PERFORMANCE ASSESSMENT AND INTEGRATION OF DIFFERENT TRITIUM EXTRACTION TECHNOLOGIES IN THE OUTER FUEL CYCLE

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Introduction

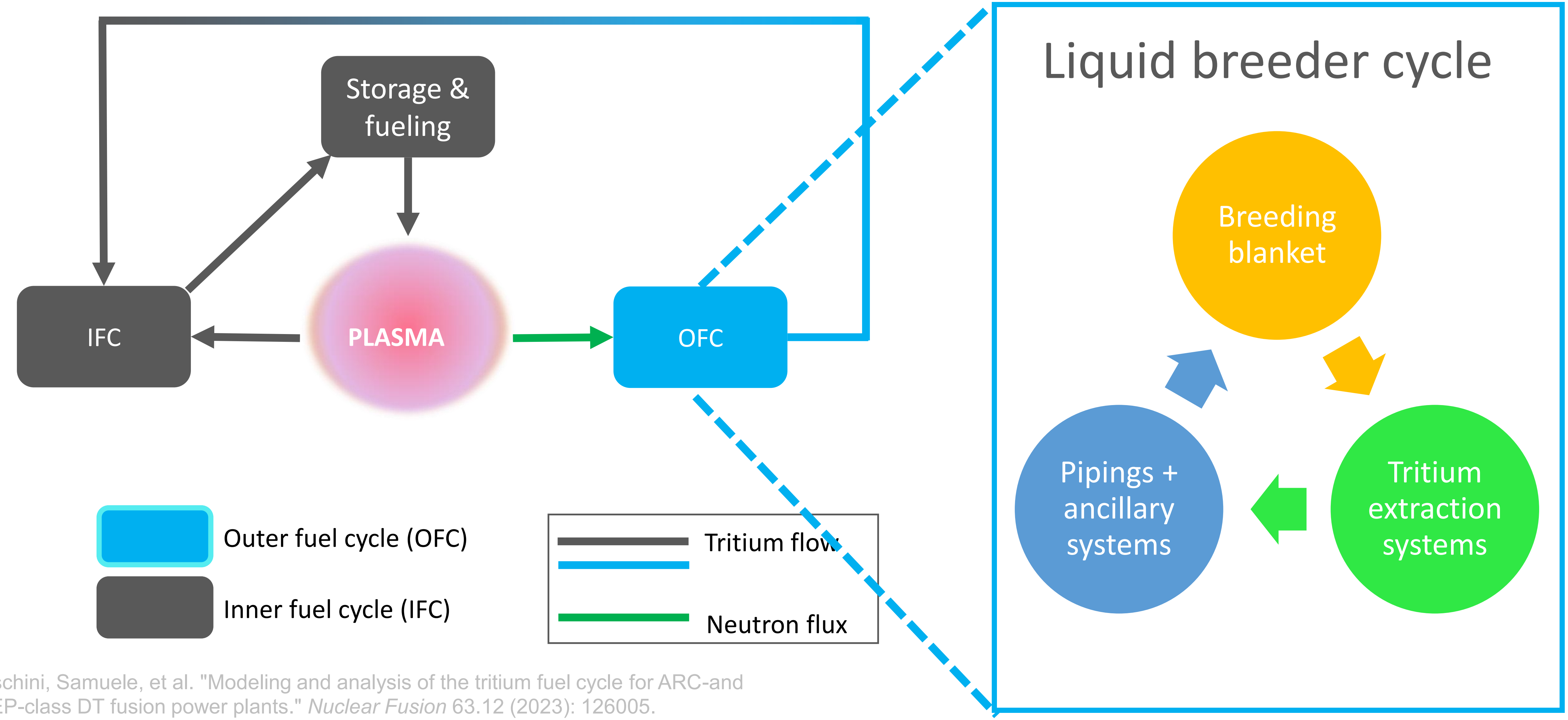
Main tritium extraction technologies

TRIOMA code for outer fuel cycle (OFC) analysis

Analysis of different configurations of OFC and insights

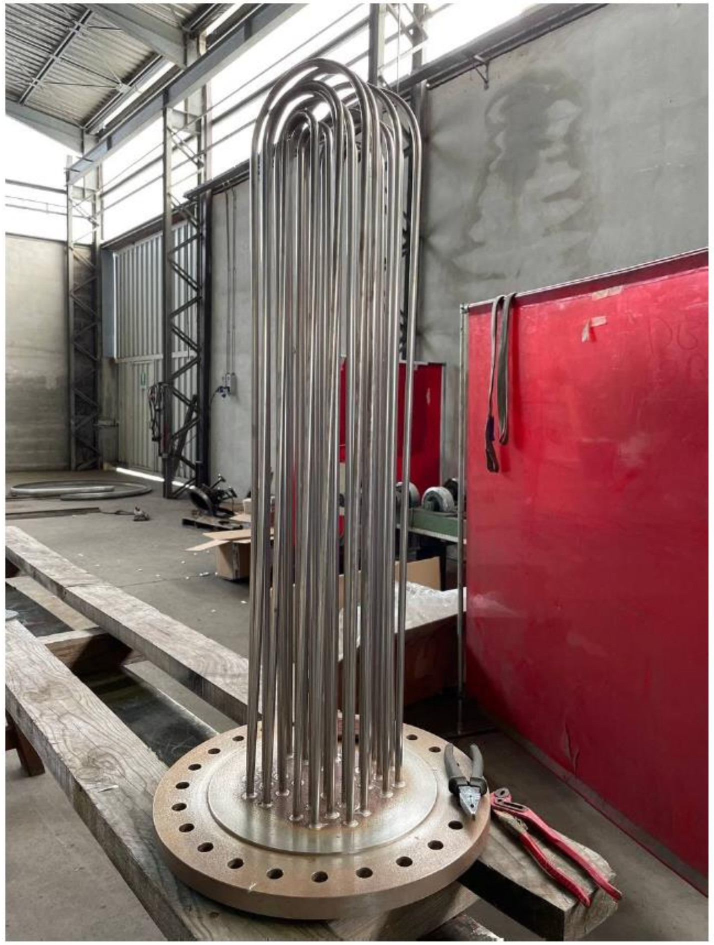
