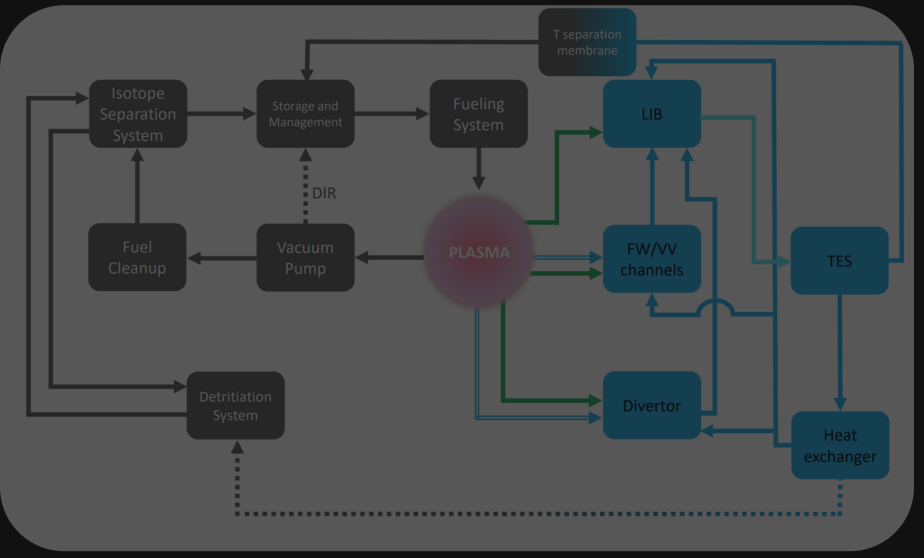
Guaranteed
Digital Twin-free

Overview of the PSFC blanket and fuel cycle modelling activities



Remi Delaporte-Mathurin, Nikola Goles, James Dark, Kaelyn Dunnell, Chirag Khurana, Collin Dunn, Sara Ferry, Abhishek Saraswat, Ethan Peterson, Stefano Segantin, Huihua Yang, Weiyue Zhou, Kevin Woller

Plasma Science & Fusion Center

The tritium issue

Data source: Pearson et al, Fusion Engineering and Design 136 (2018) 1140–1148

$$\mathrm{T} \xrightarrow{\text{☢}} \mathrm{He} + \mathrm{e}^-$$

Half-life: 12 years

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} + \mathrm{n}$$

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

$$\mathrm{n} + {}^{7}\mathrm{Li} \rightarrow \mathrm{T} + \mathrm{He} + \mathrm{n} - 2.5\ \mathrm{MeV}$$

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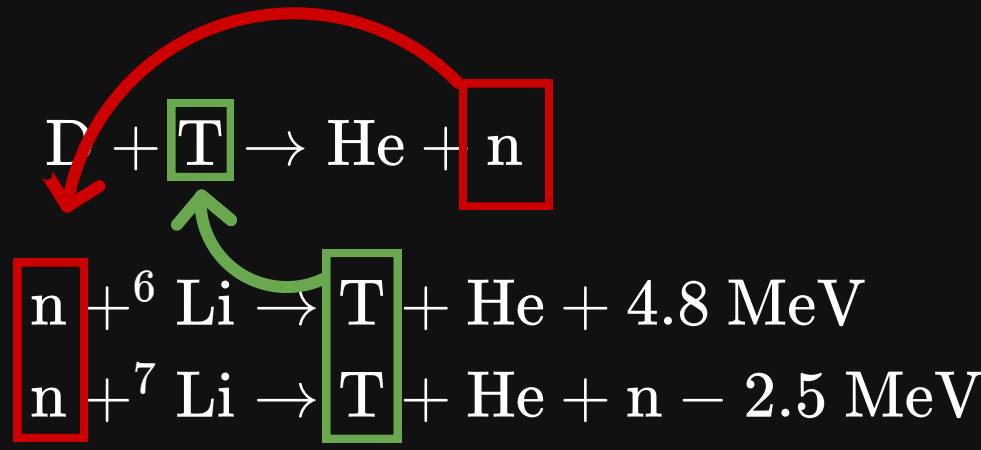
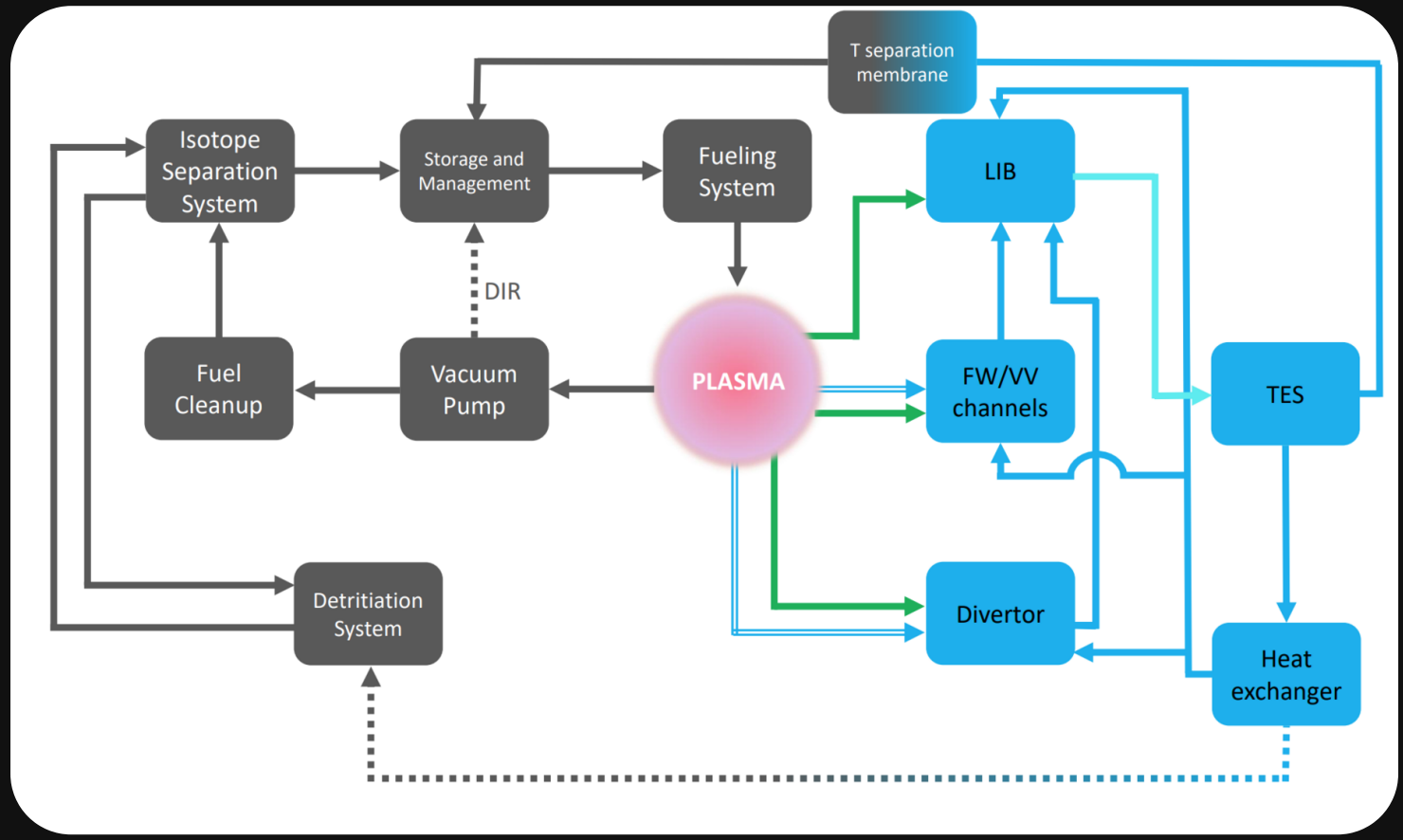
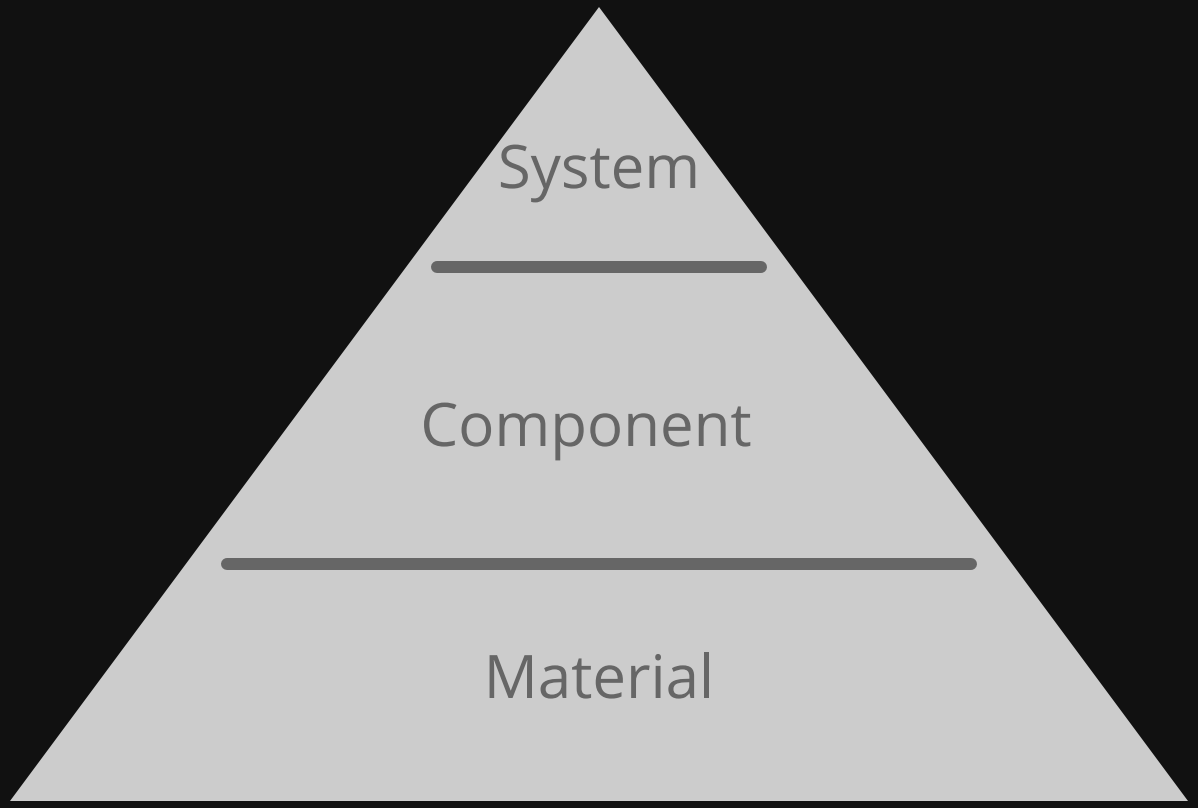


The fusion fuel cycle



Samuele Meschini *et al* 2023 Nucl. Fusion 63 126005

Multi-scale tritium design



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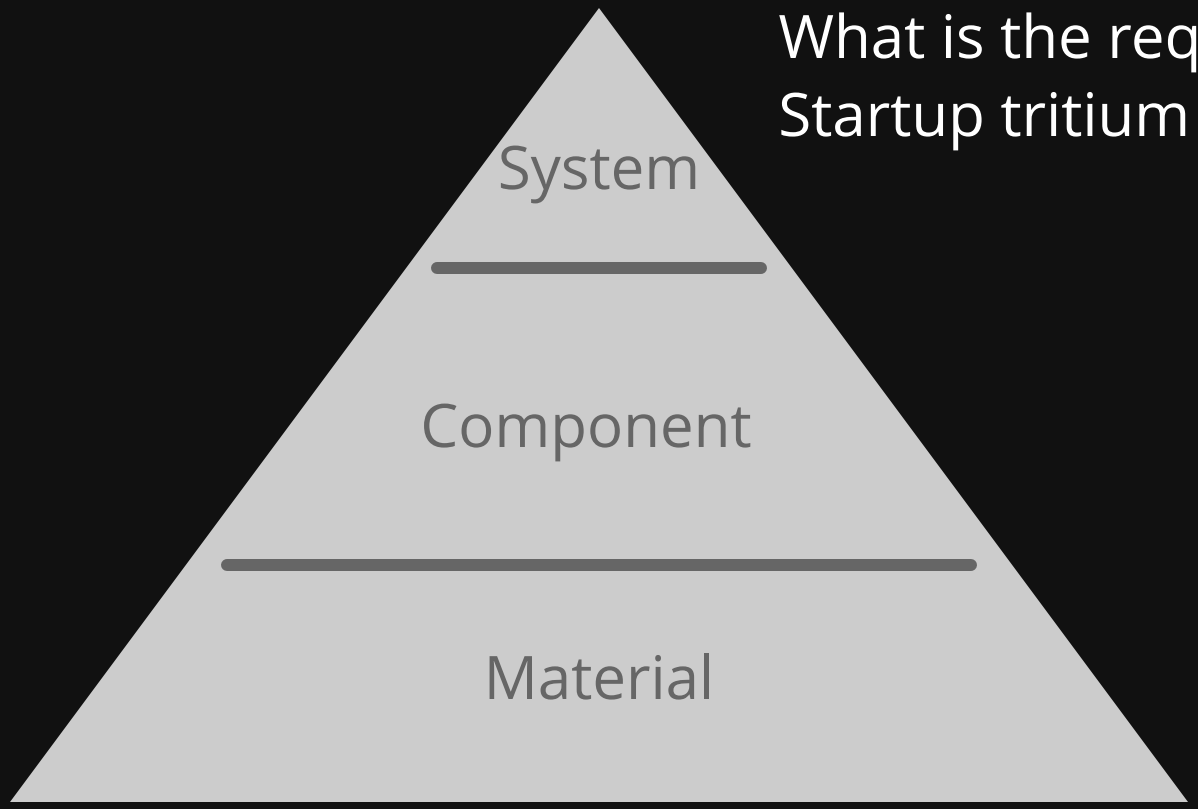
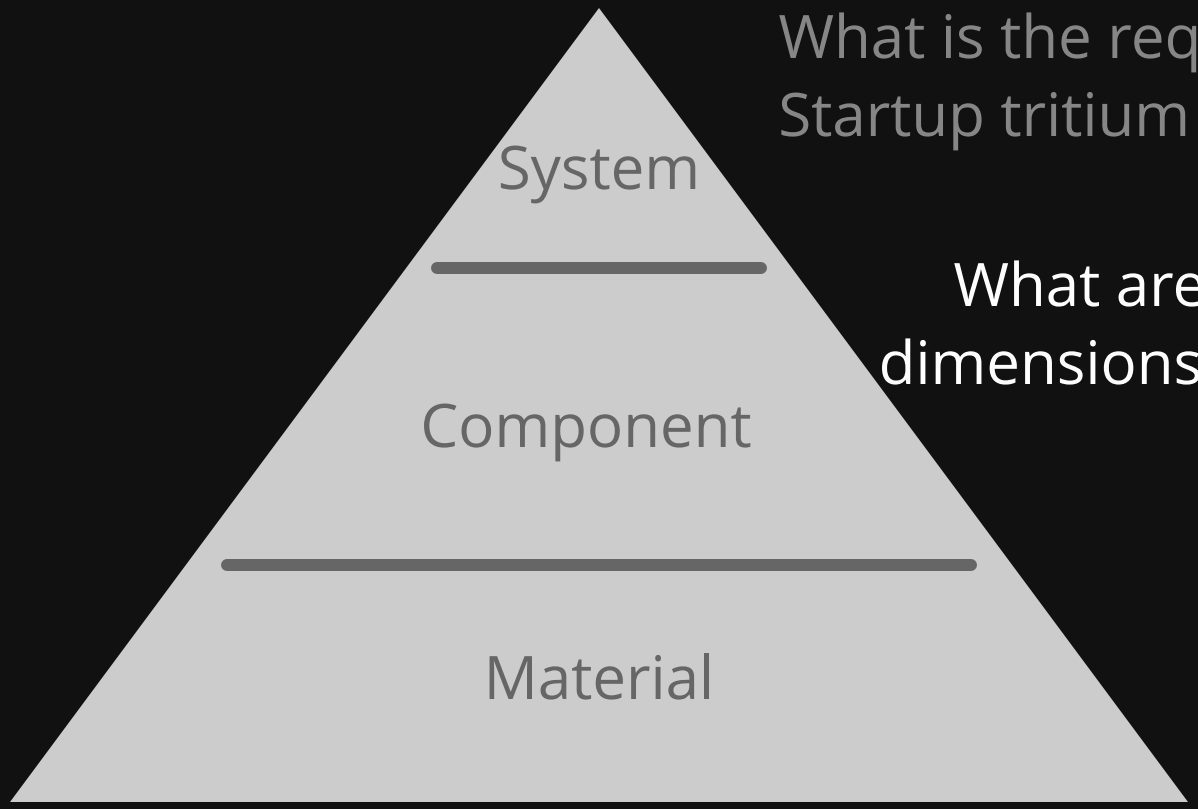


What is the required TBR?
Startup tritium inventory?

