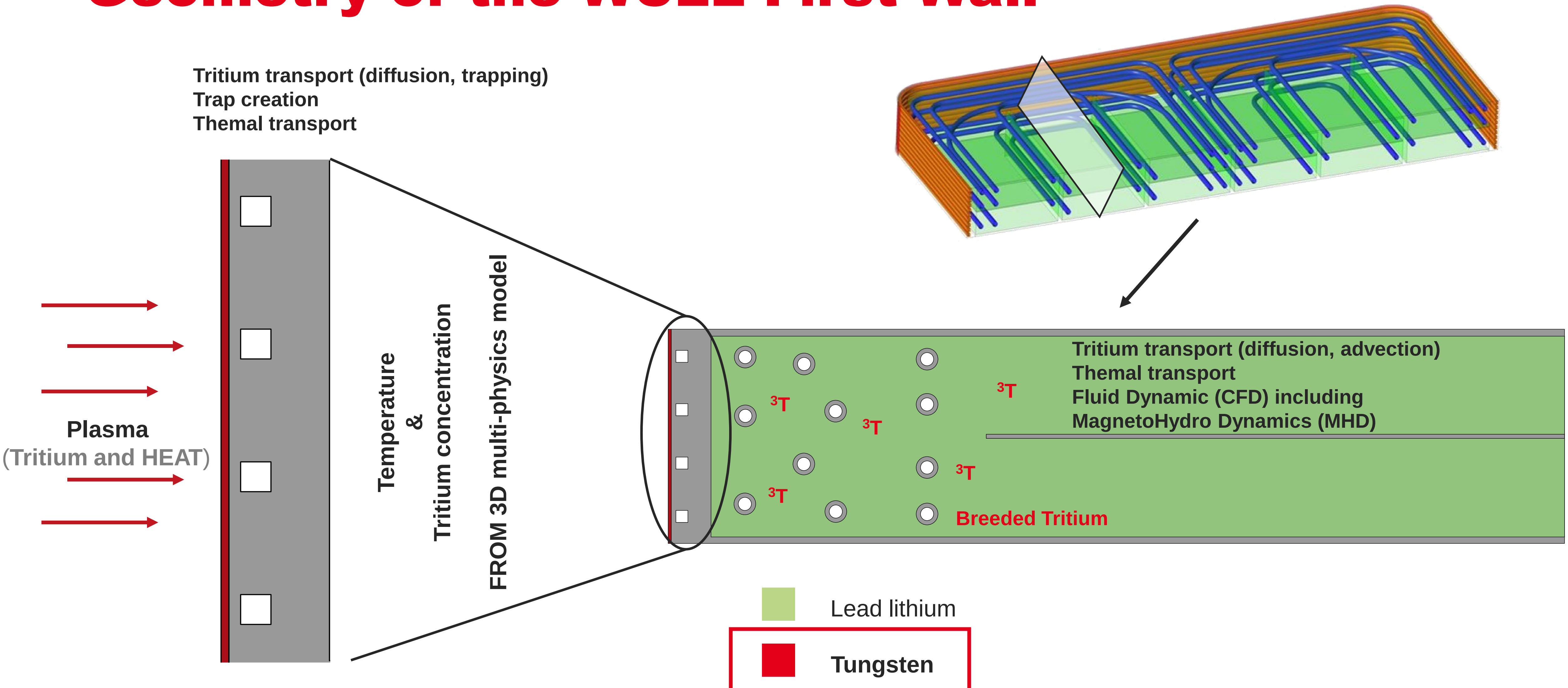


$T_{\text{cool}} = 585$ K

$\phi_{\text{inc,plasma}} = 5 \times 10^{19}$ m^{2}s^{-1}

$\phi_{\text{heat,plasma}} = 0.5$ MWm^{-2}

Geometry of the WCLL First Wall



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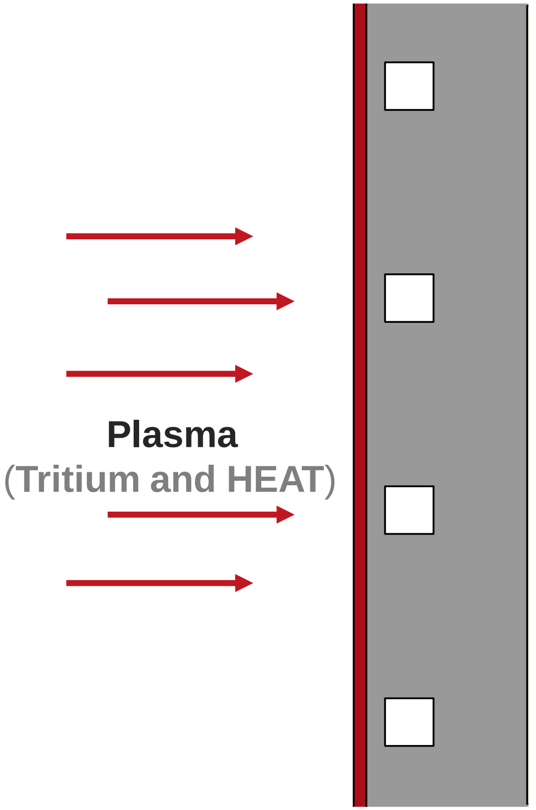
Geometry of the WCLL First Wall

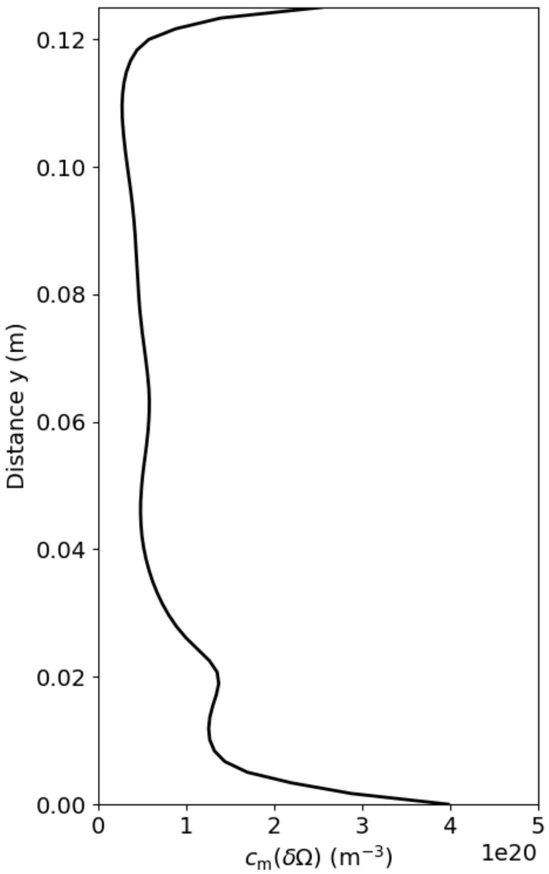
Politecnico di Torino:
G. Ferrero and R. Testoni