Conclusions

A BASIC FUEL CYCLE MODEL



Meschini, Samuele, et al. "Modeling and analysis of the tritium fuel cycle for ARC-and STEP-class DT fusion power plants." *Nuclear Fusion* 63.12 (2023): 126005.

Tritium extraction technologies


Permeation against vacuum

Packed tower extractor


Liquid Vacuum contactor

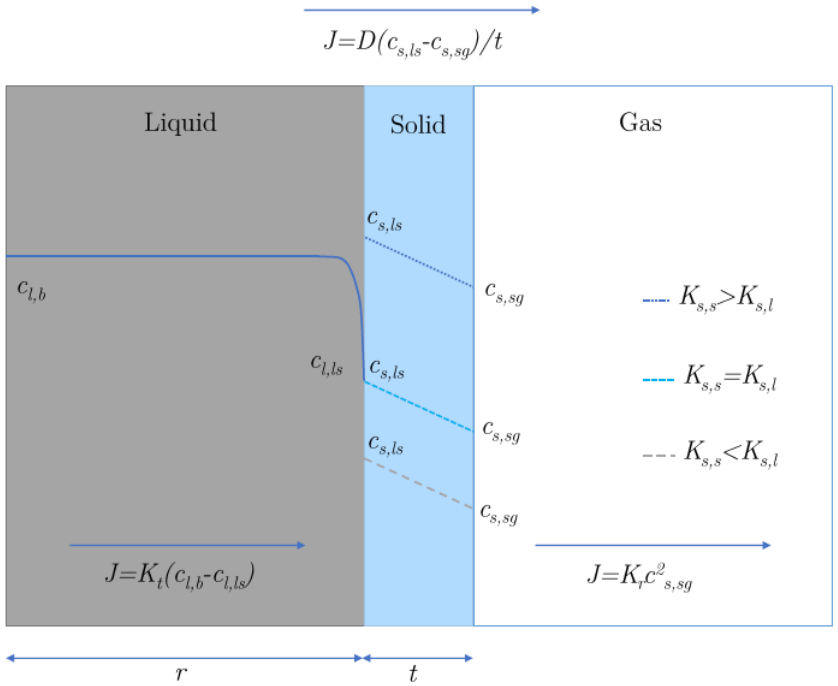

Vacuum sieve tray

Permeation against vacuum (PAV)