Multi-scale tritium design



What is the required TBR?
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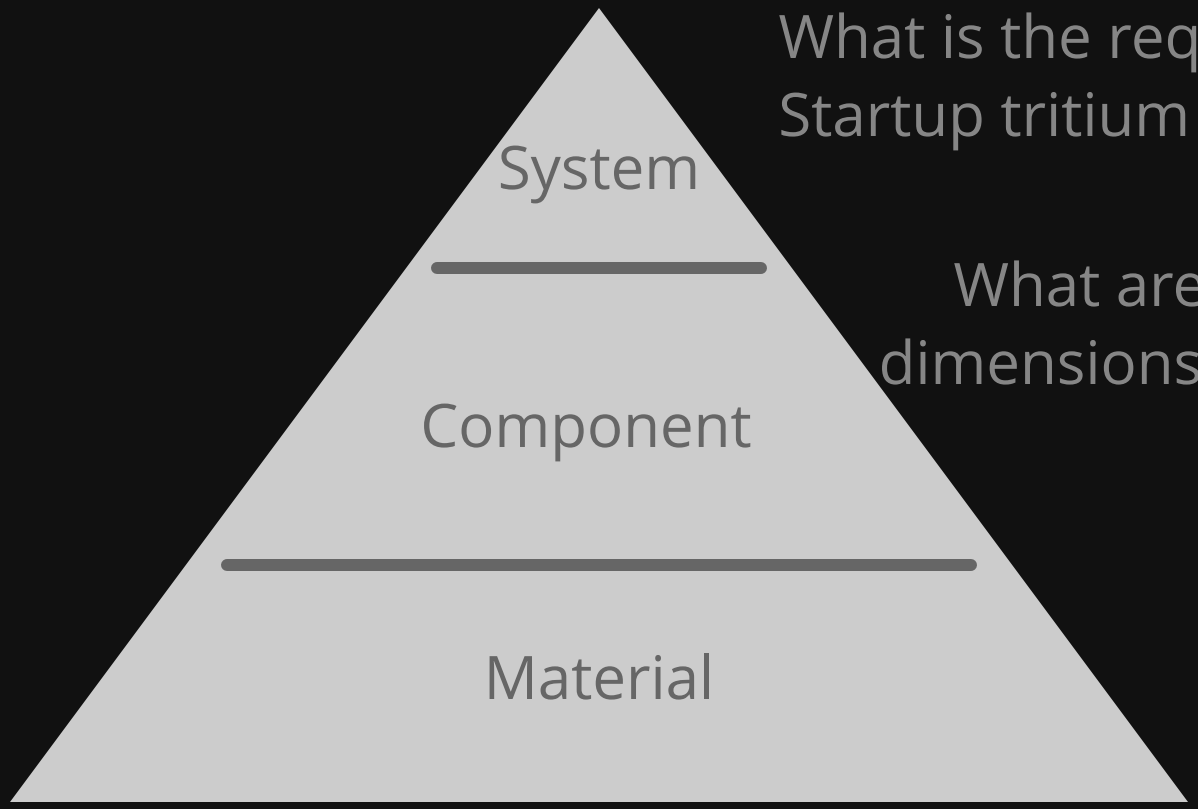
What are the minimum dimensions of the extractor?

What is the T concentration at the blanket outlet?

How much T is retained in the plasma facing materials?

Multi-scale tritium design



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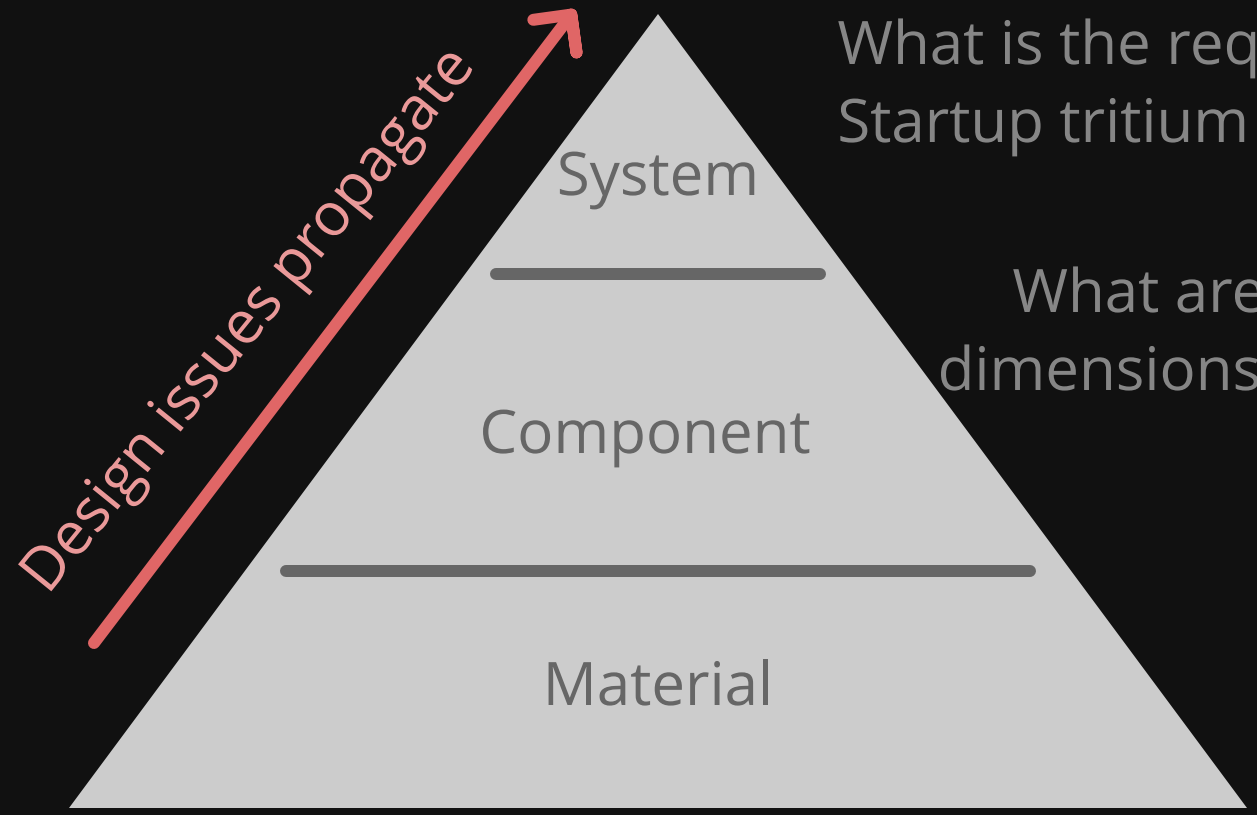
Trapping properties of tungsten?

Permeation reduction factor of this coating?

Multi-scale tritium design



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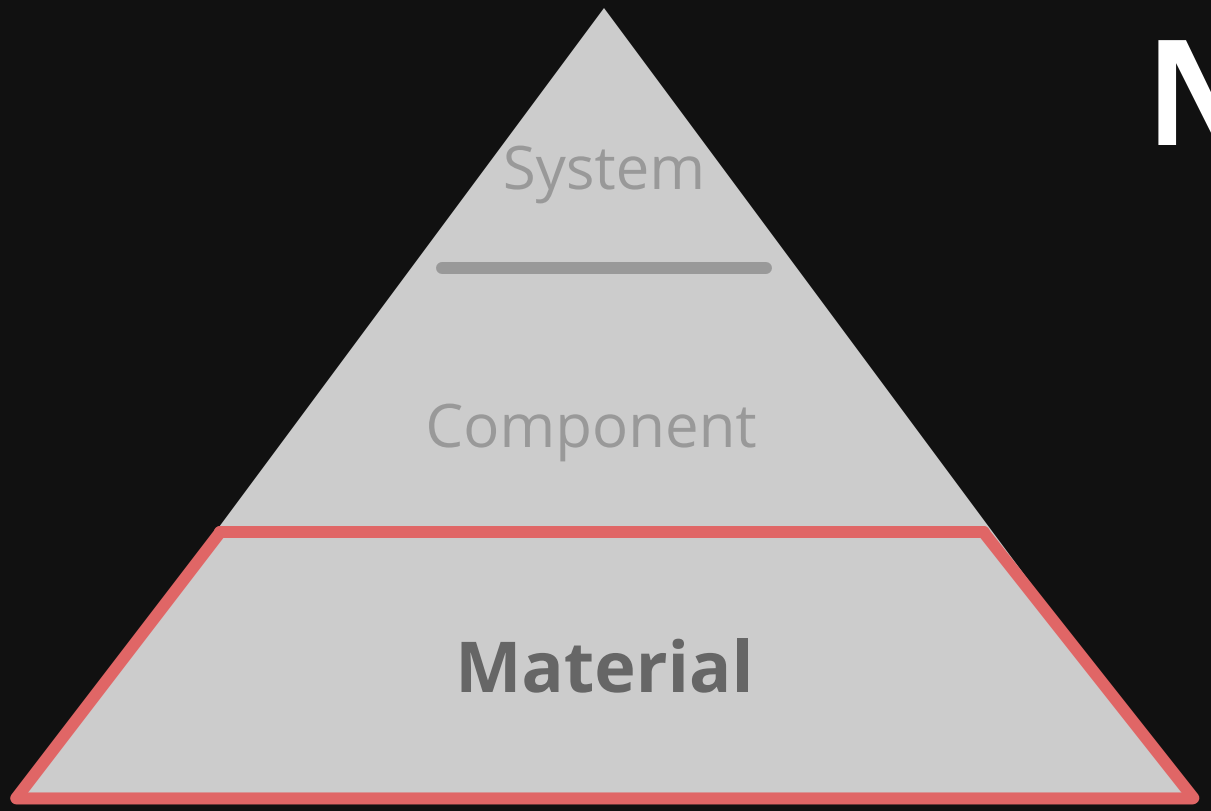
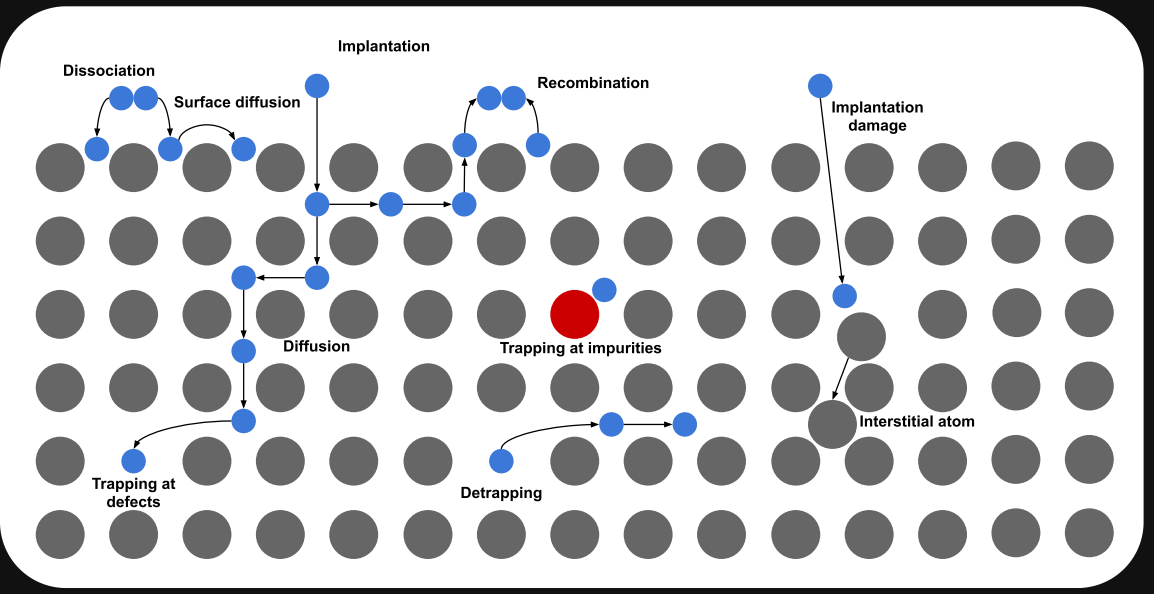
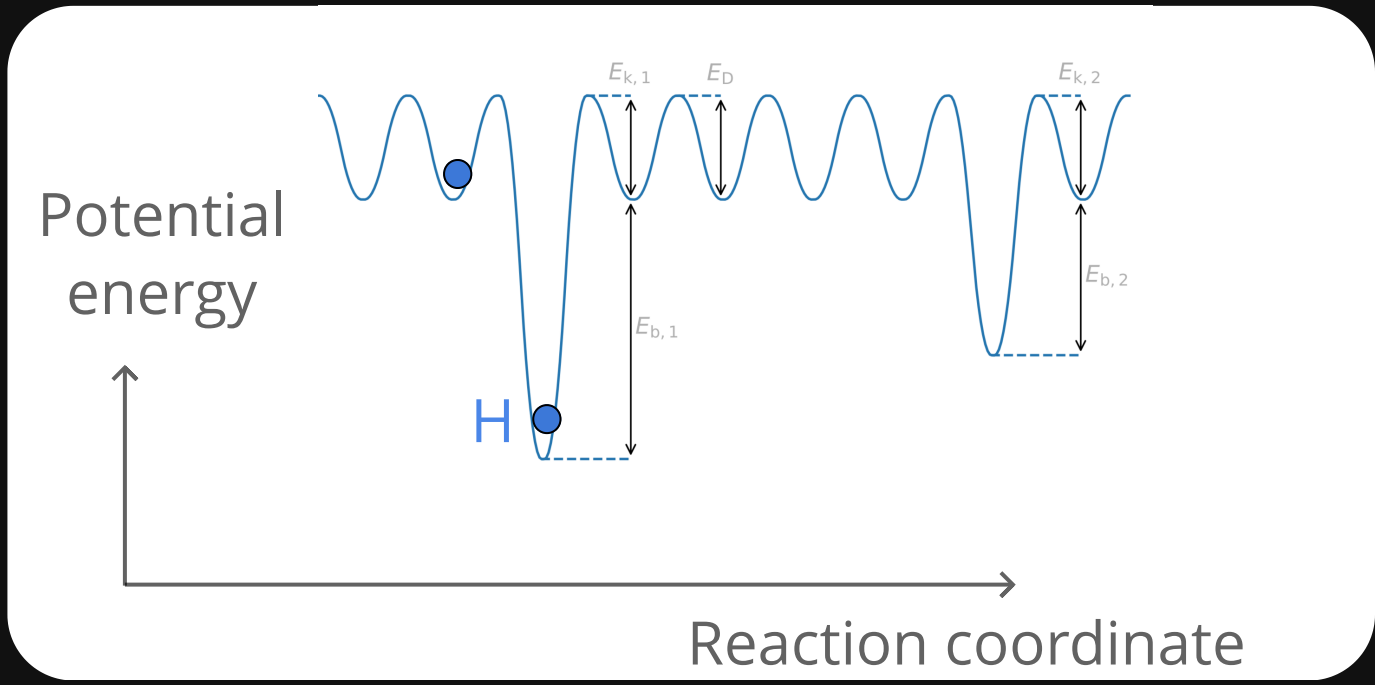


Material tritium science

Hydrogen transport theory





$$\frac{\partial c_{\mathrm{m}}}{\partial t} = \nabla \cdot (D \nabla c_{\mathrm{m}}) + S - \sum \frac{\partial c_{\mathrm{t,i}}}{\partial t}$$