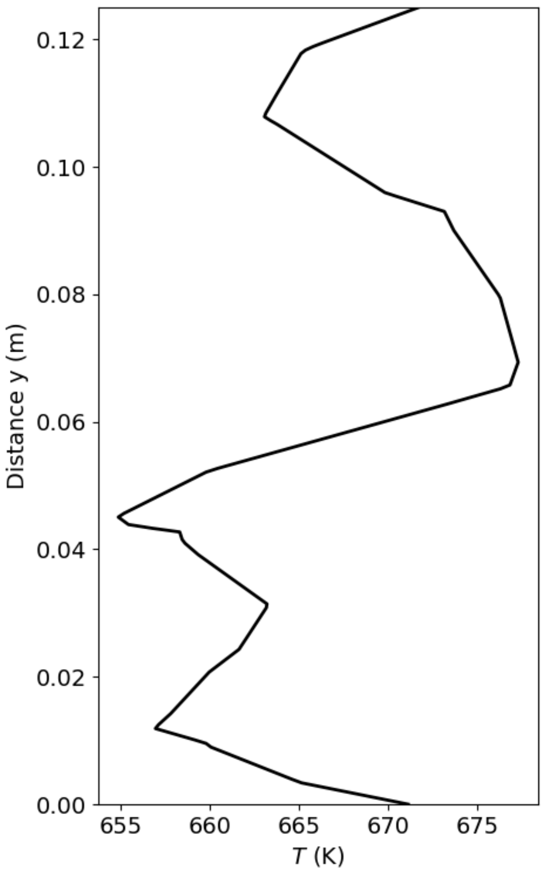
Tungsten

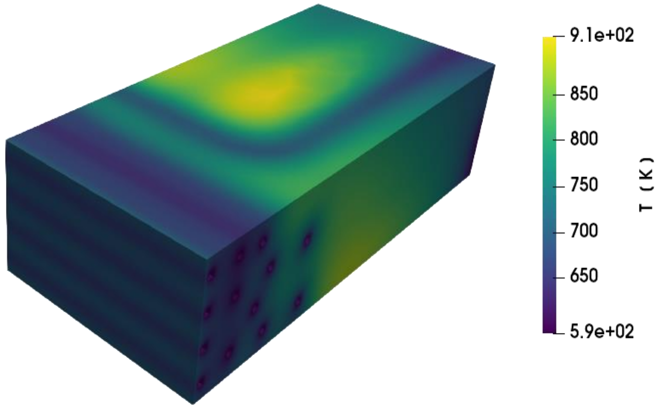
Eurofer



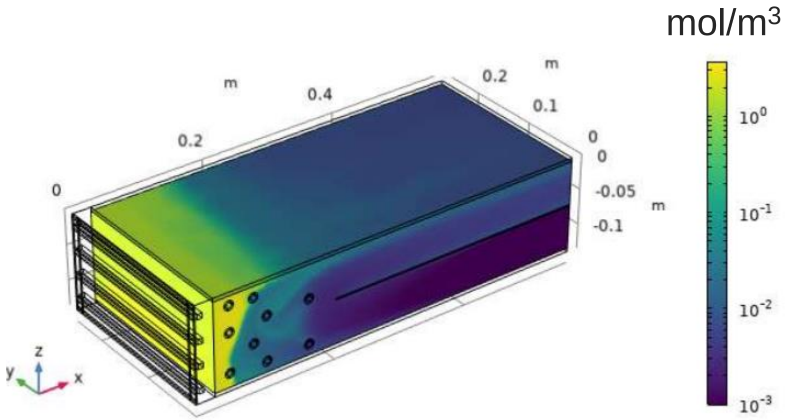
Results of 3D multi-physics model
(Tritium and thermal transport CFD with MHD)







Temperature (K)



Tritium concentration

$T_{\mathrm{cool}} = 585$ K

$\phi_{\mathrm{inc,plasma}} = 5 \times 10^{19}$ m^{2}s^{-1}

$\phi_{\mathrm{heat,plasma}} = 0.5$ MWm^{-2}

Model parametrization: Tungsten

T. Schwarz-Selinger et al, Mater. Res. Express (2023)

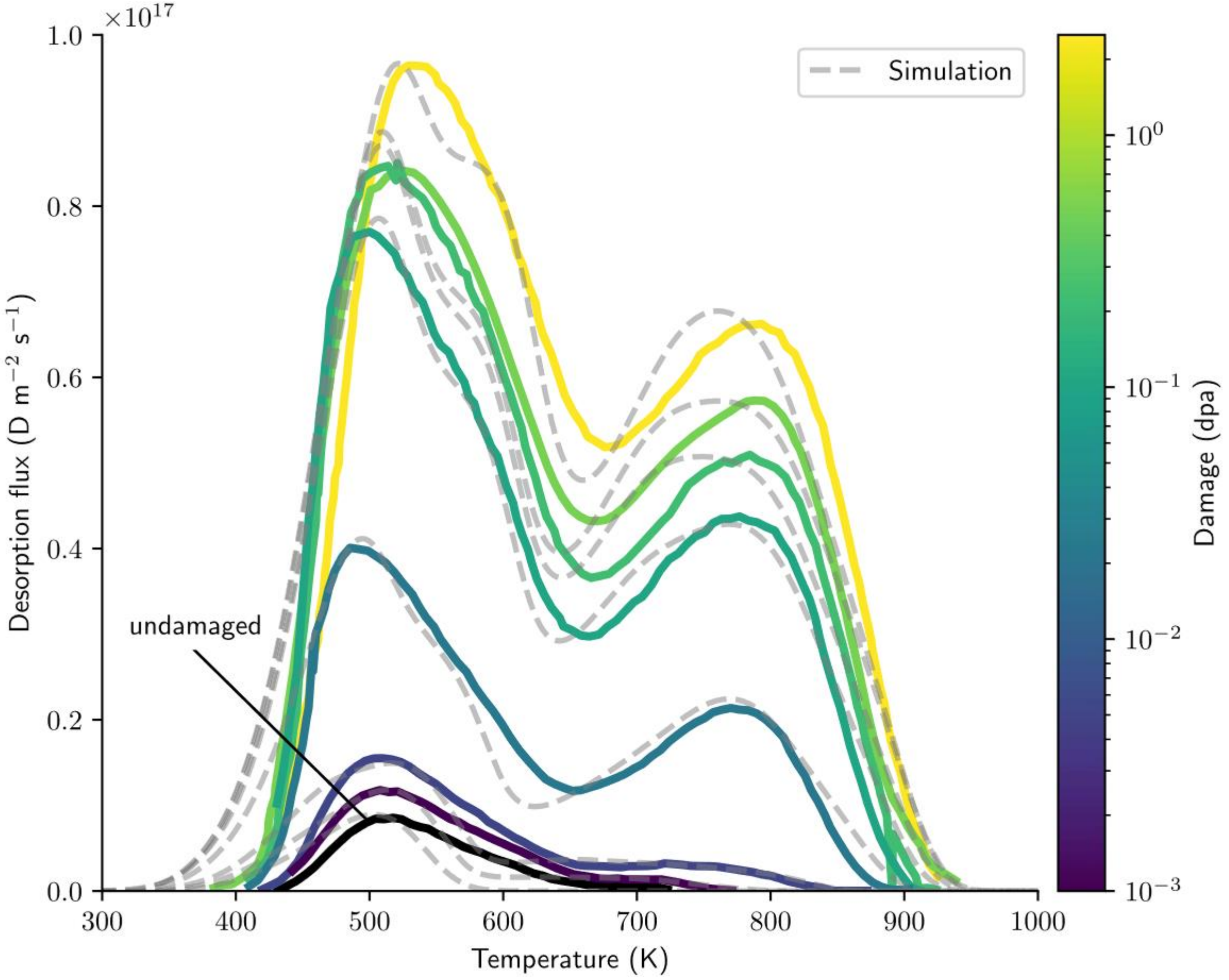
Simulations of **self-damaged tungsten** to mimic accumulation of neutron damage

Model from J. Dark et al, NF (2024)

	Detrapping energy
native 1	0.85 eV
native 2	1.00 eV
Small Vacancy clusters	1.15 eV and 1.35 eV
Medium Vacancy Clusters	1.65 eV and 1.85 eV
Big vacancy Clusters and Voids	2.05 eV