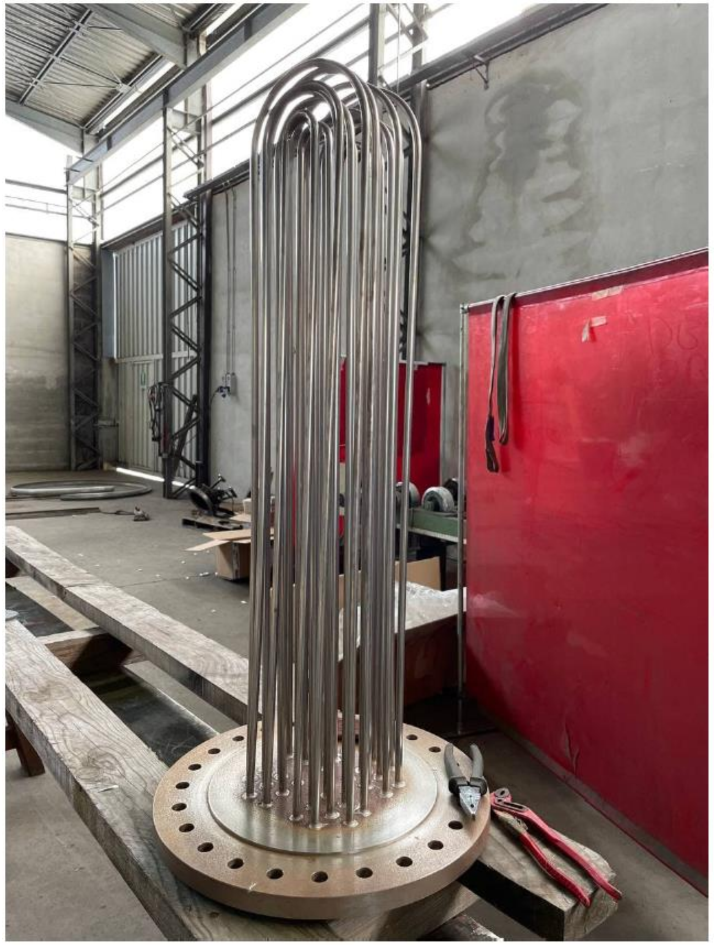
PAV-ONE mockup by ENEA at Brasimone

Pipe with highly permeable structural material (Vanadium, Niobium…)

Vacuum or sweep gas to keep external atmosphere tritium-free



C. Alberghi, L. Candido, M. Utili, and M. Zucchetti. Development of new analytical tools for tritium transport modelling. Fusion Engineering and Design, 177:113083, 2022.



"F. Papa et al. Experimental characterization of tritium extraction systems and tritium anti-permeation barriers in heavy liquid metal systems. PhD thesis, Universita degli Studi di Roma" La Sapienza", 2023.»