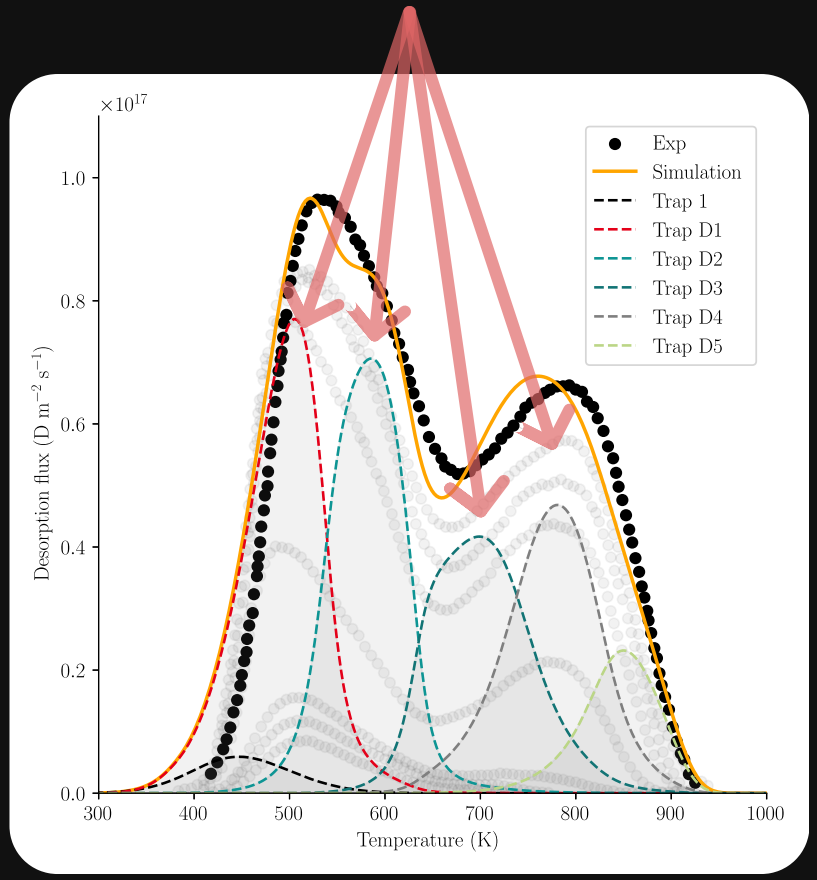
$$\frac{\partial c_{\mathrm{t,i}}}{\partial t} = k_i \, c_{\mathrm{m}} \left(n_{\mathrm{trap,i}} - c_{\mathrm{t,i}} \right) - p_i c_{\mathrm{t,i}}$$

McNabb & Foster model

(diffusion and trapping)

TDS is used to determine trap properties

Different traps/defects



- James Dark *et al* 2024 *Nucl. Fusion* 64 086026
- Delaporte-Mathurin *et al* 2021 *NME* Volume 27, June 2021, 100984

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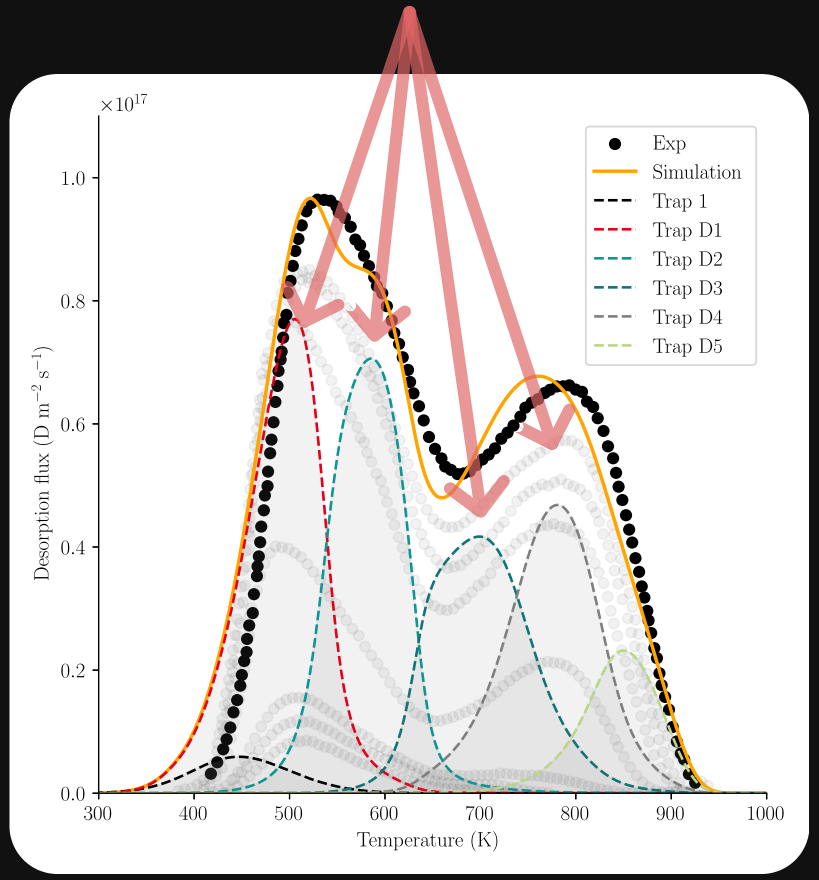
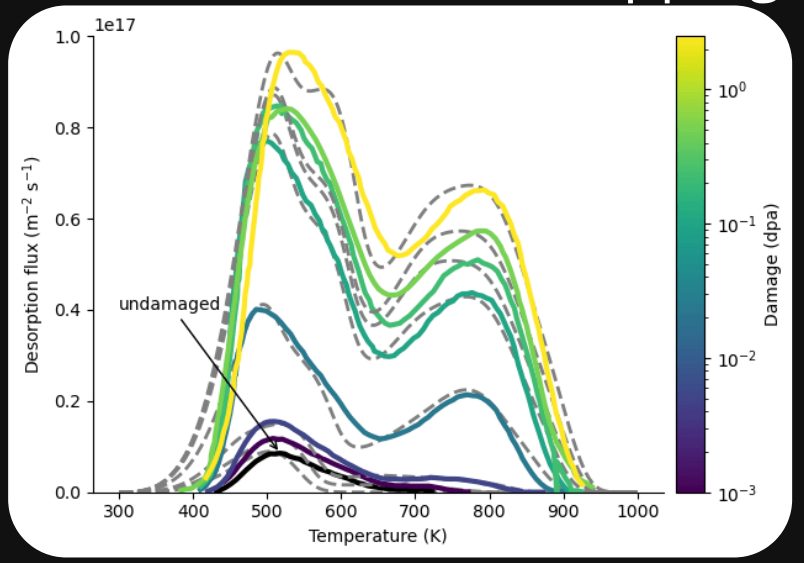


Studying the influence of neutron-induced trapping



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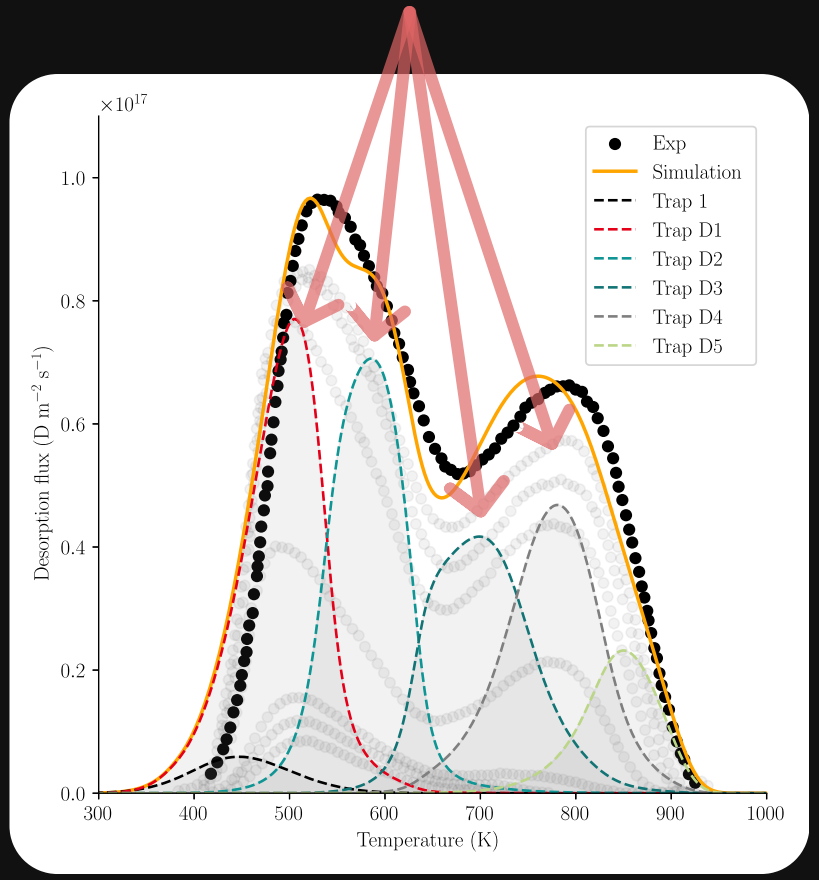

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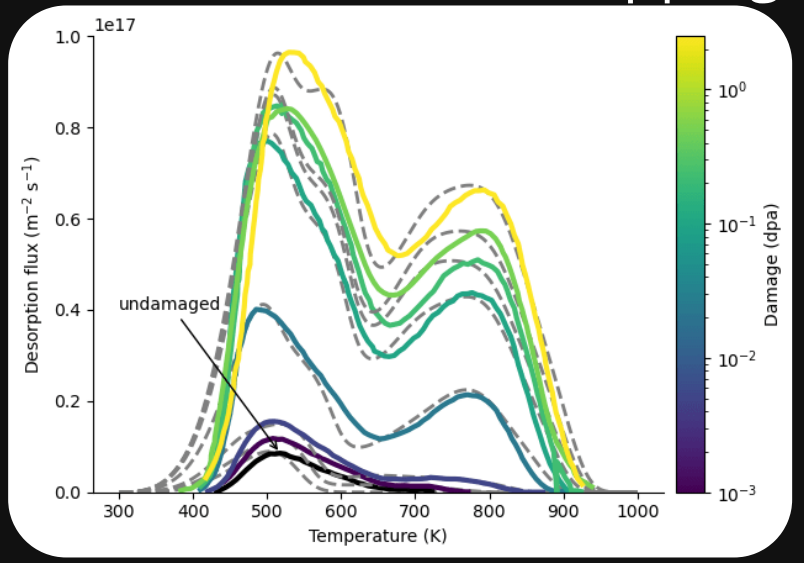
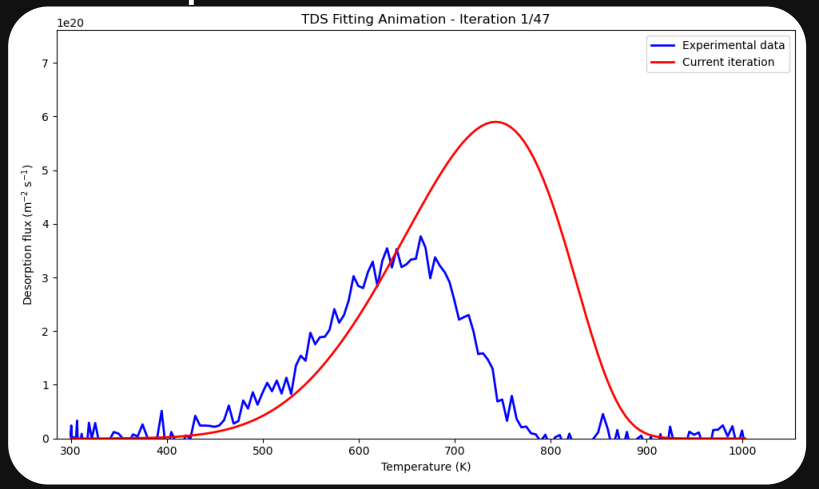


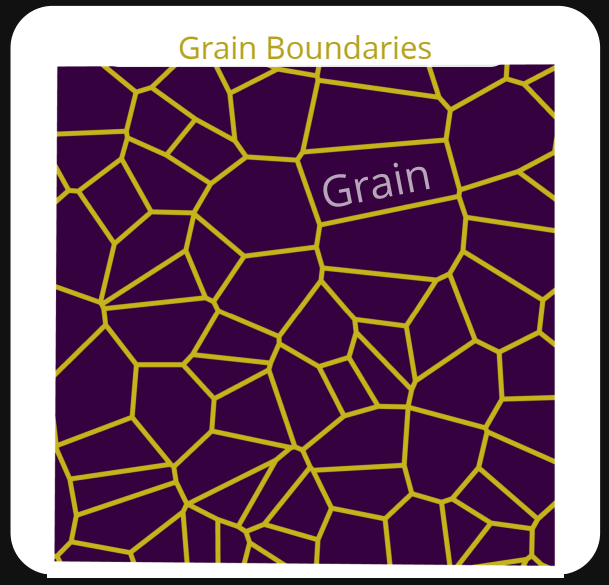
Integrated with parametric optimisation tools



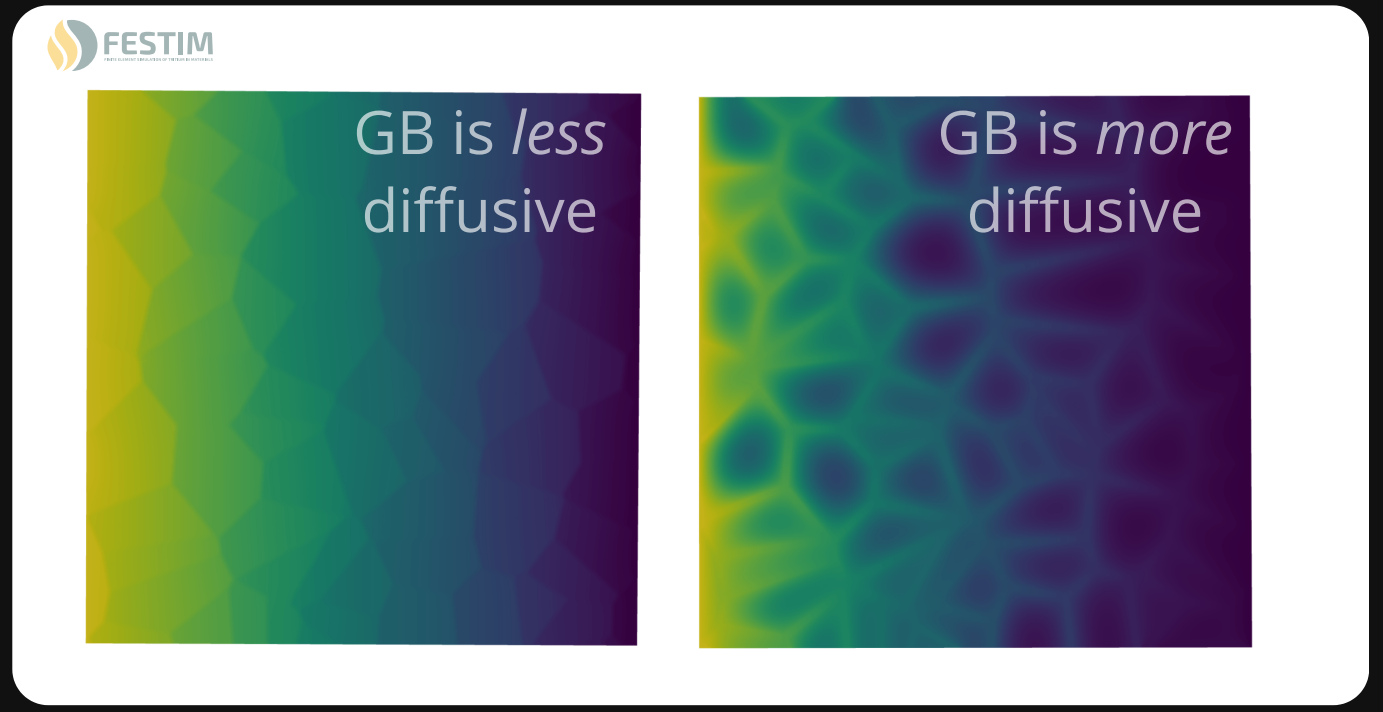
Does this qualify as Machine Learning?🤷

- James Dark *et al* 2024 *Nucl. Fusion* 64 086026
- Delaporte-Mathurin *et al* 2021 *NME* Volume 27, June 2021, 100984