2 W models $E_{\text{diff}} = 0.2$ eV

Wud: Undamaged W with only native traps
Wd: damaged W with all traps



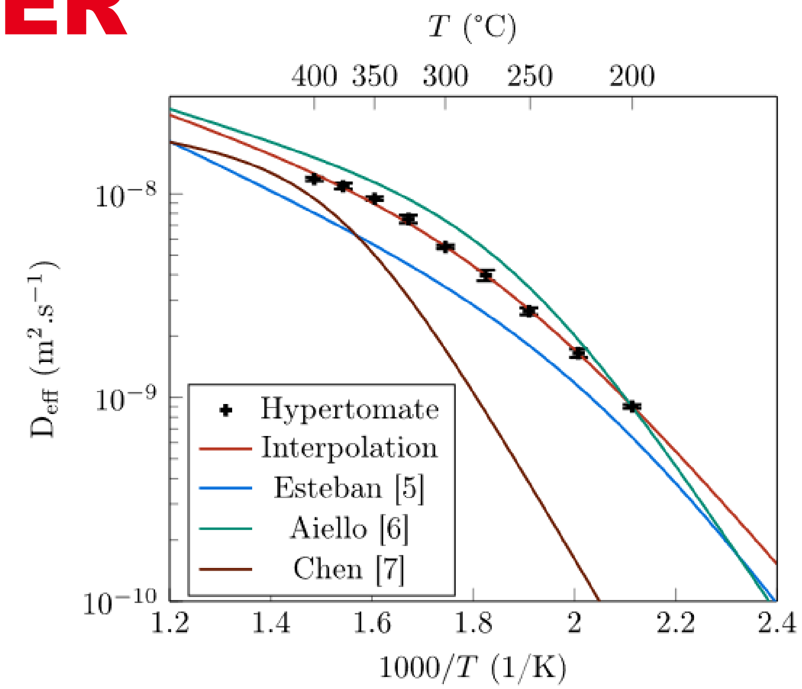
Model parametrization: EUROFER

Simulations of **TDS and permeation** of gas exposed Eurofer

F. Montupet-Leblond et al, NME (2021)

	Detrapping energy
native 1	0.51 eV

$E_{\mathrm{diff}} = 0.16$ eV



(a) Hydrogen effective diffusivity in Eurofer97

Permeation analysis with $D_{\mathrm{eff}}(T)$

Model parametrization: EUROFER

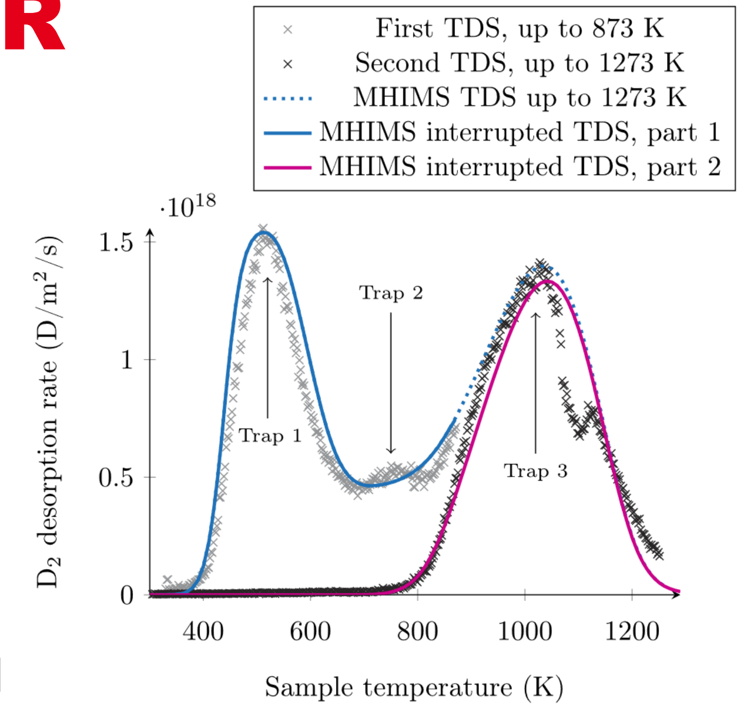
Simulations of **TDS and permeation** of gas exposed Eurofer

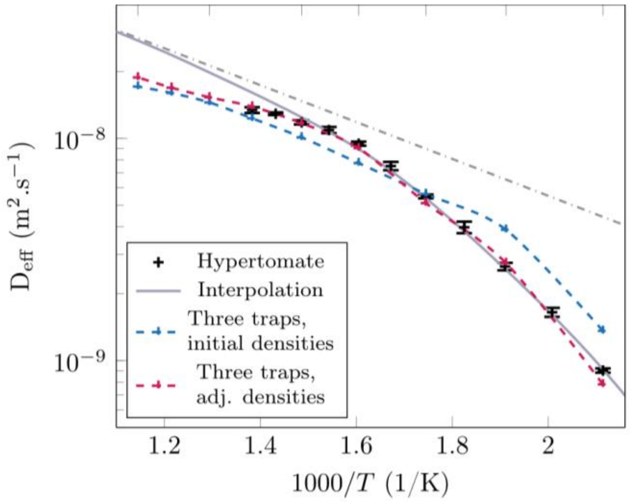
F. Montupet-Leblond et al, NME (2021)

	Detrapping energy
native 1	0.51 eV
native 2	**1.27 eV**
Native 3	**1.65 eV**

$E_{\text{diff}} = 0.16$ eV

Simulation of TDS and Permation



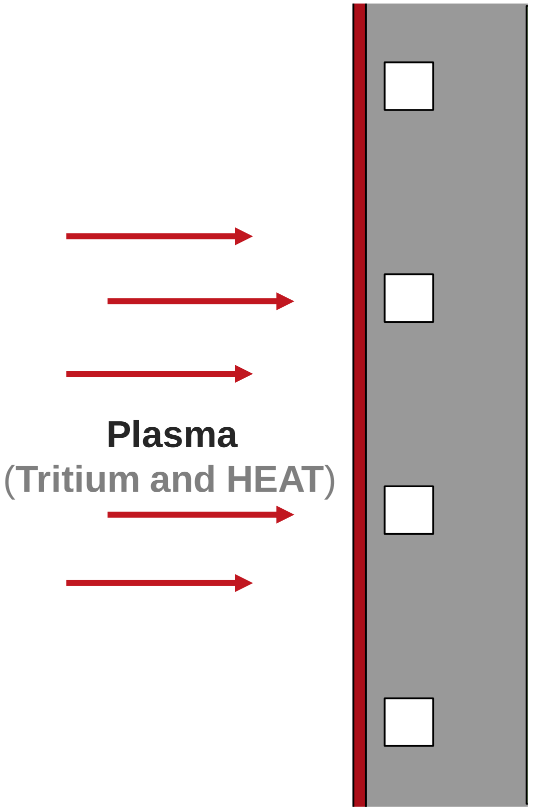


2 Eurofer models

E1t: Only native trap 1 (From simple permeation analysis)
E3t: all 3 traps (adding high E_{dt})

F. Montupet-Leblond et al, NF (2022)

Model parametrization



4 First Wall models:

- Undamaged W (2 traps) and Eurofer with 1 trap
- Undamaged W (2 traps) and Eurofer with 3 traps
- Damaged W (2+5 traps) and Eurofer with 1 trap
- Damaged W (2+5 traps) and Eurofer with 3 traps

Reference model
J. Dark et al, NF (2021)

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   Tritium inventory and permeation