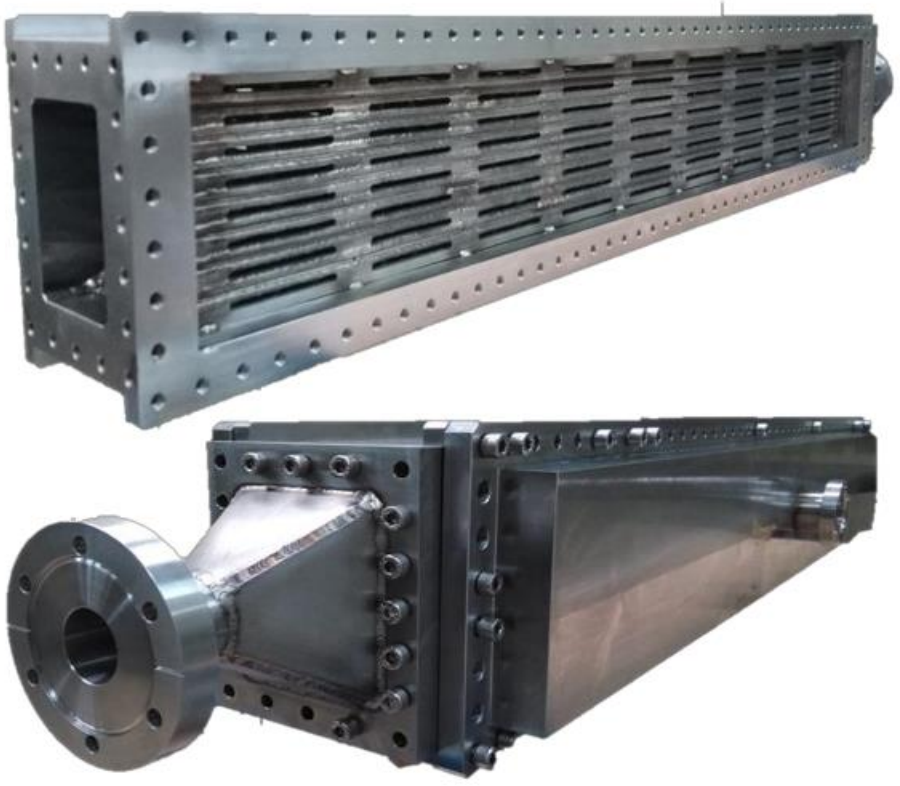
Liquid Vacuum contactor

CLIPPER mock-up at CIEMAT

Liquid flows in direct contact with vacuum / sweep gas

Free surface, no permeation across structural material

Support structure can leverage highly permeable materials and act as a PAV.



Rapisarda, D. "The CIEMAT LiPb Loop Permeation Experiment."

Packed tower extractors (GLC)

Mockup by ENEA at Brasimone in the TRIEX-II loop

Previous tests with the MELODIE mockup

The liquid breeder flows in countercurrent with a sweep gas, through a packed matrix which increases mass transfer and contact area

Used regularly in industry

"F. Papa et al. Experimental characterization of tritium extraction systems and tritium anti-permeation barriers in heavy liquid metal systems. PhD thesis, Universita degli Studi di Roma" La Sapienza", 2023.»