Hydrogen transport through microstructures

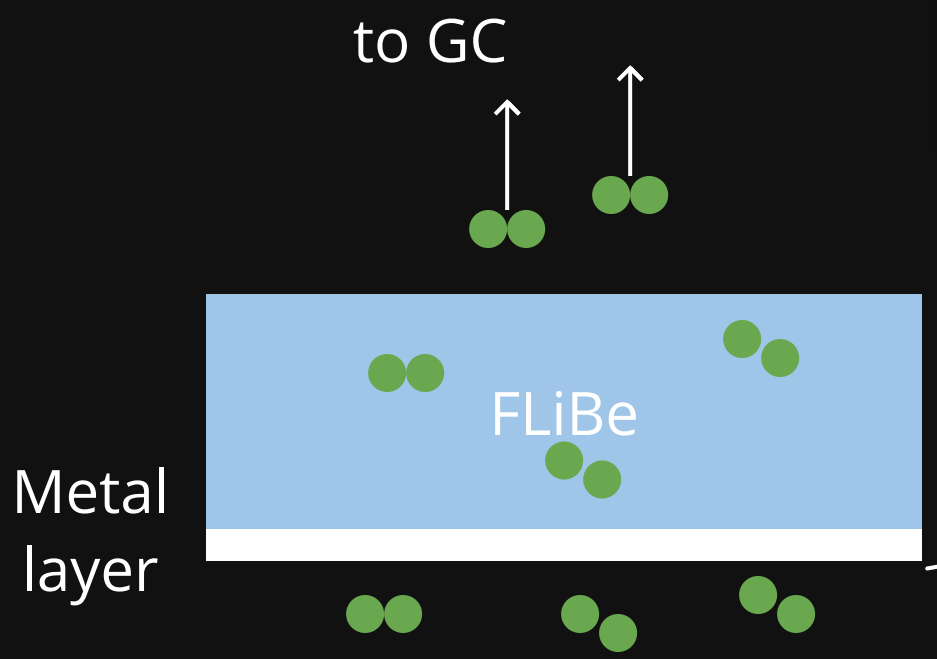


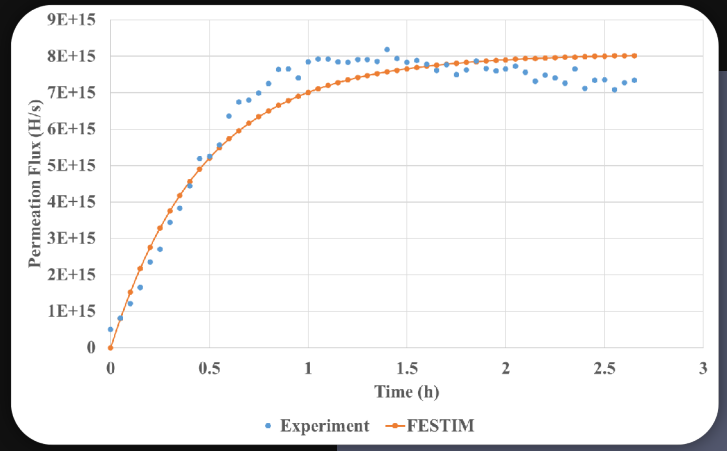
Representative Volume Element (RVE)

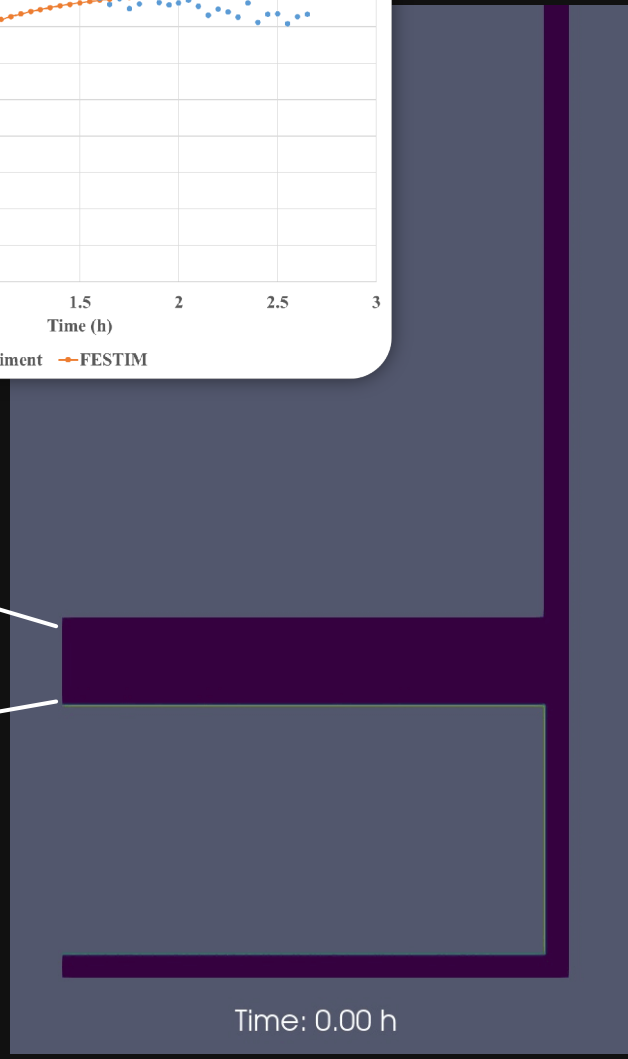


- Impact of GB width?
- Can be used to derive anisotropic diffusivity
- Tutorial available online

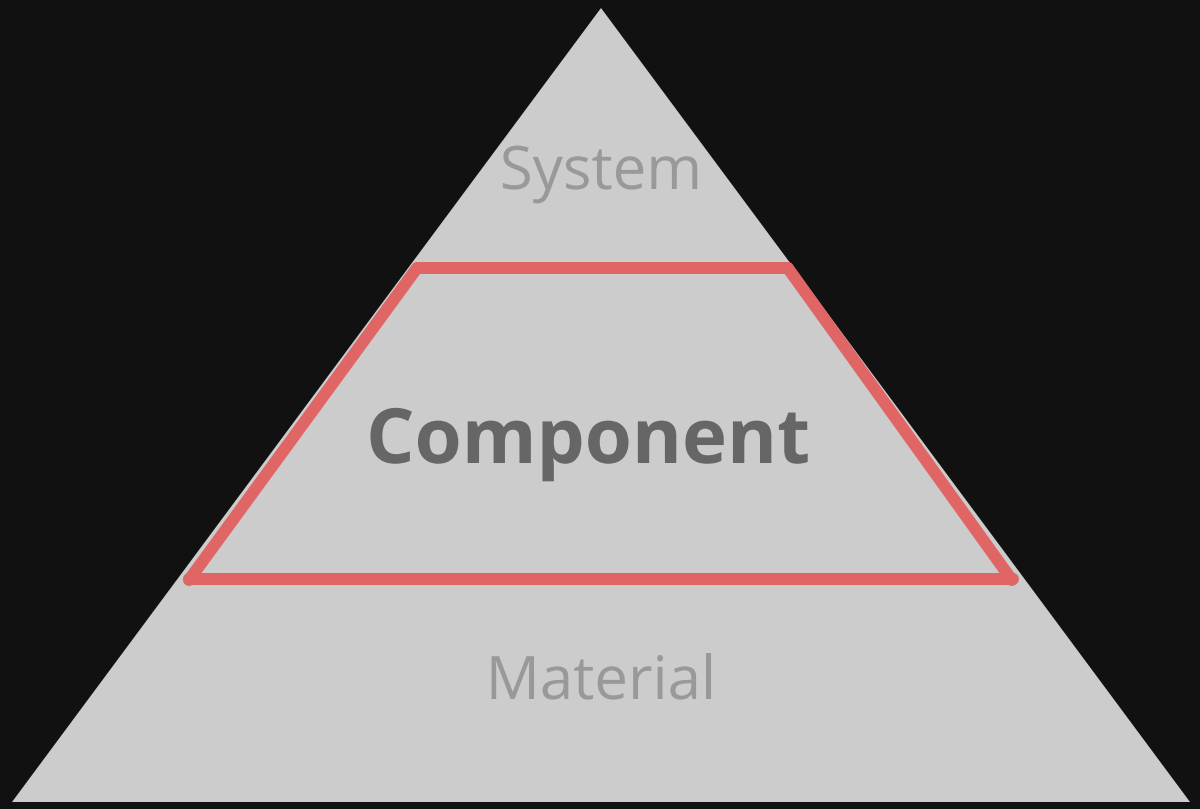
HYPERION: hydrogen permeation through liquids





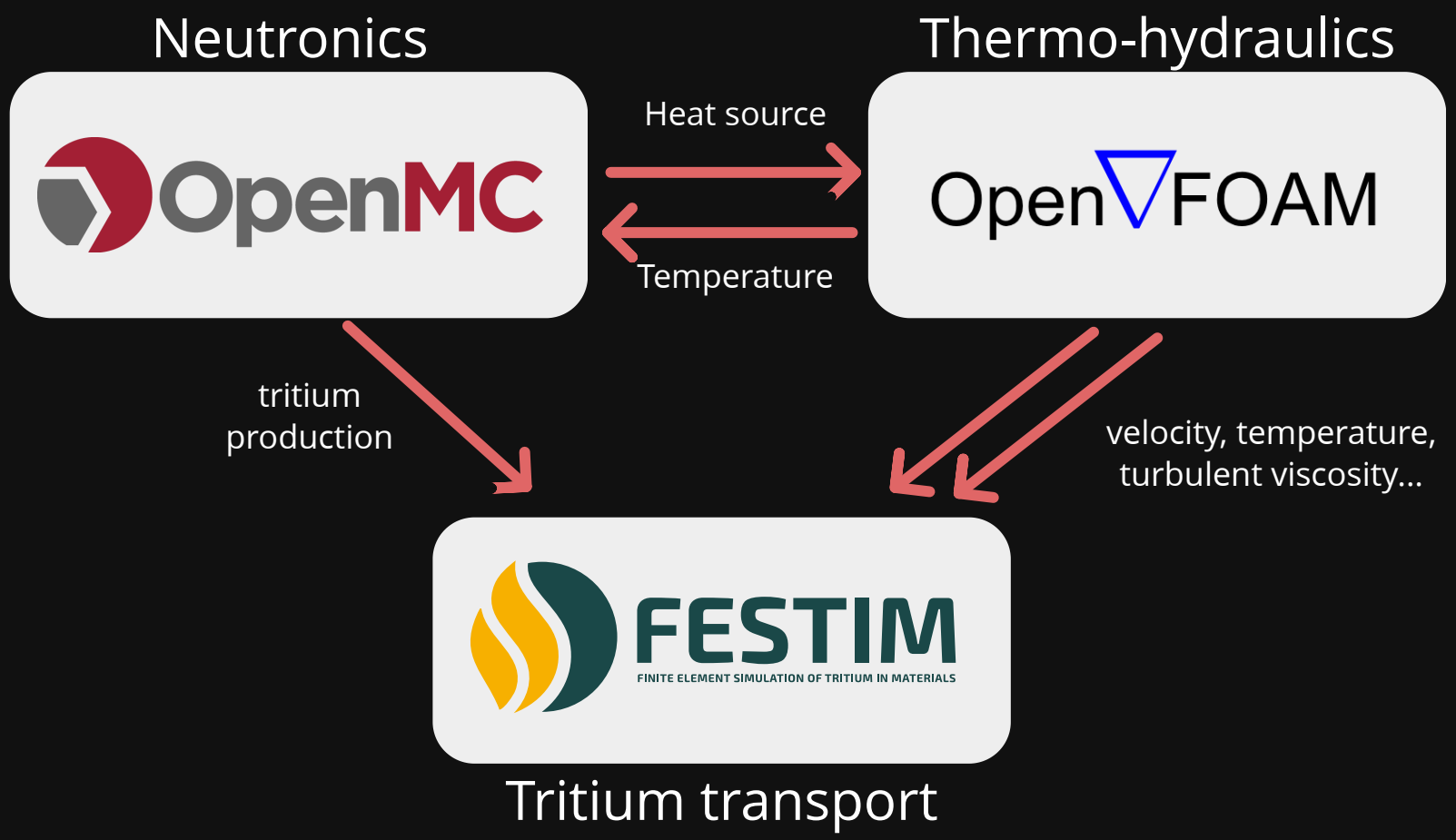


See Huihua Yang's talk: Validation of FESTIM Hydrogen Transport Modeling in FLiBe Through HYPERION Permeation Data