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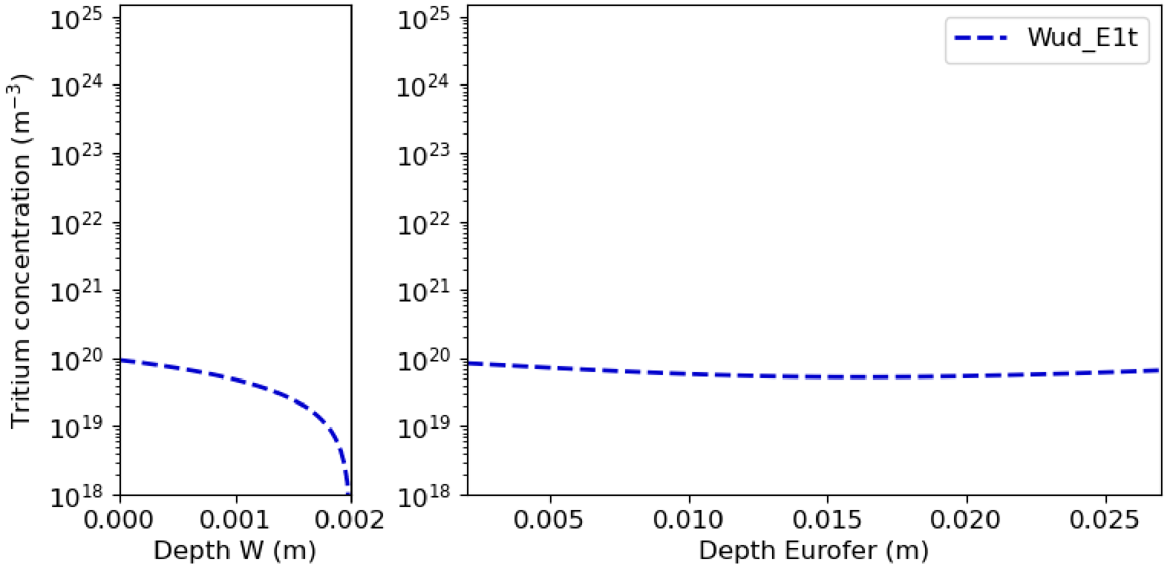
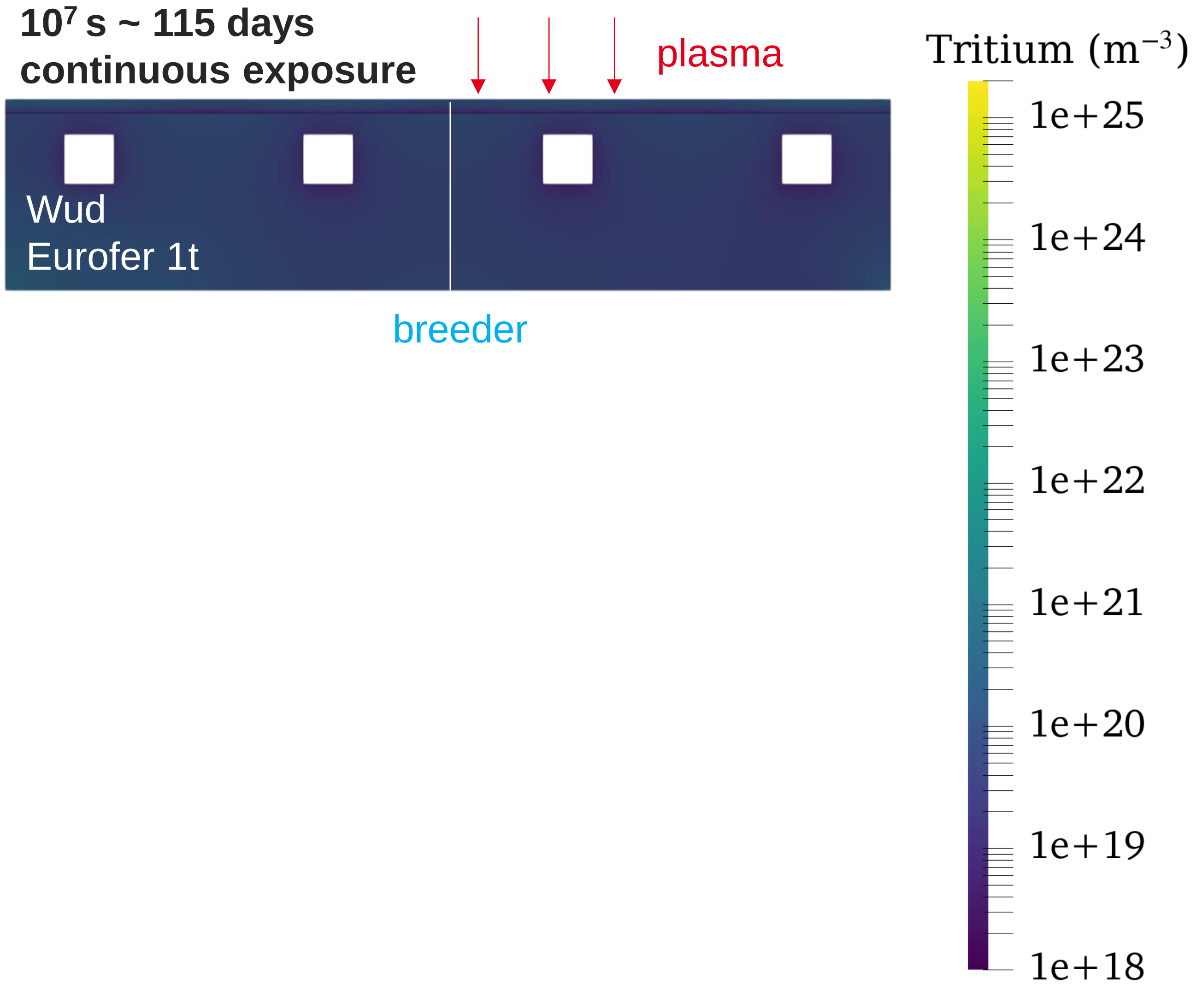
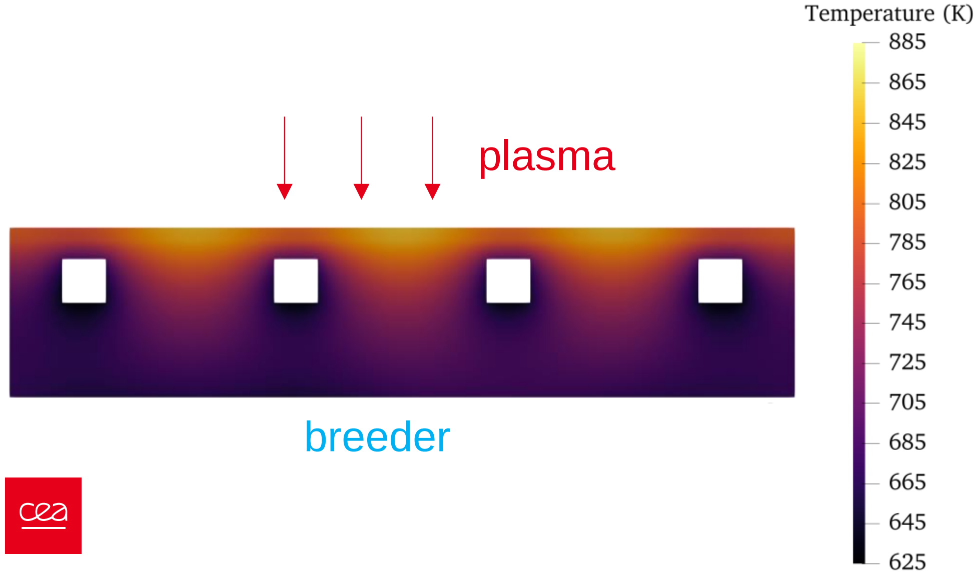
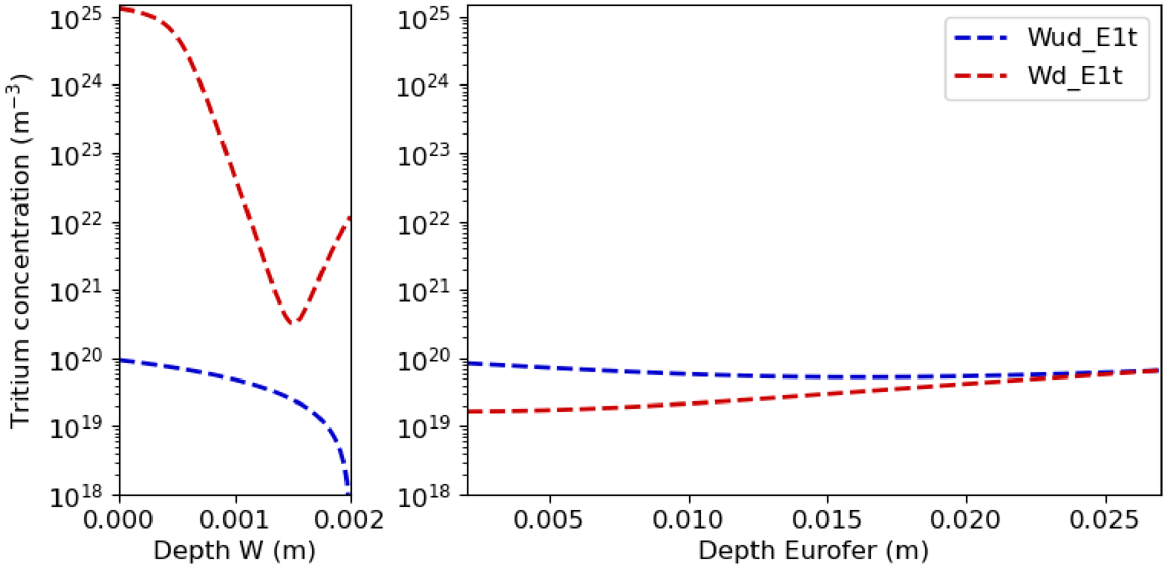
Tritium spatial distribution: 2D fields