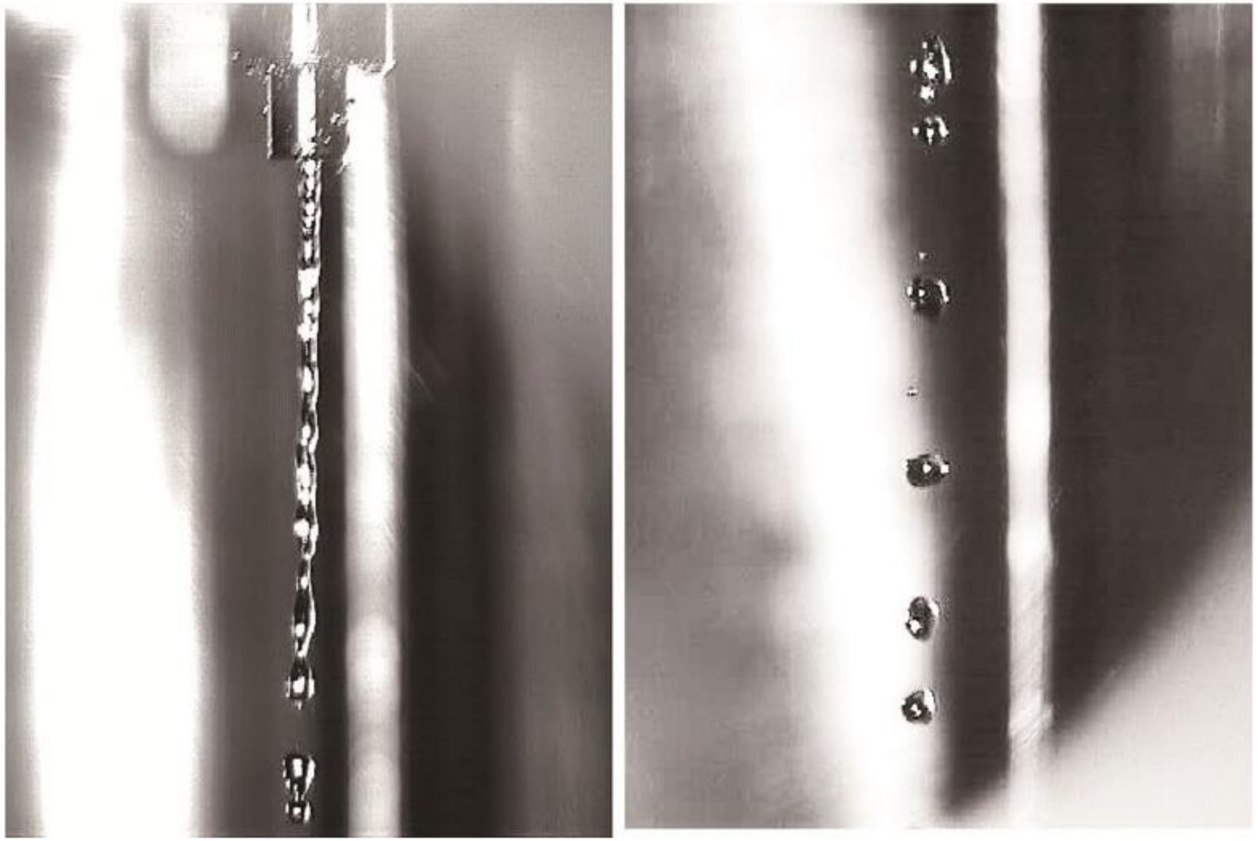
Vacuum Sieve tray

Test facility in Japan

The breeder flows through sprayer structures

Sub-mm droplets of breeder are directly in contact with vacuum/sweep gas

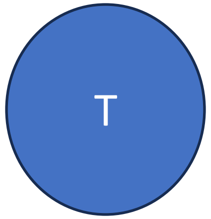
Used in industry



Okino, Fumito, et al. "Continuous deuterium extraction from falling lithium-lea droplets in a vacuum." Fusion Engineering and Design 202 (2024): 114349.

Liquid metal (e.g. PbLi)

Tritium is dissolved in **atomic** form

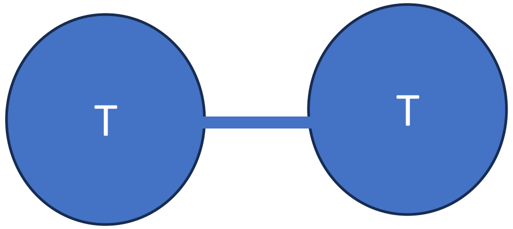


Tritium follows Sieverts' Solubility Law, which is also valid for metallic structures

$$c_T = K_S \cdot \sqrt{p_{T_2}}$$

Molten Salt (e.g. FLiBe)

Tritium is in **molecular** form



Tritium follows Henry's Solubility Law

$$c_{T_2} = K_H \cdot p_{T_2}$$

Complex chemistry interactions (corrosion control of TF) !

TF cannot permeate structural material, but interacts with it (corrosion)

The TRIOMA code

TRIOMA code:

- **Python**
- **System**-level
- **Open**-Source
- **Object**-oriented
- **Analytical** formulation
- **Fast**
- **Liquid Breeders**

TRIOMA (TRItium Object-oriented and Modular Analysis)

license MIT | launch binder | CI and Deploy passing | codecov 82% | Stars 7 | Forks 0

TRIOMA can model

- Tritium extraction systems
- Tritium saturators
- Heat exchangers
- Breeding Blankets

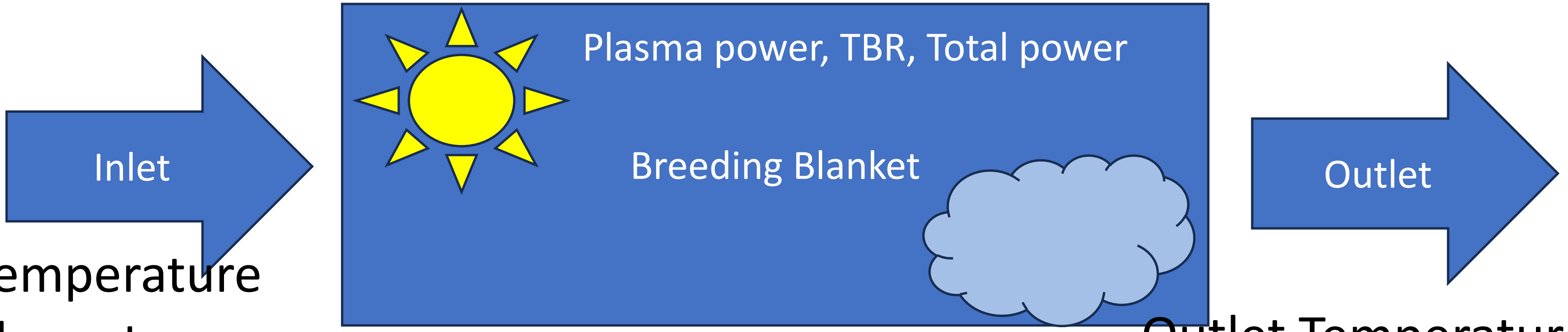
Analysis of the OFC:

- **Extraction efficiency of each component**
- **Tritium losses**
- **Tritium inventory**
- Interaction between components
- **Sensitivity** analysis
- **time dependent behavior**