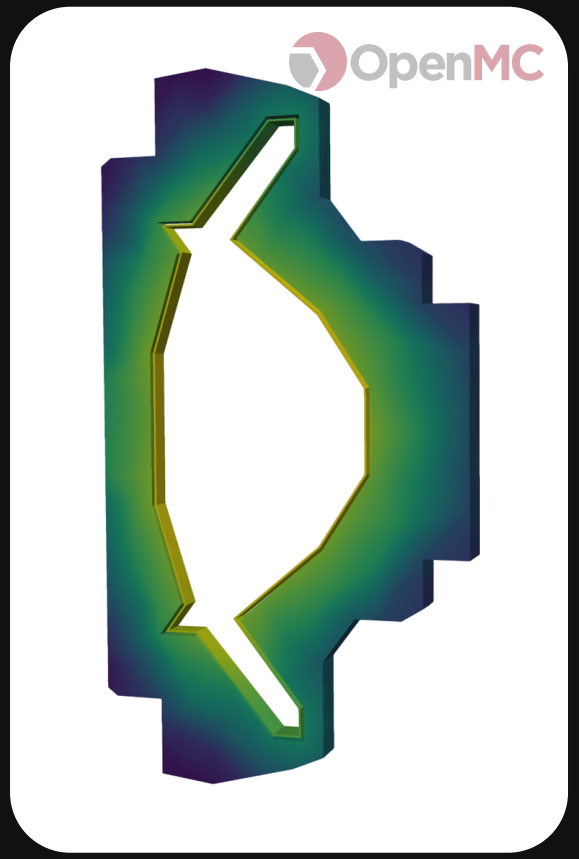


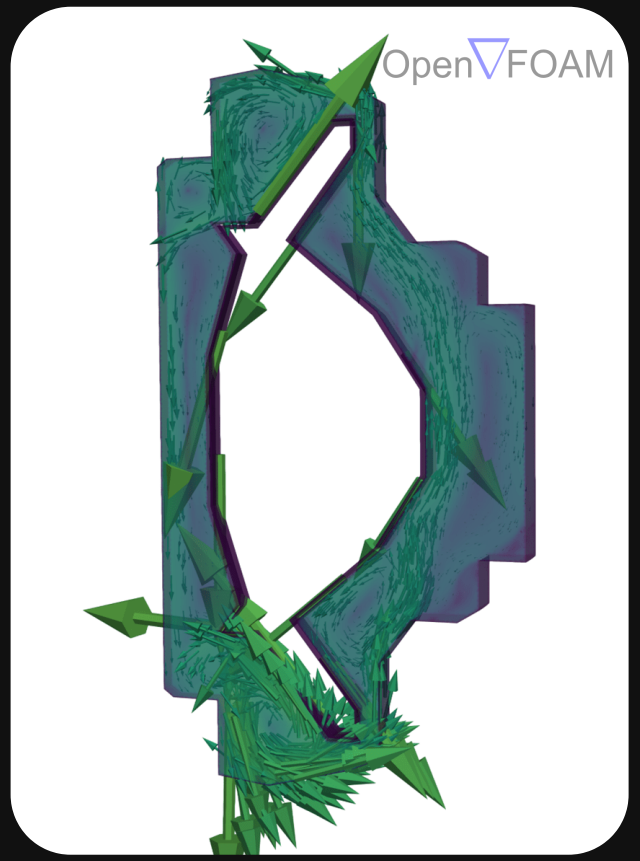
Component design

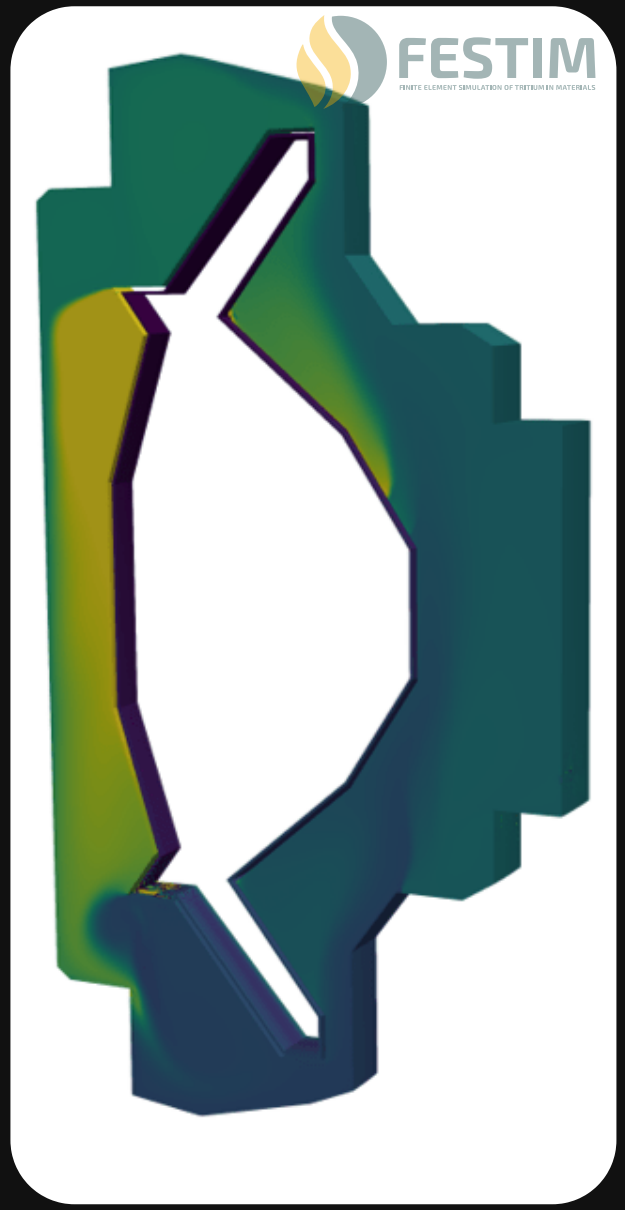
The multiphysics approach of FESTIM



Tritium transport modelling of the ARC Liquid Immersion Blanket



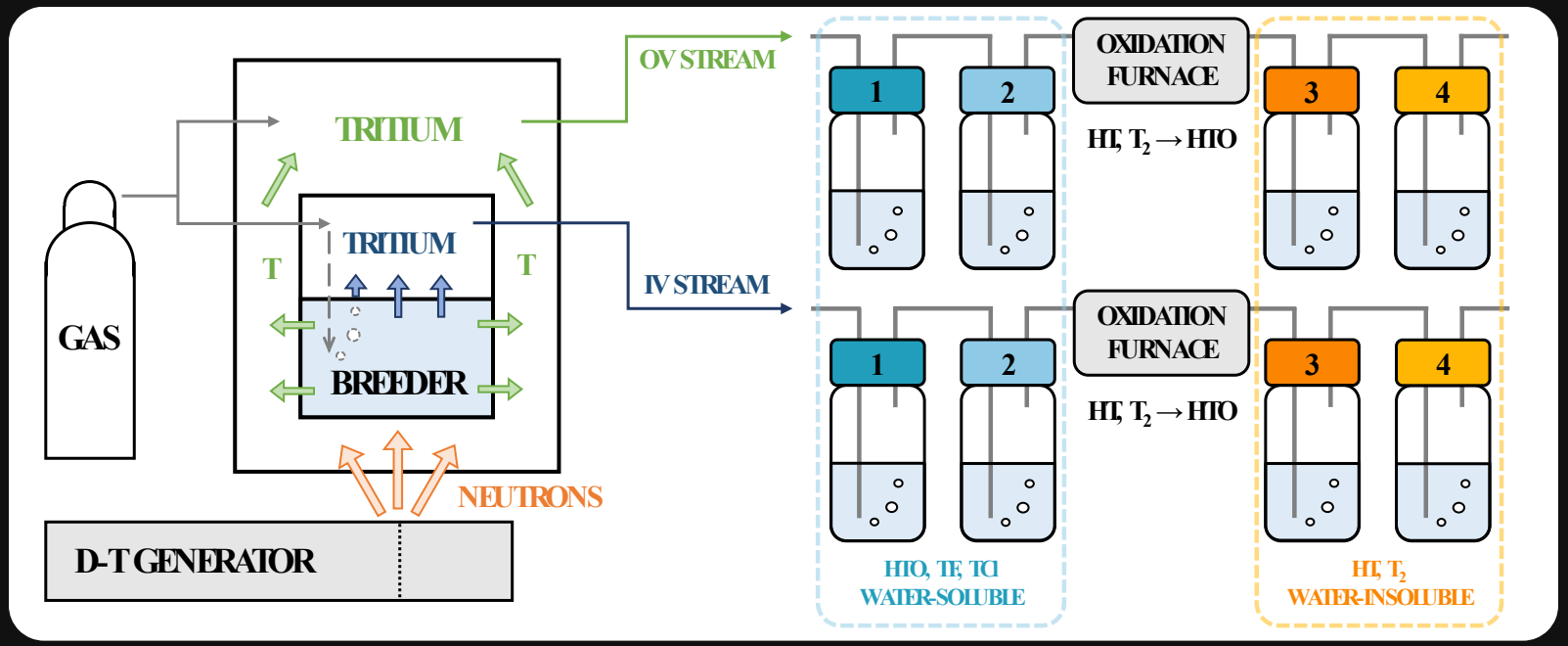




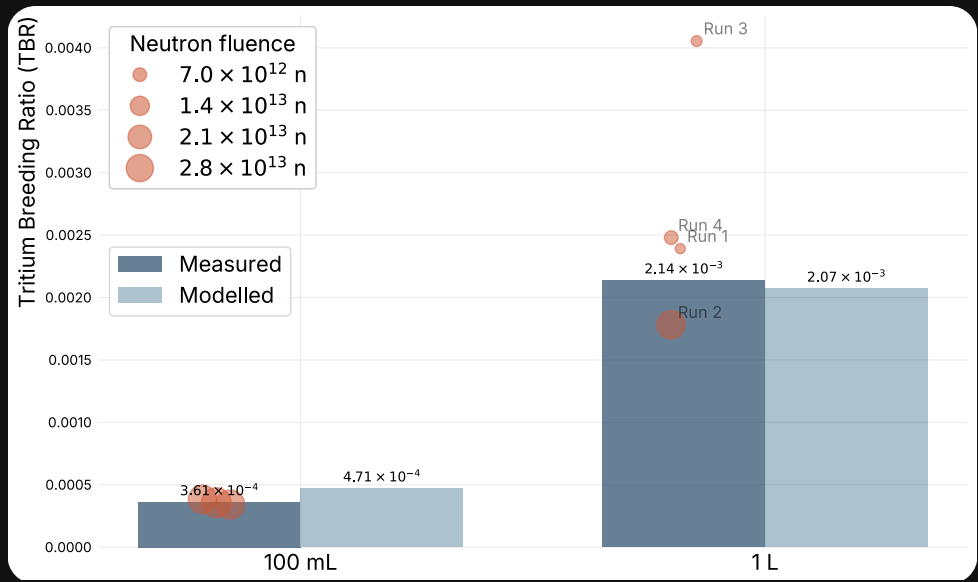
See James Dark's talk: Multi-physics tritium transport modelling of the ARC breeding blanket with FESTIM

Dark *et al*, Tritium 2025,
10.13140/RG.2.2.28729.84321

LIBRA: derisking breeding blankets



- TBR *measurement* and neutronics
- Tritium speciation
- Extraction dynamics
- Tritium permeation

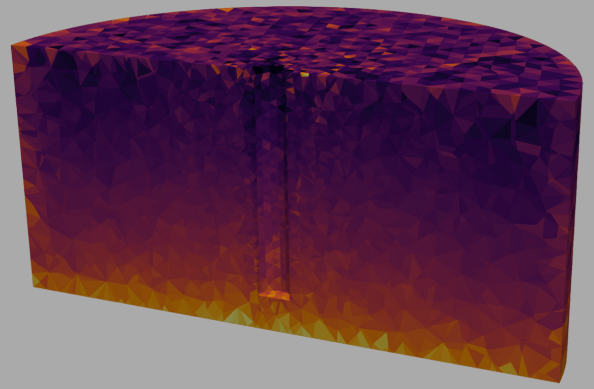


Rémi Delaporte-Mathurin *et al* 2025 *Nucl. Fusion* 65 026037
Rémi Delaporte-Mathurin *et al* "BABY 1L: First Tritium Breeding Campaign Results." *arXiv preprint arXiv:2509.26174* (2025).

LIBRA produces validation data for multiphysics models

Tritium production

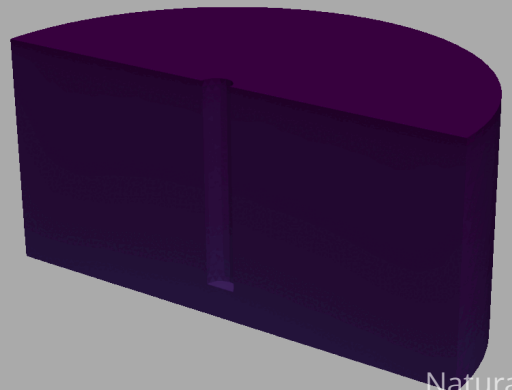
OpenMC



[T/n/cm3]

Tritium concentration

FESTIM



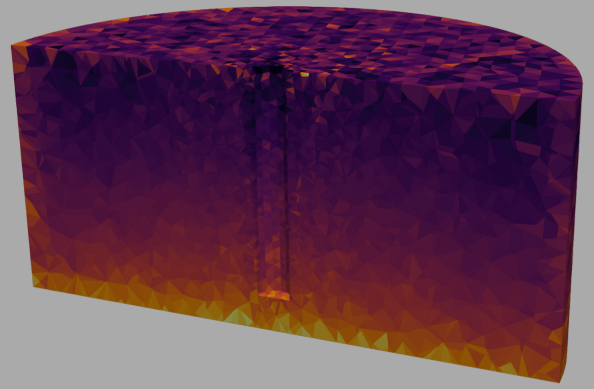
Max conc. 1.4E13 T/m3

Natural convection neglected

LIBRA produces validation data for multiphysics models

Tritium production

OpenMC



[T/n/cm3]

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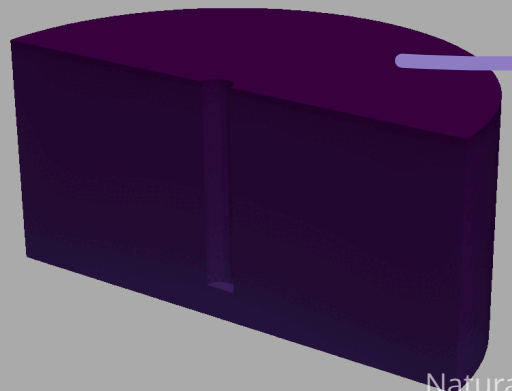

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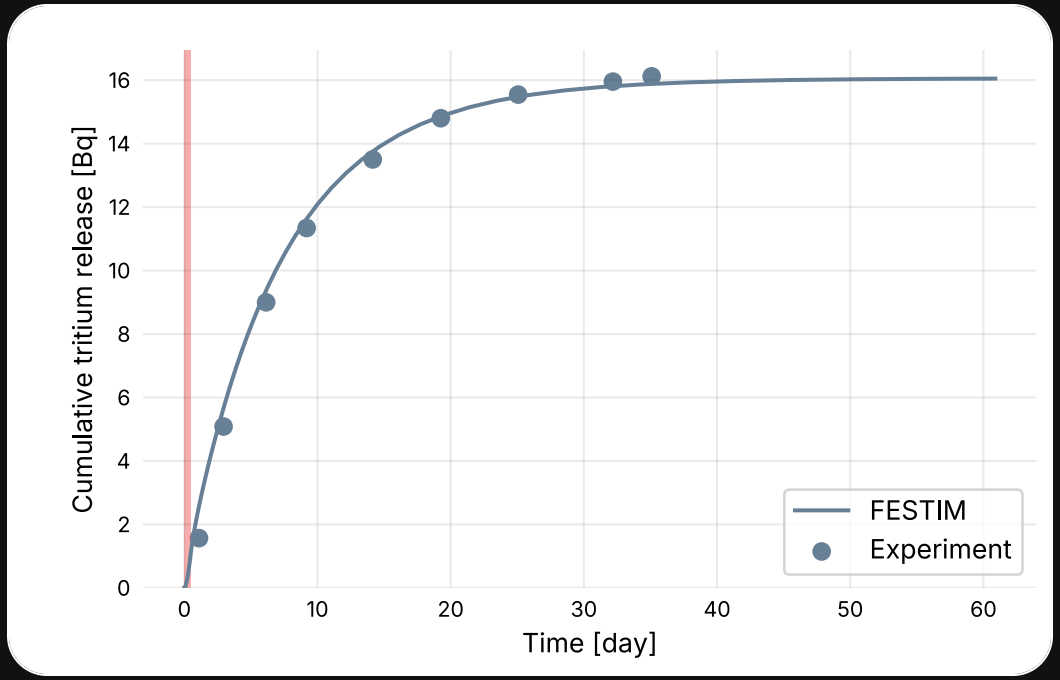
Natural convection neglected

Outgassing flux



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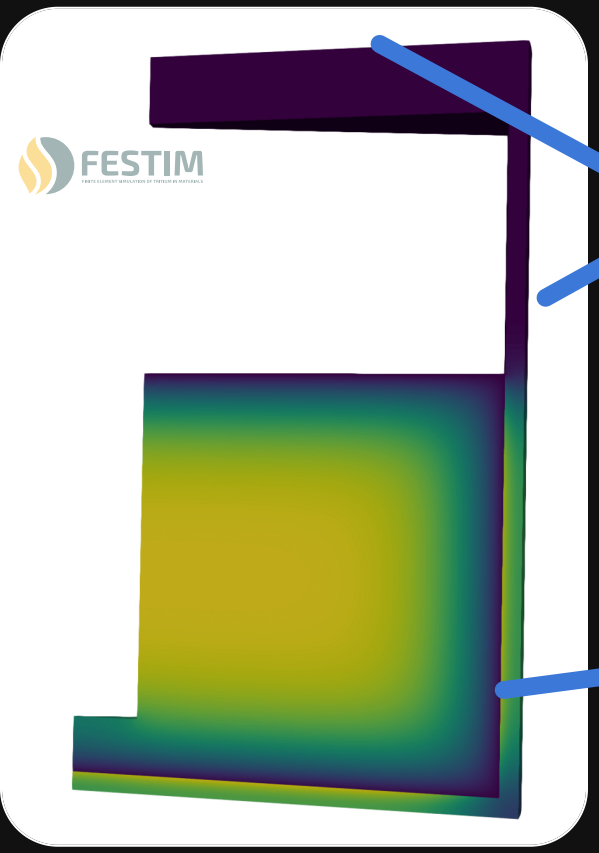


Surface recombination

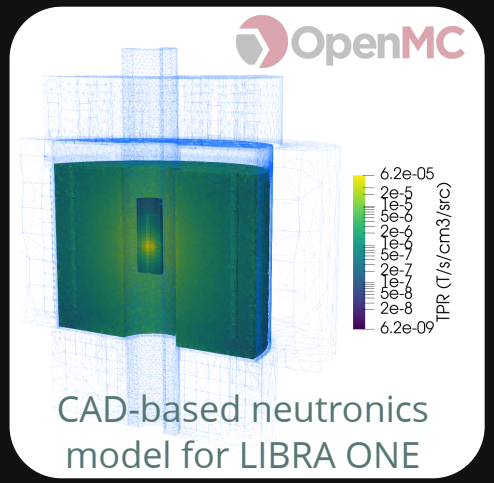
$$\mathrm{H_2} + \mathrm{T(ad)} \rightleftarrows \mathrm{HT} + \mathrm{H(ad)}$$

$$2\mathrm{T(ad)} \rightleftarrows \mathrm{T_2}$$

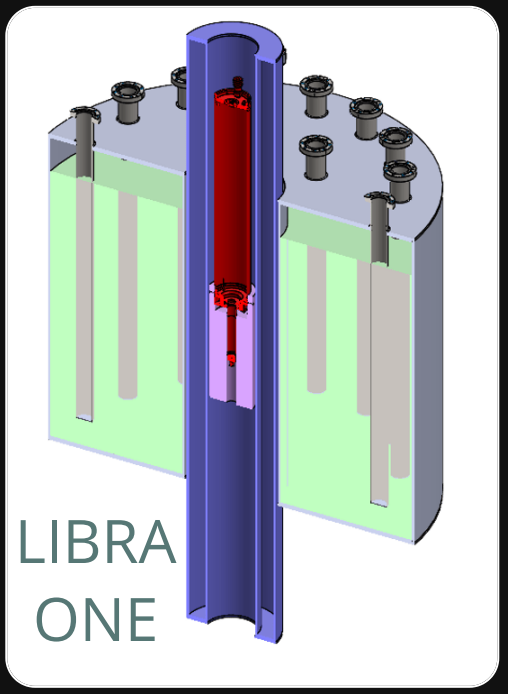
$$\varphi = K_r\, c_T^2 + K_r'\, c_T\, P_{\mathrm{H_2}}$$