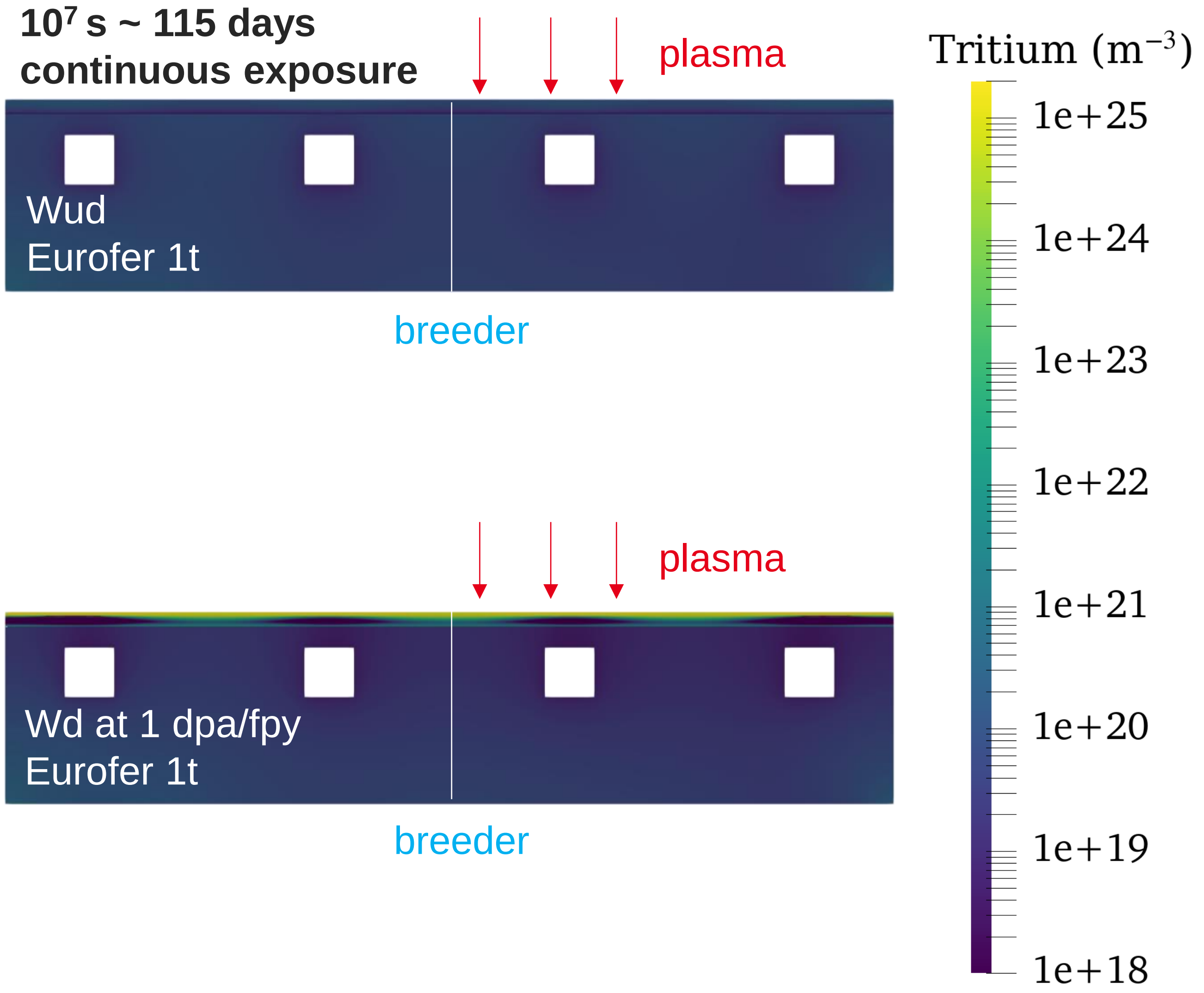


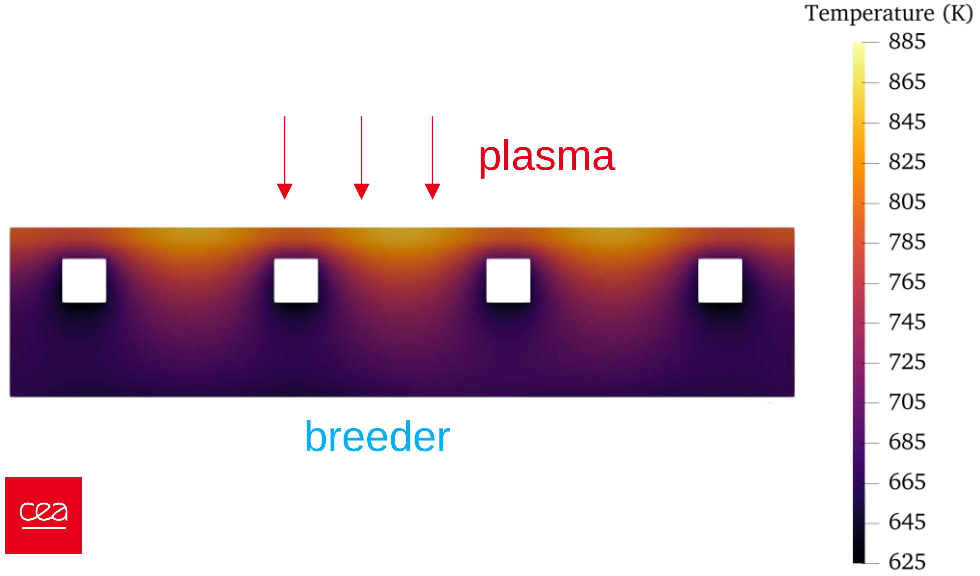




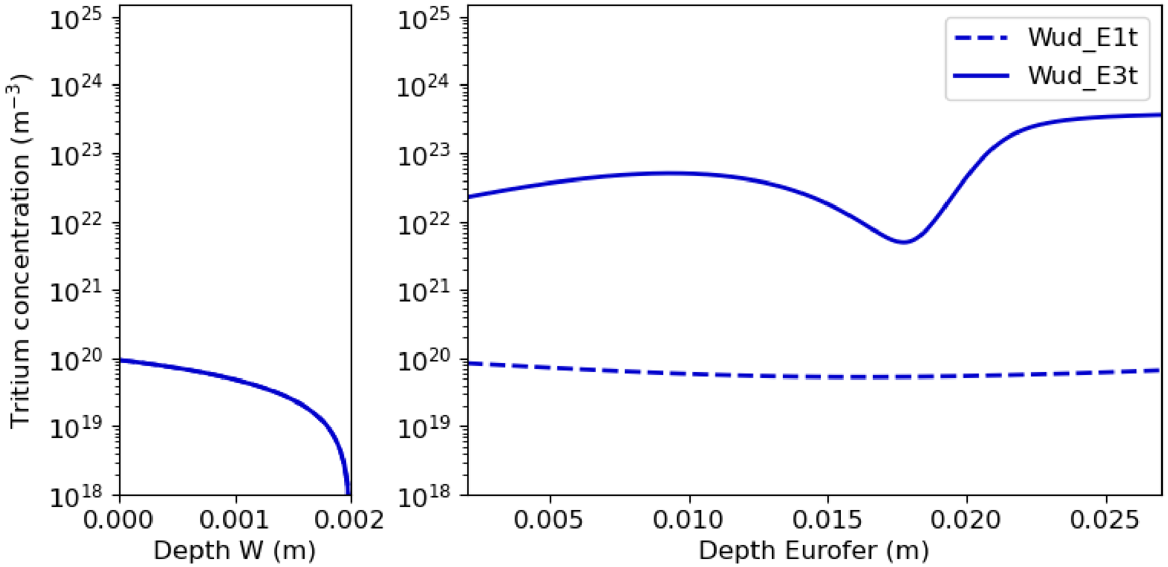
Tritium spatial distribution: 2D fields



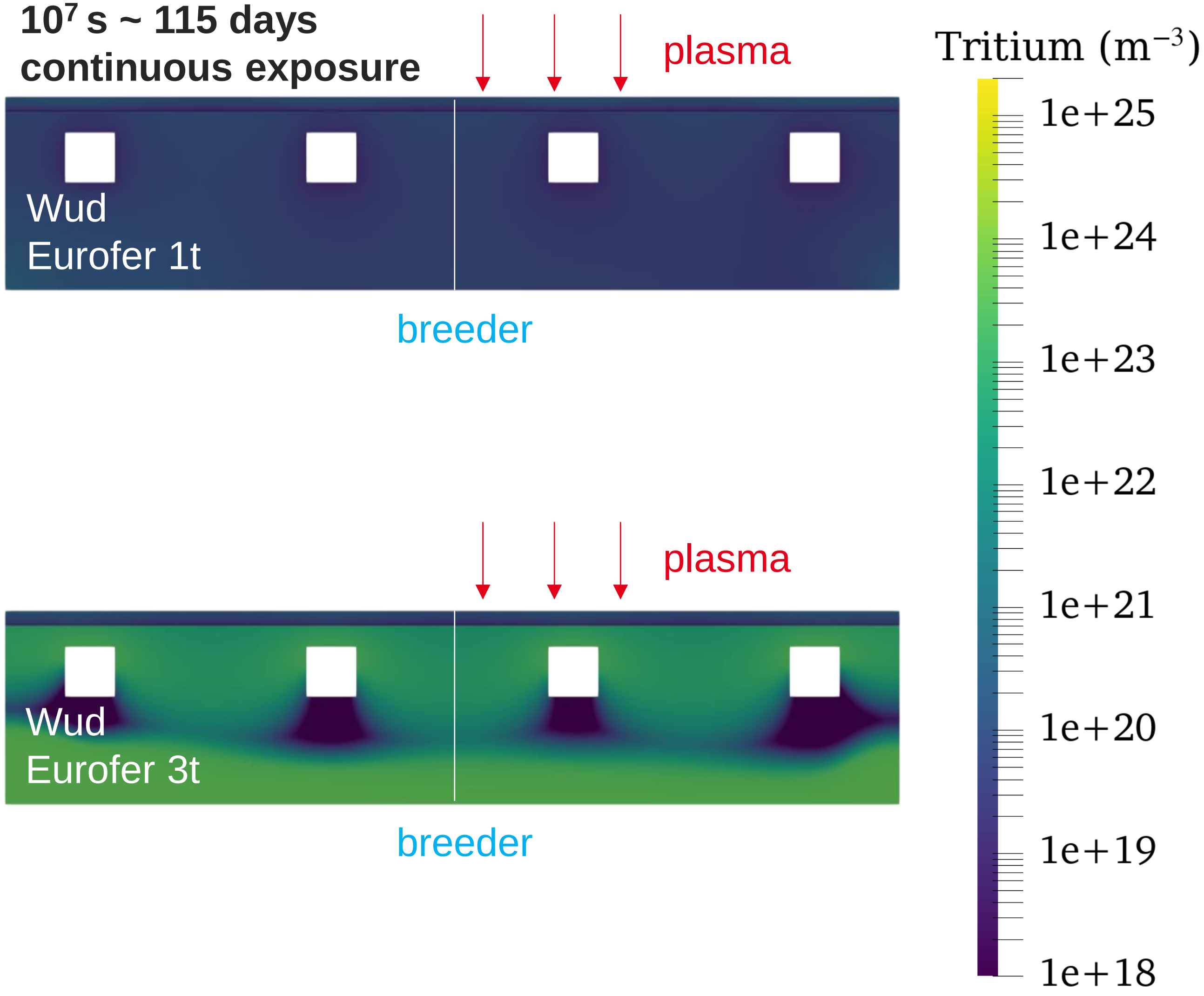


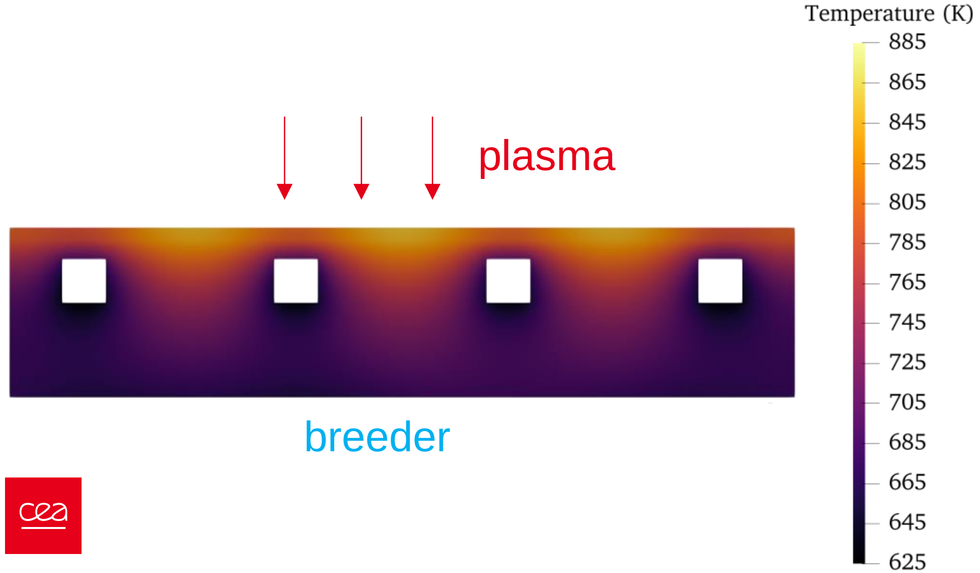


Tritium spatial distribution: 2D fields

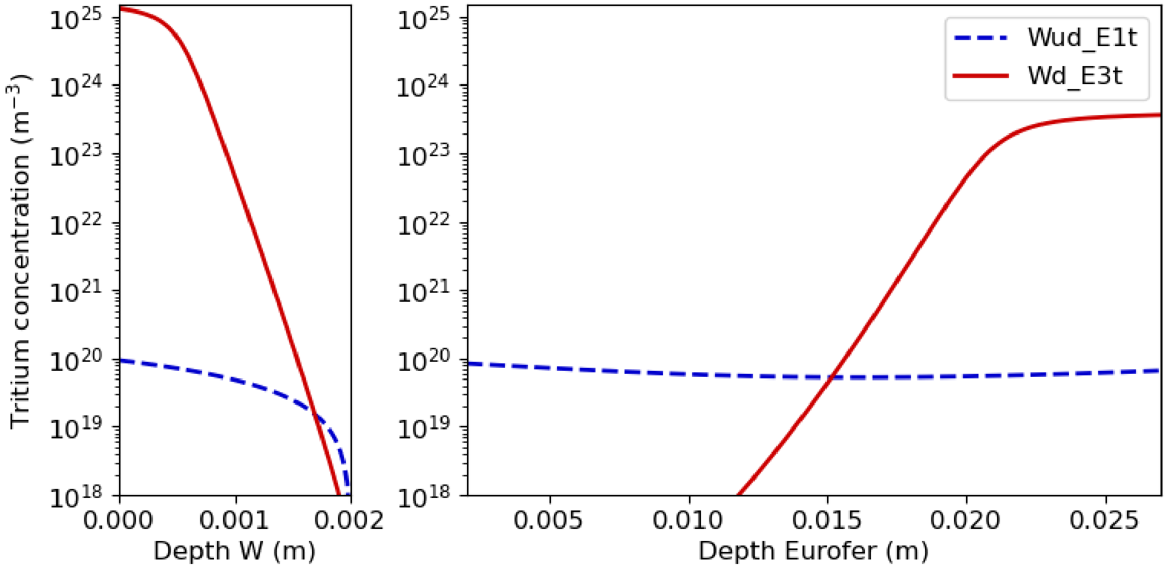


10^7 s ~ 115 days continuous exposure

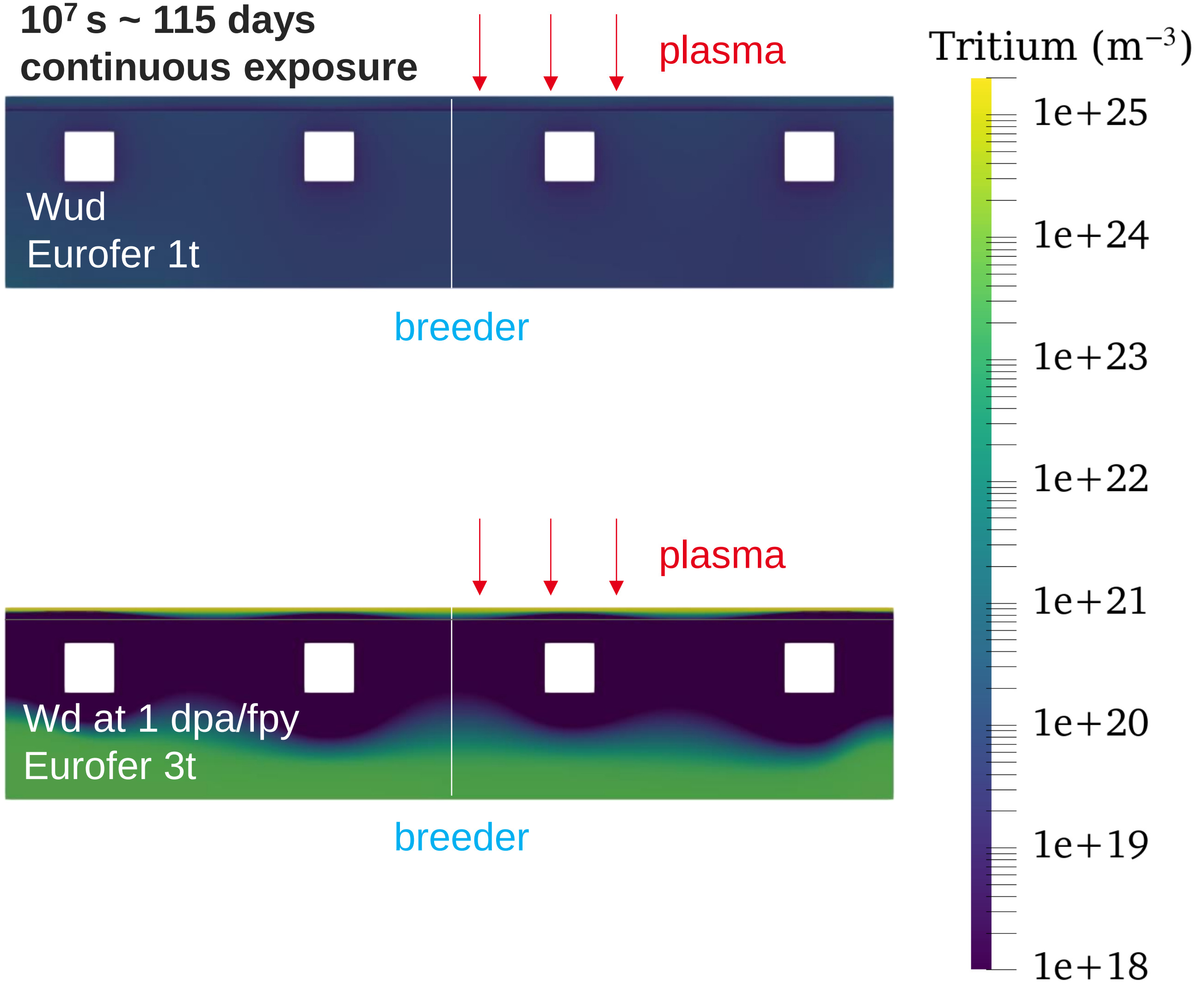


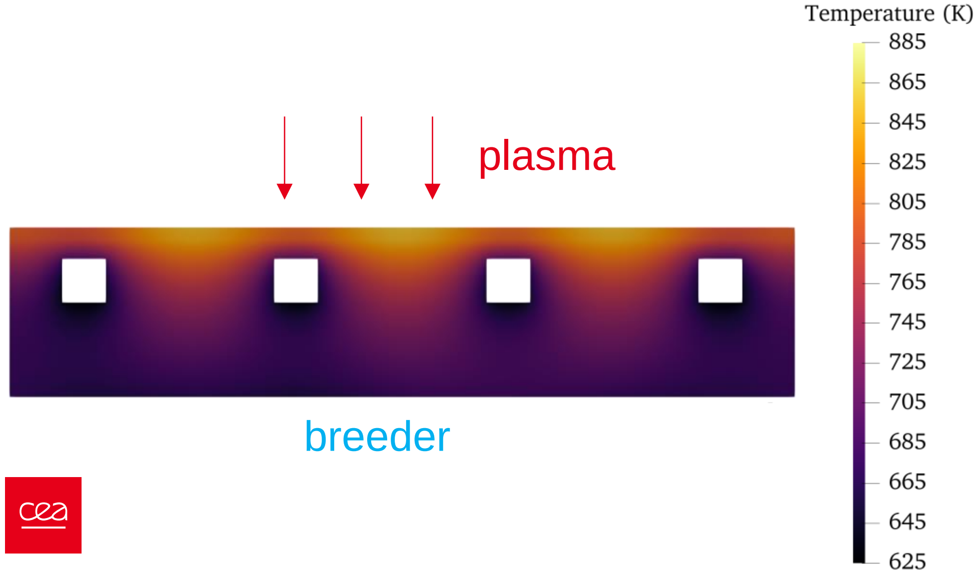


Tritium spatial distribution: 2D fields



10^7 s ~ 115 days continuous exposure

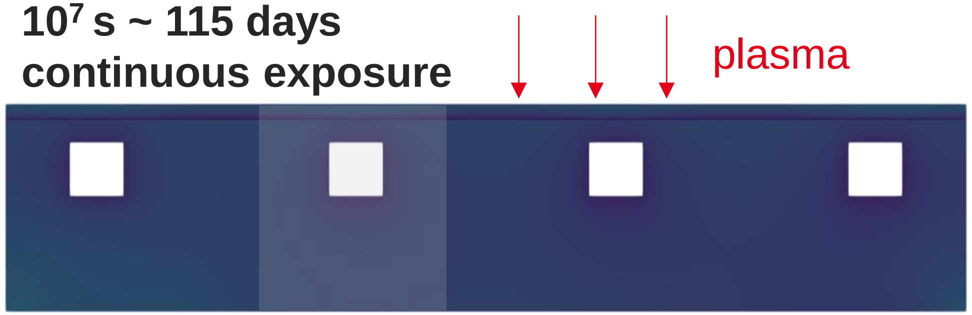