Interface discontinuity

$$\frac{c^-}{K_H} = \left(\frac{c^+}{K_S}\right)^2$$



CAD-based neutronics model for LIBRA ONE



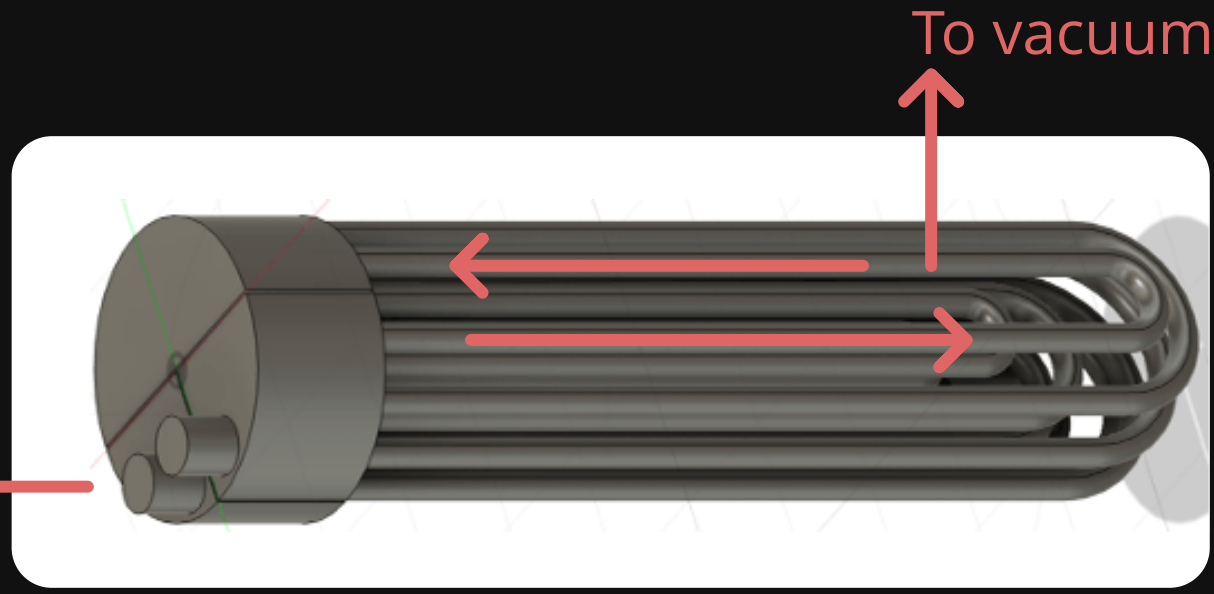
Next step: include sparging modelling for tritium extraction

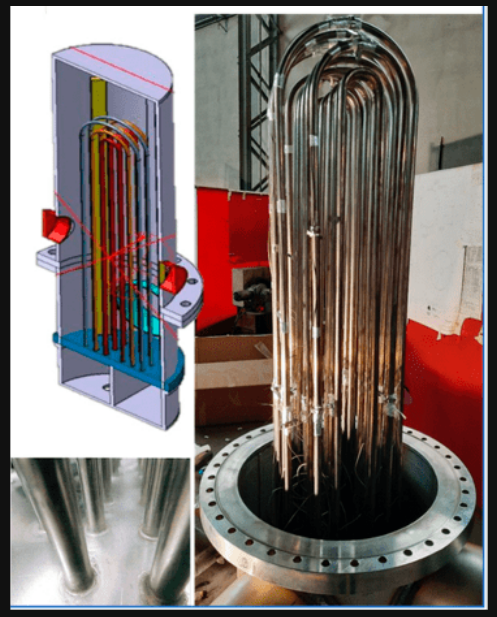
See Stefano Segantin's poster: Digital Engineering for Fusion: Uncertainty Quantification in Neutronics Modeling

Tritium extraction: Permeation Against Vacuum

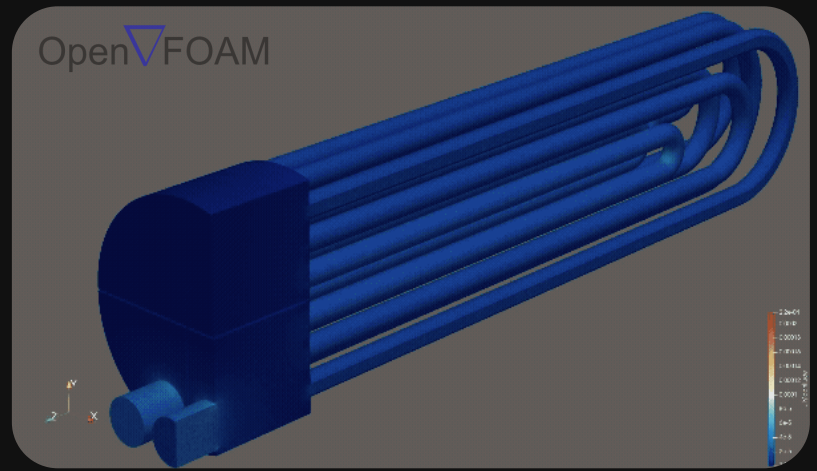
Goals:

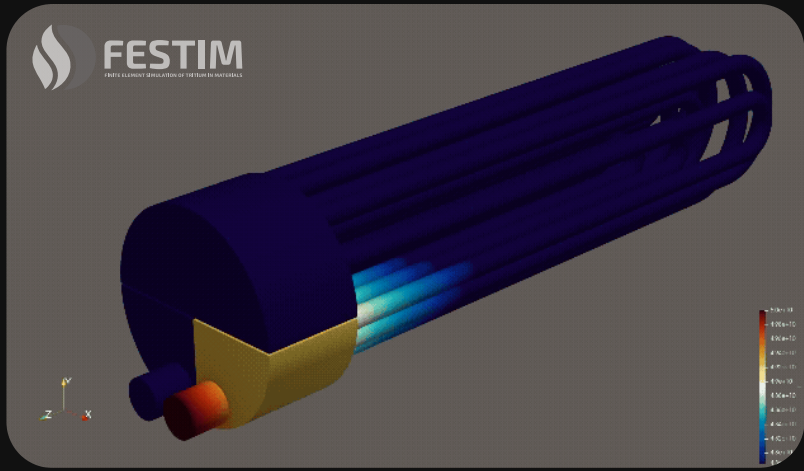
- Estimate extraction efficiency
- Inform and optimise design





Utili, Marco, et al. "Design and integration of the WCLL Tritium Extraction and Removal System into the European DEMO tokamak Reactor." *Energies* 16.13 (2023): 5231



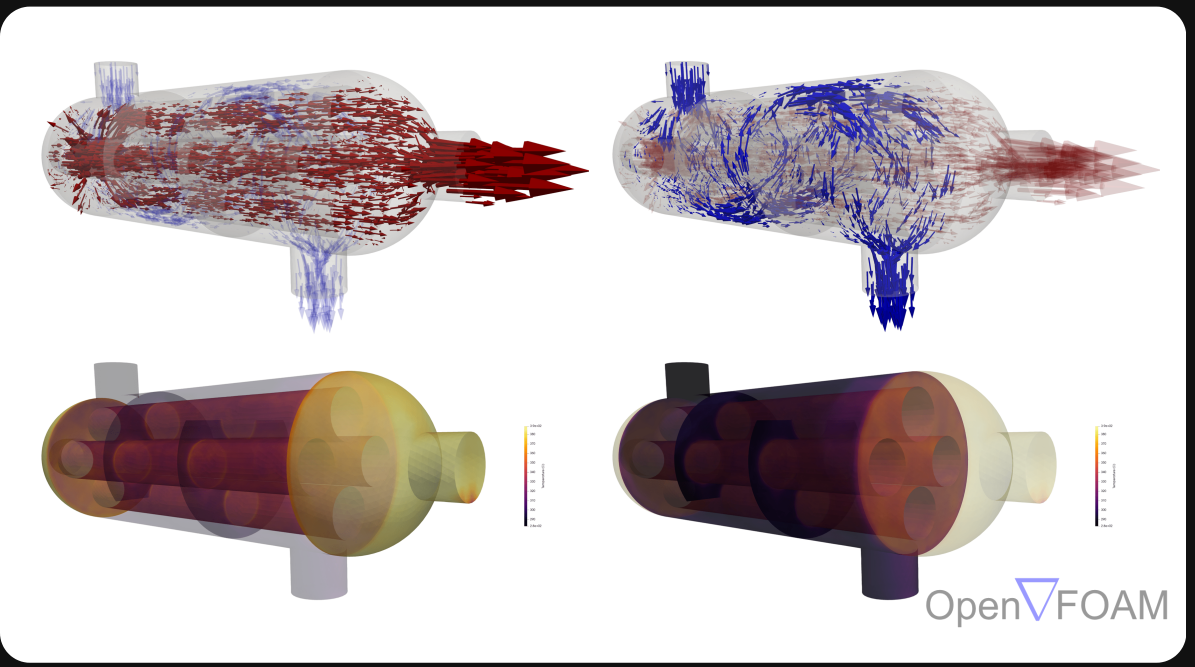


Students: Chirag Khurana, Kaelyn Dunnell

Tritium contamination in Heat Exchangers

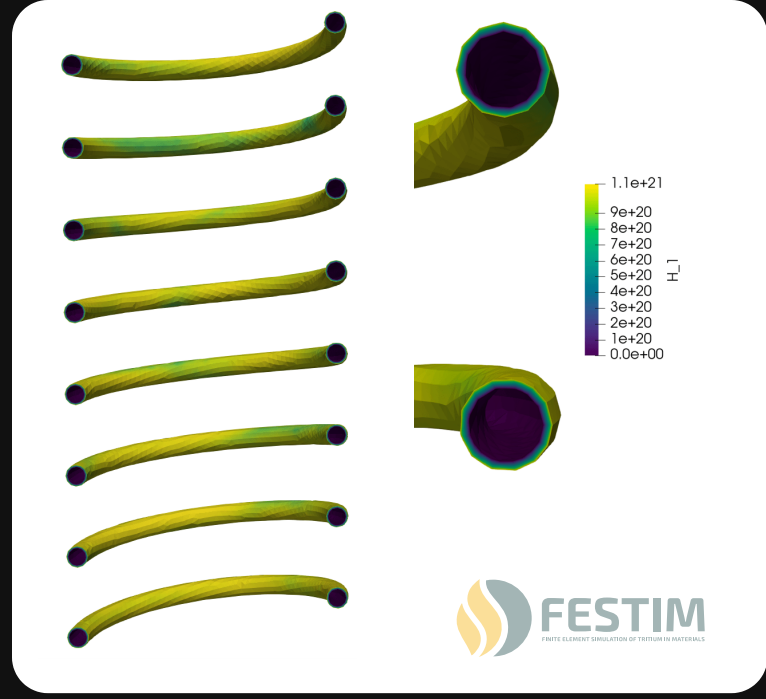
Goals:

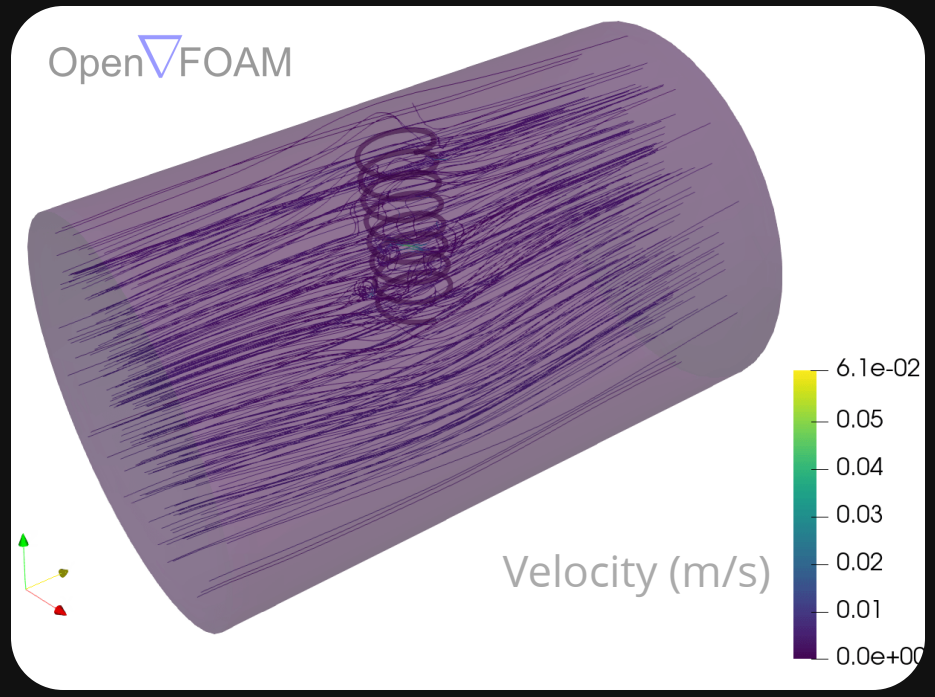
- Estimate tritium contamination to secondary coolant
- Inform and optimise design

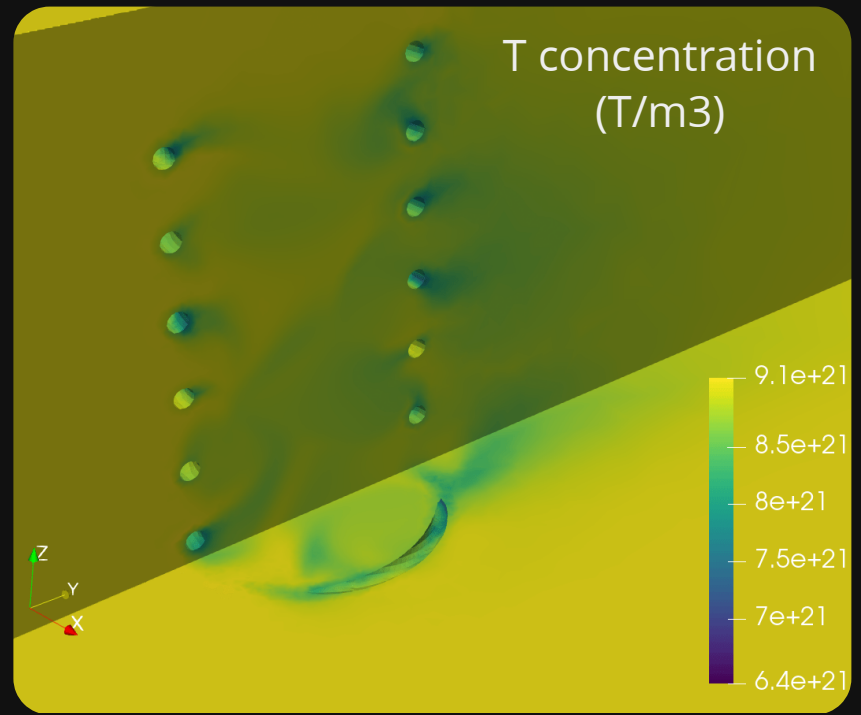


Students: Chirag Khurana, Kaelyn Dunnell

Designing permeation probes for tritium detection

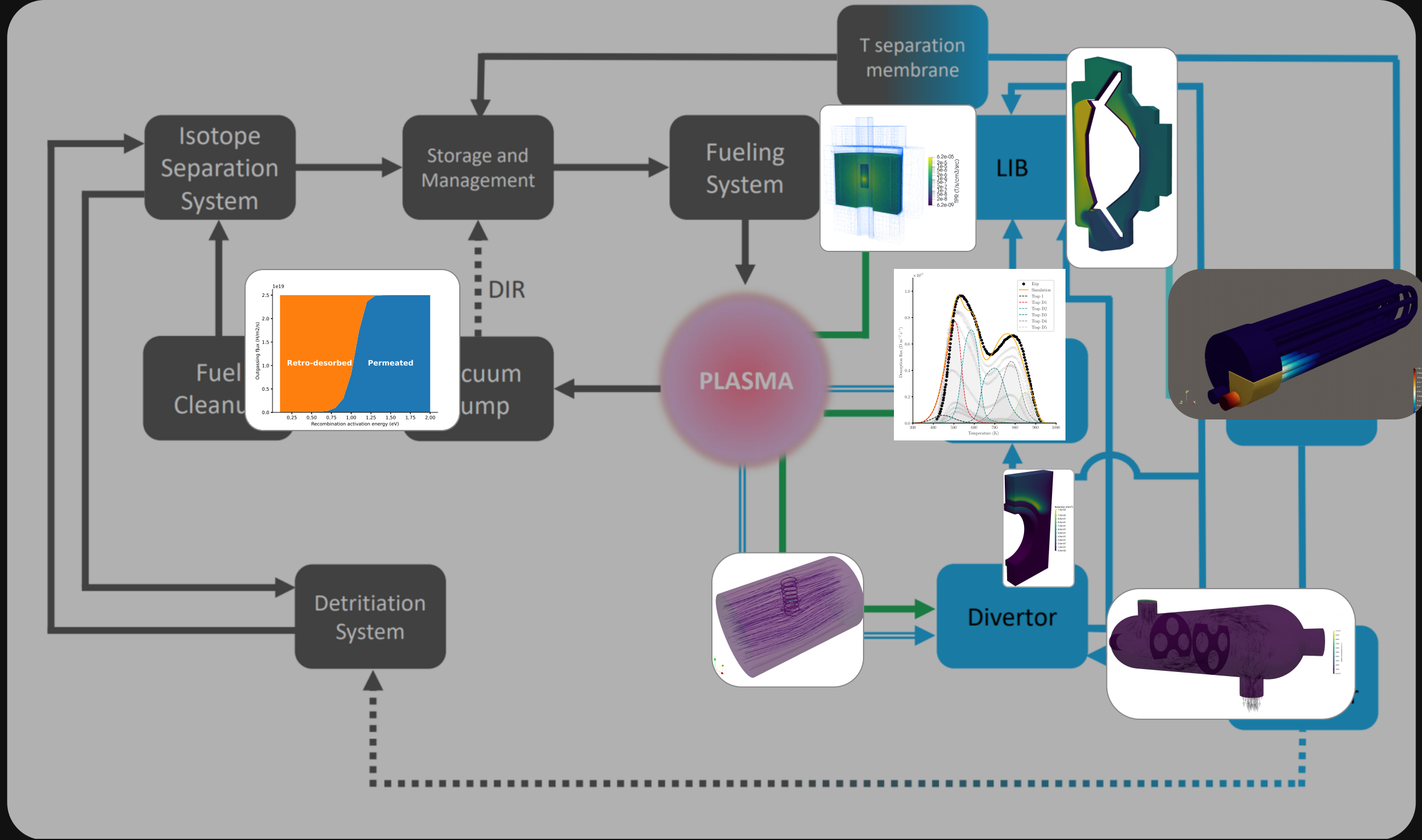


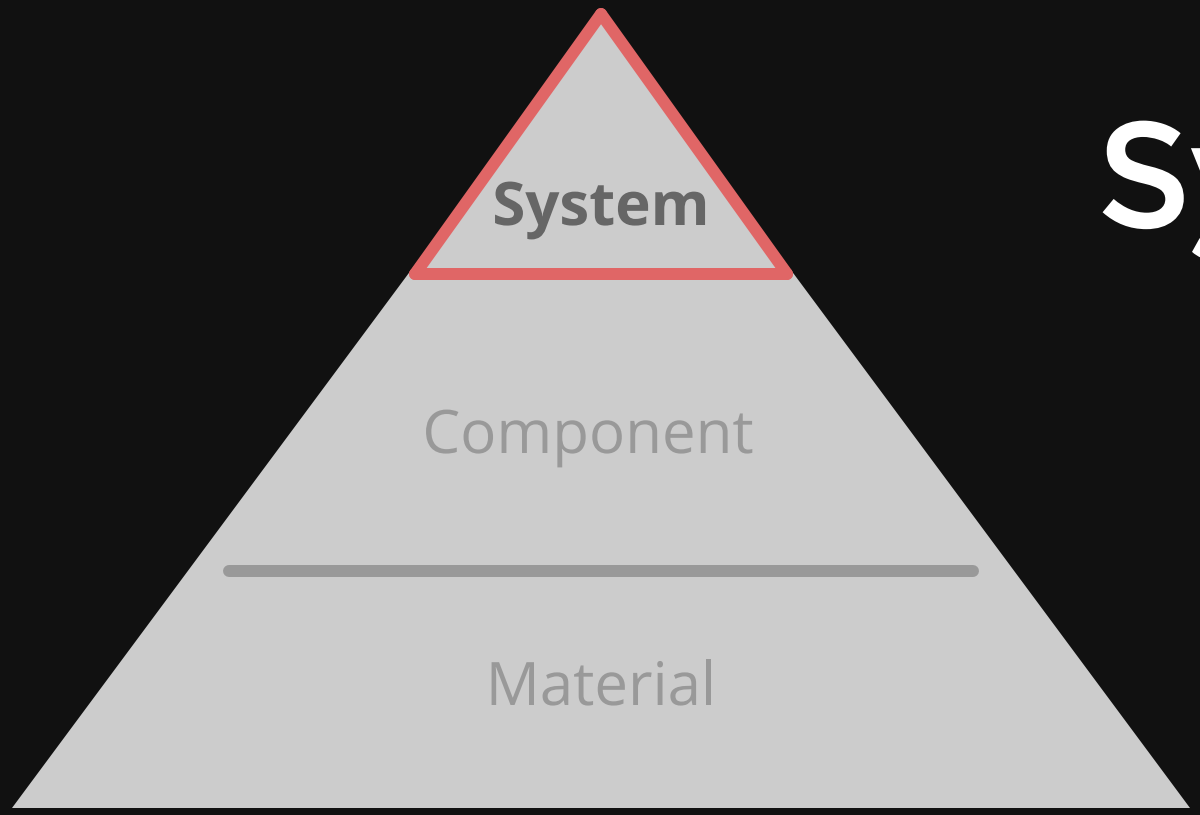




- 1D assumption may not be valid
- Can we optimise placement?
- Is the diffusion-limited assumption valid?
- Provide a behaviour law for tritium sensing

Student: Kaelyn Dunnell

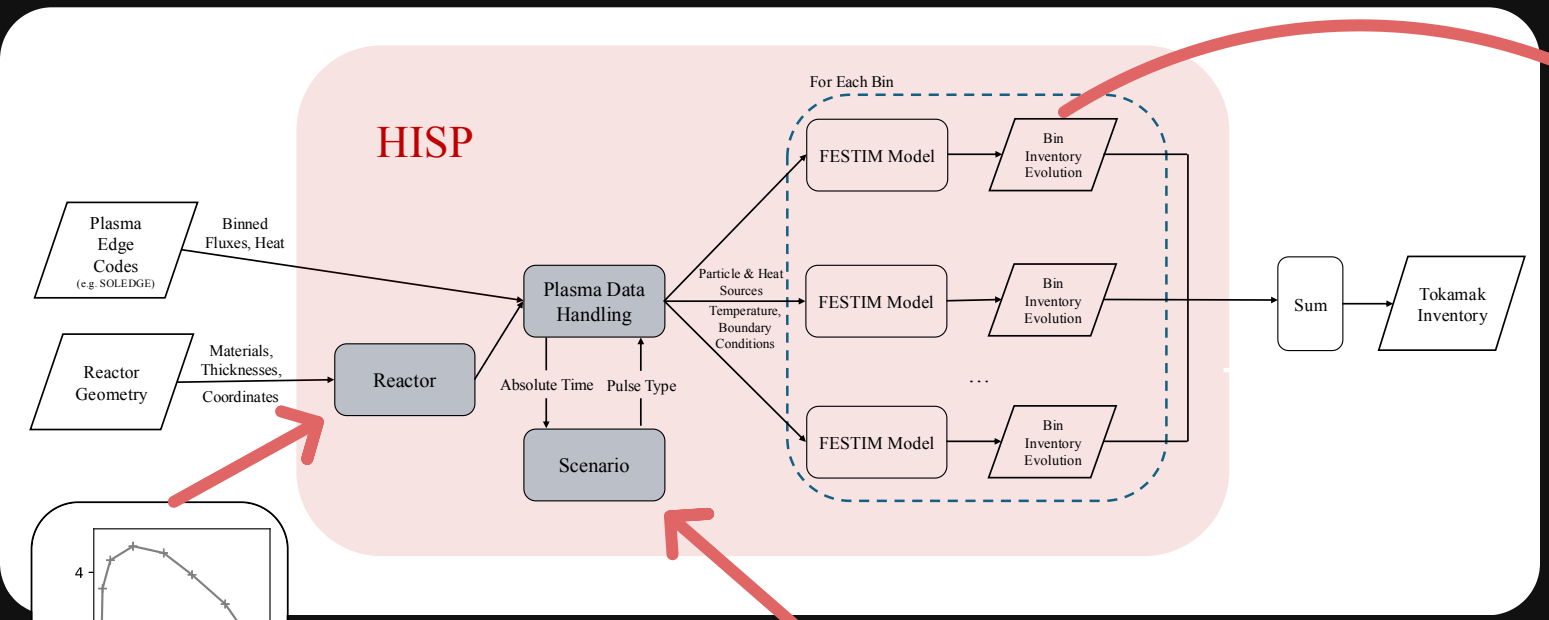

T separation membrane
Isotope Separation System
Storage and Management
Fueling System
LIB
DIR
Fuel Cleanu
cuum ump
PLASMA
Detritiation System
Divertor
Retro-desorbed
Permeated
Outgassing flux (H/m2/s)
Recombination activation energy (eV)
TPR (T/s/cm3/src)
Exp
Simulation
Trap 1
Trap D1
Trap D2
Trap D3
Trap D4
Trap D5
Temperature (K)

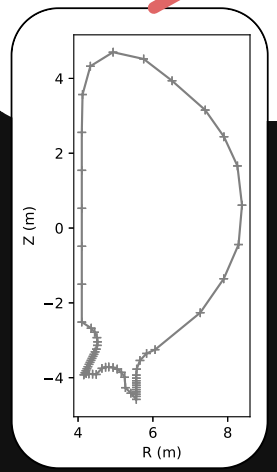


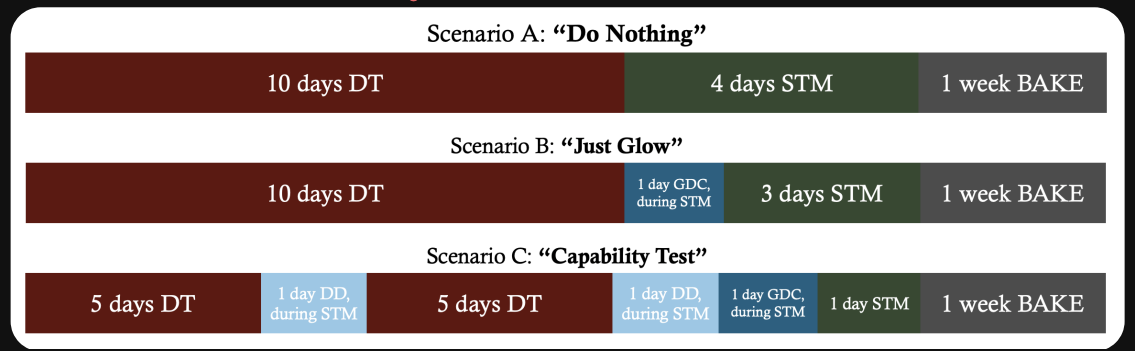
System analysis

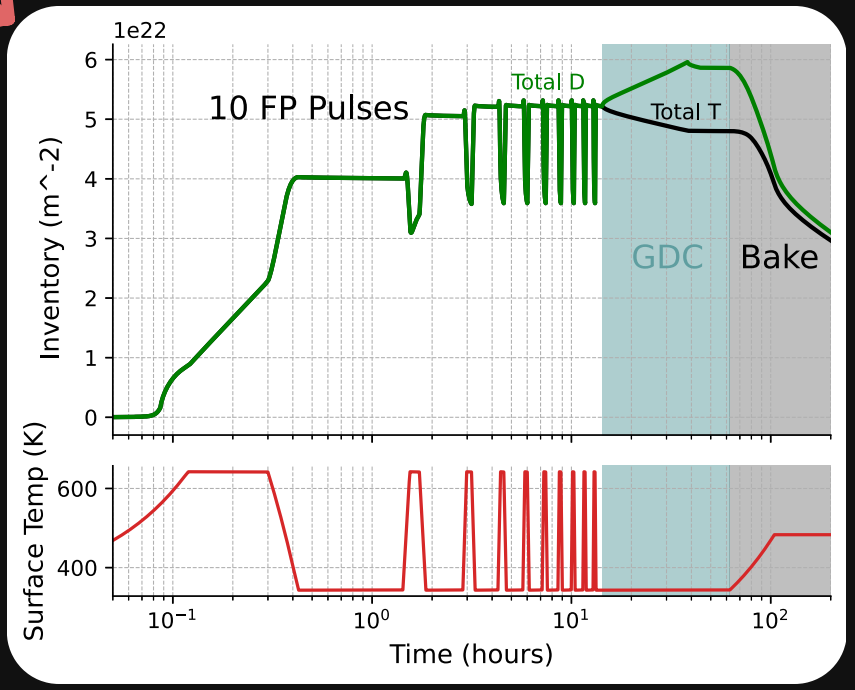
HISP couples plasma codes to FESTIM

Goal: find the best strategy for minimising ITER's tritium inventory









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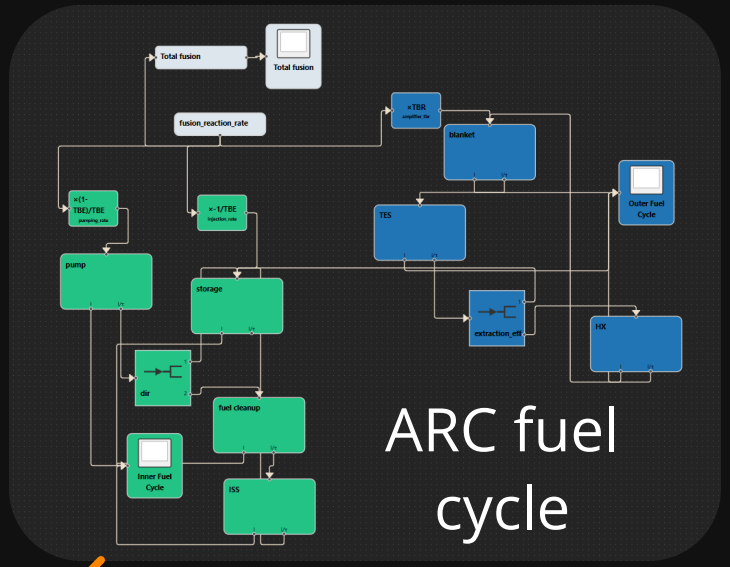
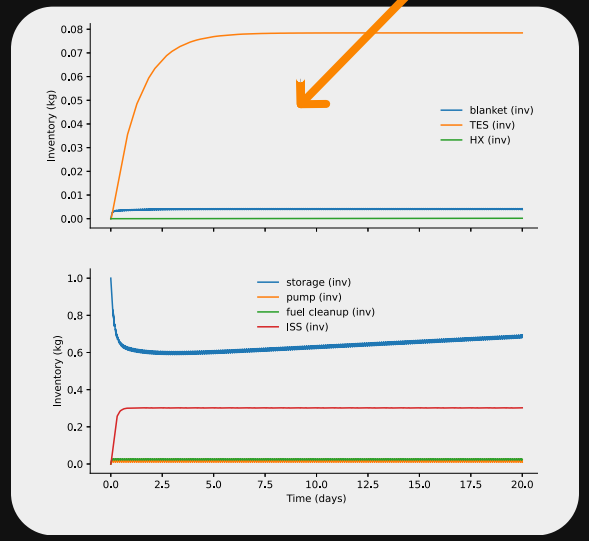
PathSim: an open-source system modelling tool