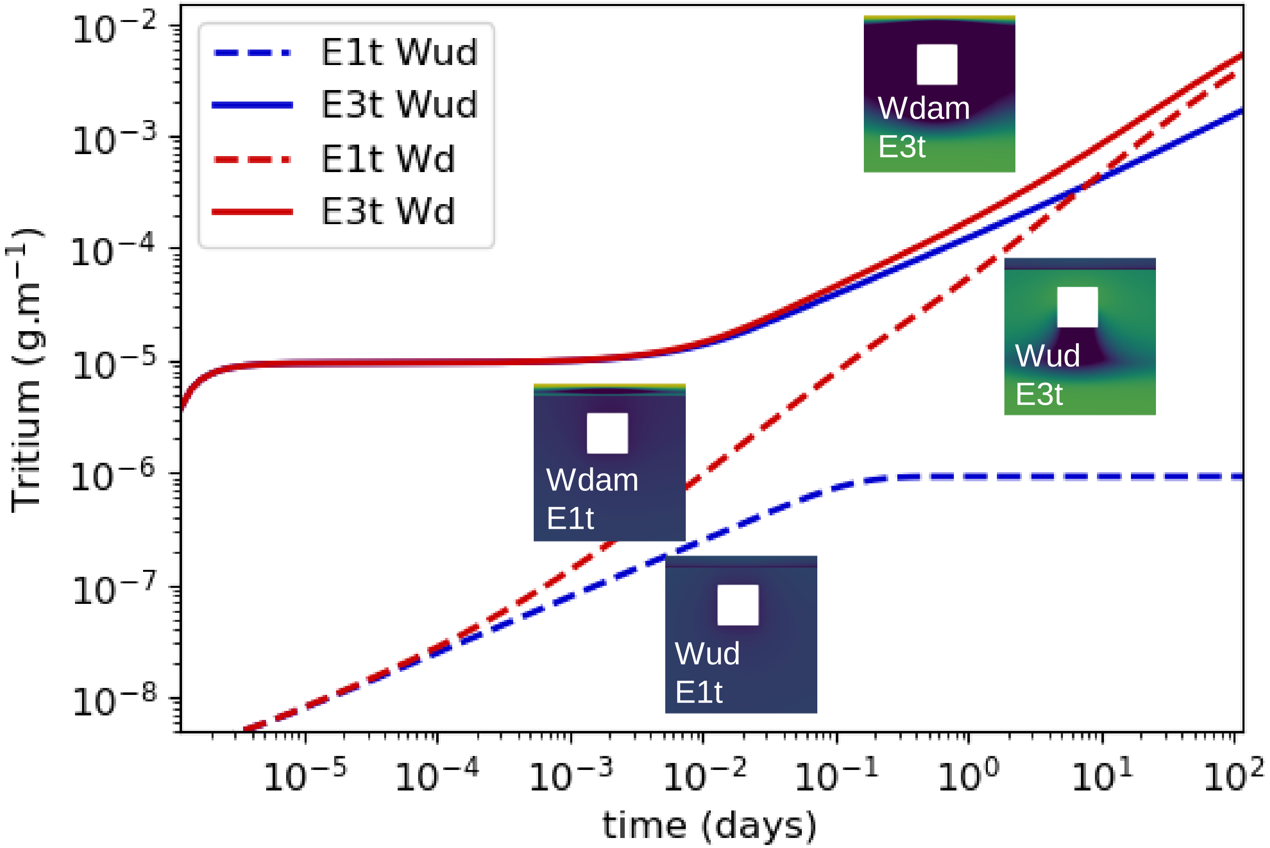


Tritium inventory

$$I_T = m_T \int_\Omega \left(c_m + \sum_i c_{t,i} \right) dxdy$$

10^7 s ~ 115 days continuous exposure





Adding the damaged traps in W

$\Rightarrow I_T \times \mathbf{4000}$

Considering 3 traps in Eurofer

$\Rightarrow I_T \times \mathbf{1800}$

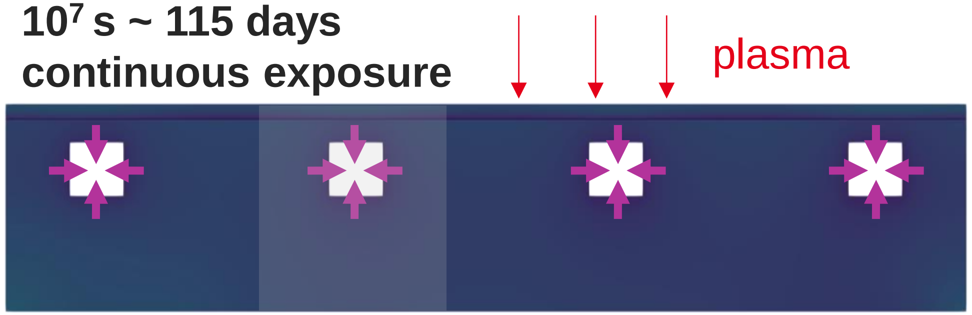
Damage traps in W + 3 traps in Eurofer

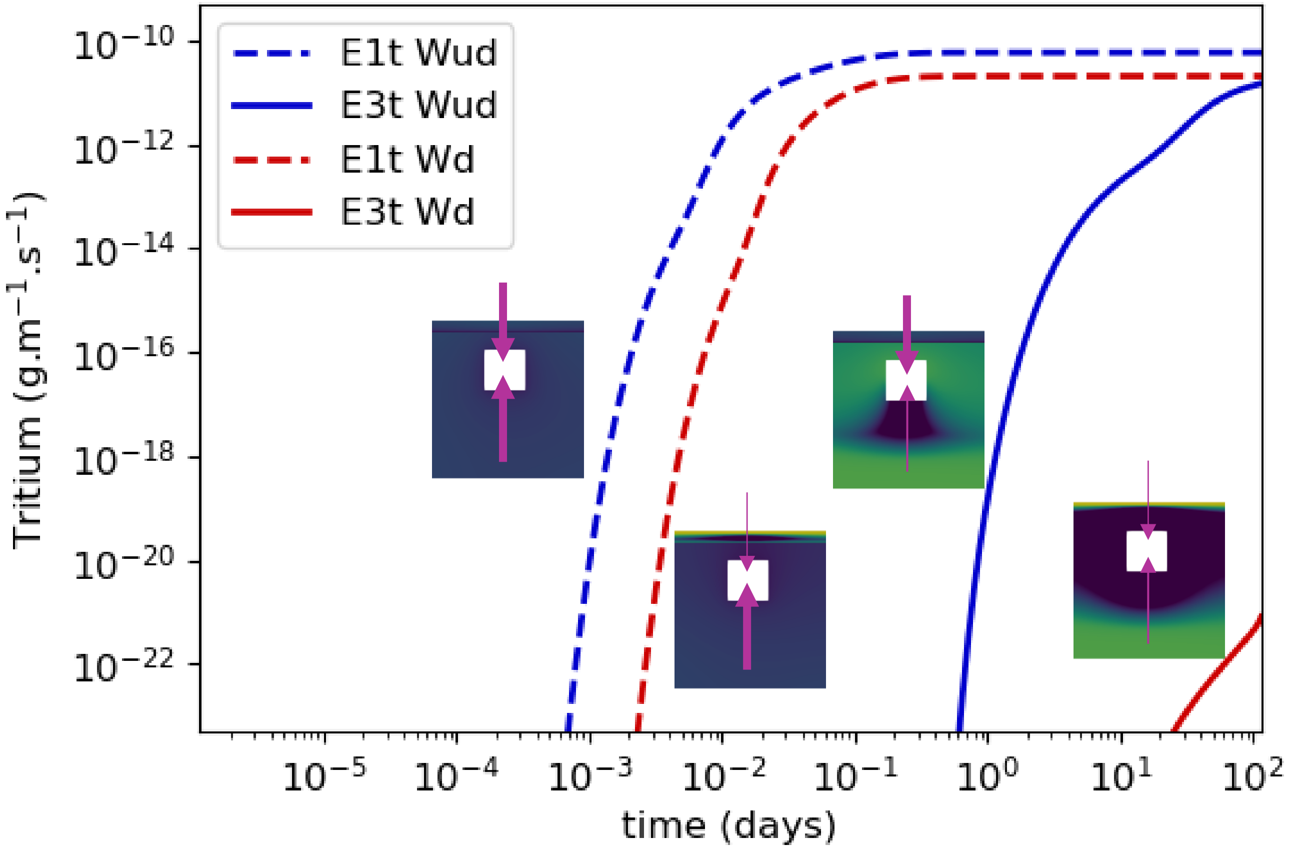
$\Rightarrow I_T \times \mathbf{5700}$

Tritium inventory

$$\varphi_{\mathrm{T,perm}} = m_{\mathrm{T}} \int_{\partial\Omega} (-D(T)\nabla c_{\mathrm{m}} \cdot \boldsymbol{n})dl$$

10^7 s ~ 115 days continuous exposure





Adding the damaged traps in W
small (~100 s) delay on permeation

Considering 3 traps in Eurofer
huge (~1 day) delays on permeation

Damage traps in W + 3 traps in Eurofer
almost no permeation

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Conclusions and perspectives

Significant impact of W damage traps and native traps in Eurofer

	T Retention	T Permeation
W damage traps	Huge increase ($\times$ 4000)	Slight delay (100 s)
3 traps in Eurofer (high E_{dt})	Increase ($\times$ 1800)	Significant delays (1 day)

W damage traps + 3 traps in Eurofer ⇒ **Tritium retention ×5700 and almost no permeation**

Trapping models can significantly affect the overall tritium cycle and self-sufficiency [Meschini et al, NF (2025)]

Perpectives

Validate the existence of high detrapping energy trap in Eurofer with more experiments

A. Theodorou HWS Chamonix (2024)
F. Montupet-Leblond at IRFM (in progress)

What are the neutron damage in Eurofer?

Can the high E_{dt} traps in Eurofer (and W) be saturated with H or D?

Ireversible traps:
F. Montupet-Leblond et al, NF (2022)

■ Additional slides

Tritium spatial distribution: 2D fields