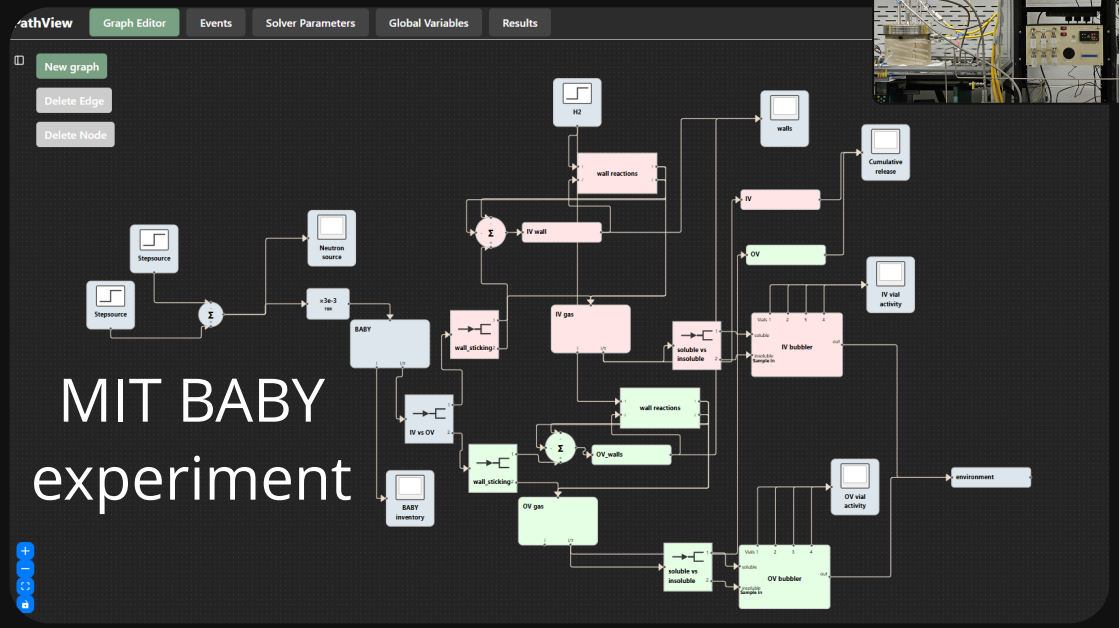


ARC fuel cycle

- PathView: open-source web-app for dynamic system modelling
- Already used for power plant modelling and LIBRA
- Seemless integration with FESTIM



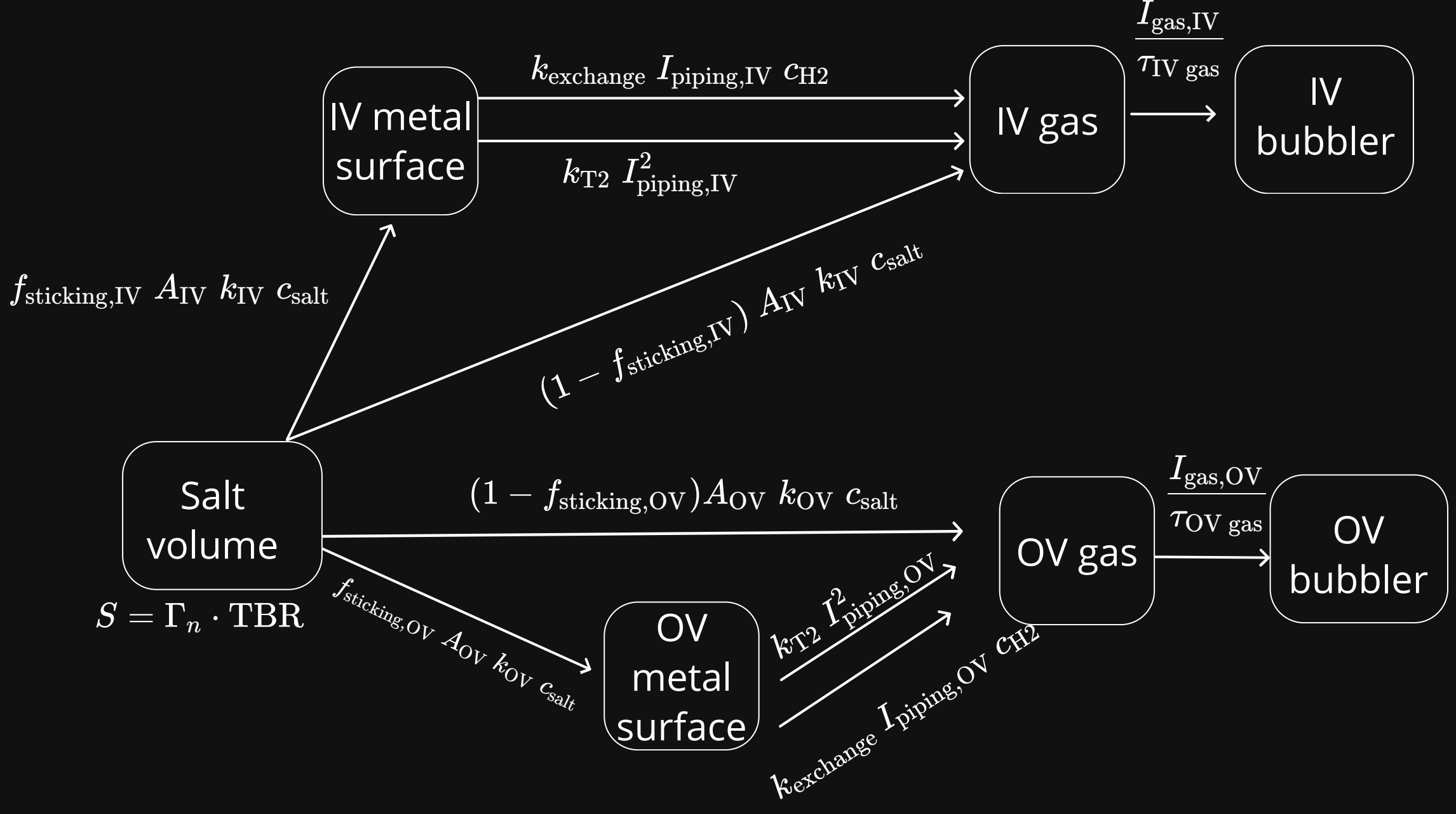
Tracking the tritium inventory in each fuel cycle component



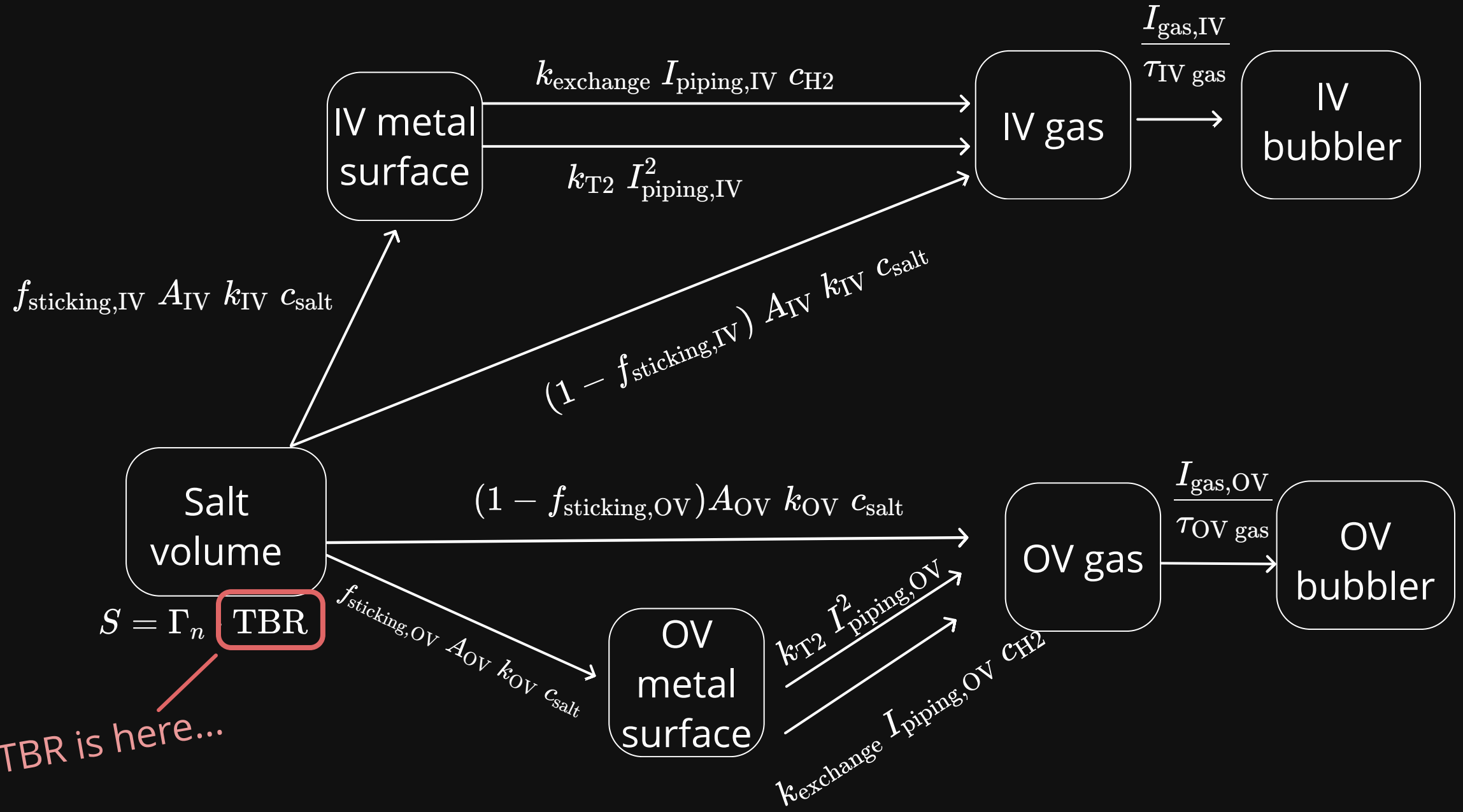
MIT BABY experiment

See Milan Rother's talk: PathSim: An Open-Source Python Framework for Digital Twin Applications in Fusion Fuel-Cycle Modeling

New tritium release model

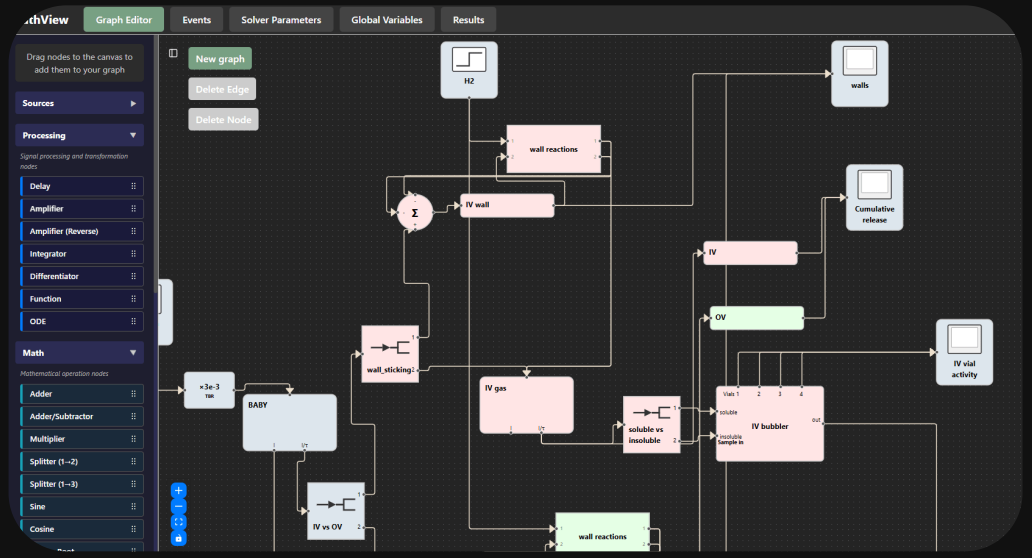


New tritium release model

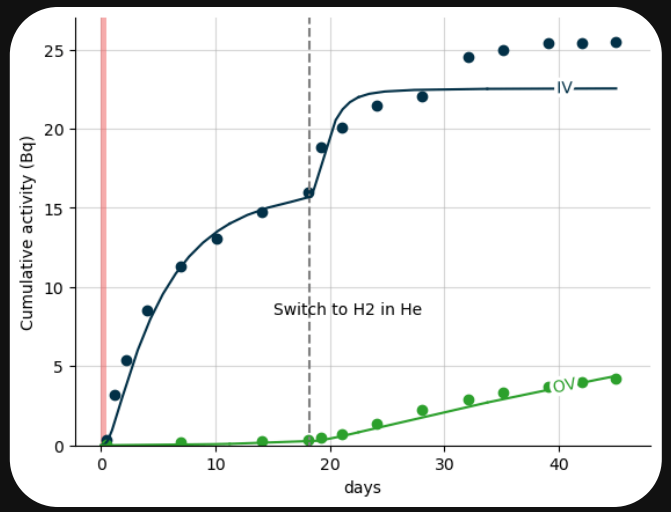


The new release model can capture the complex dynamics

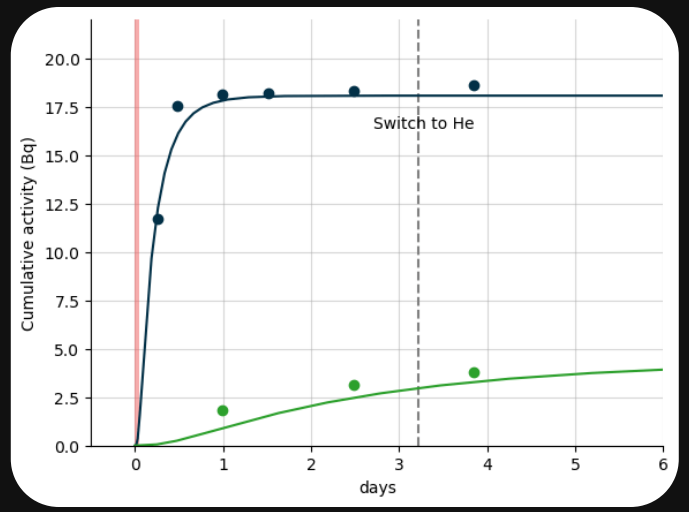
Implemented in PathView



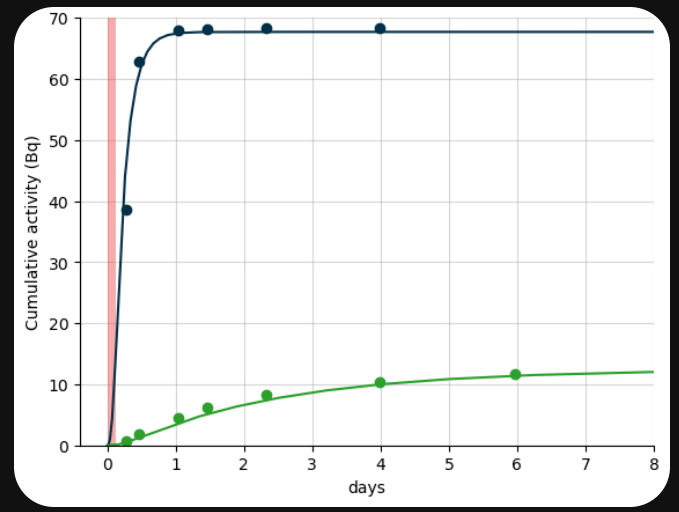
Run 3



Run 6



Run 12



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FESTIM

Tutorials

PathView

Thank you!
Any questions?

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OSSFE
10-12 March 2026
2nd edition
Munich, Germany

See you at the Open Source Software for Fusion Energy conference?