Neglects Surface effects
NO FEM
NO DISCRETIZATION

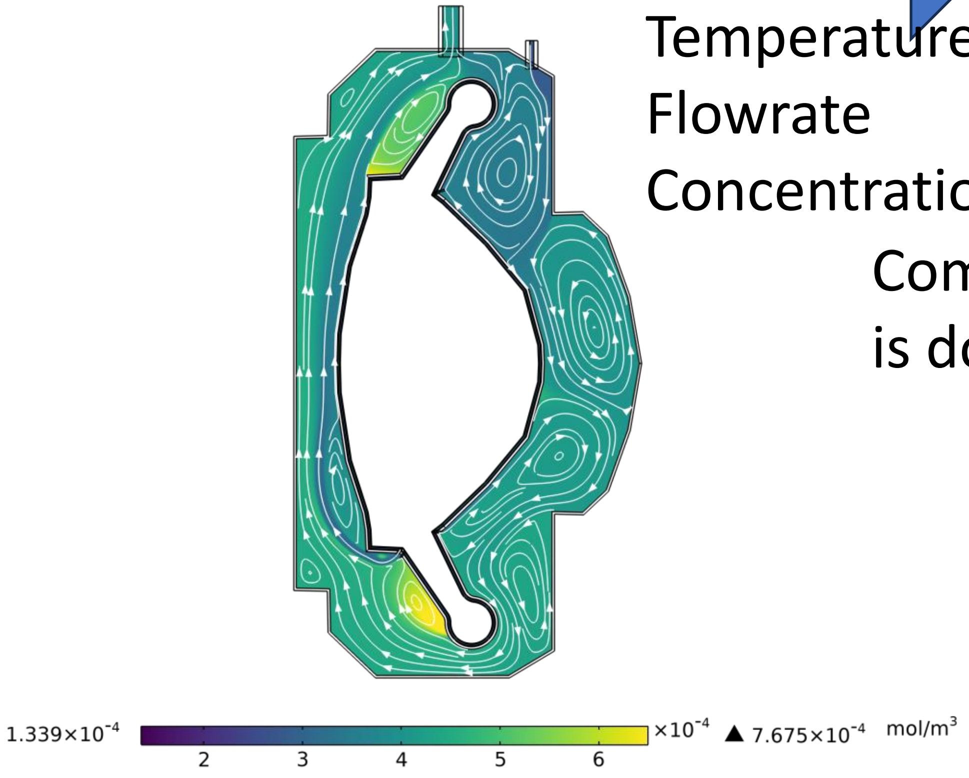
Breeding blanket in TRIOMA

Simple analysis of mass and energy conservation

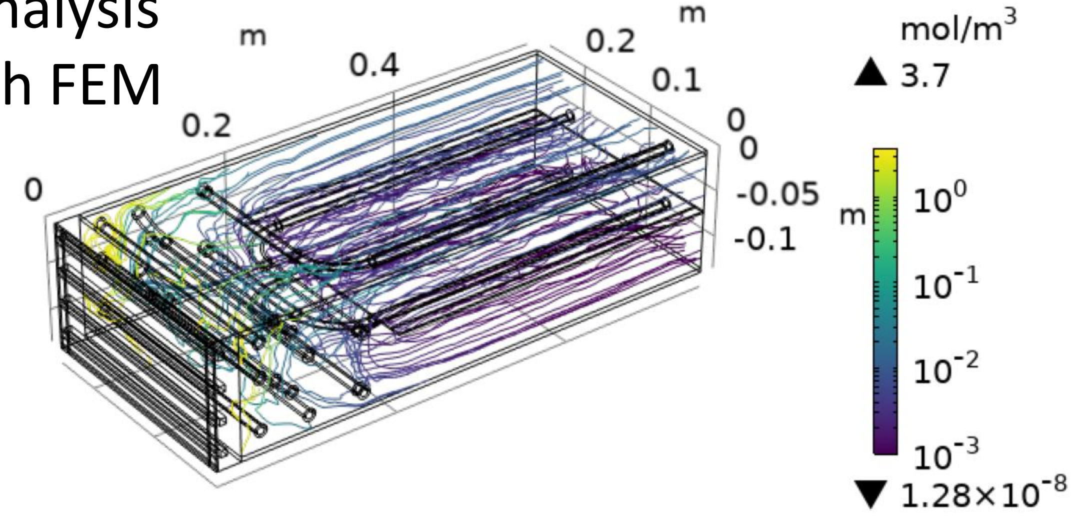


Temperature
Flowrate
Concentration

Outlet Temperature
Outlet Concentration



Complex analysis is done with FEM



Analytical approach to TES

Alberghi, Ciro, et al. "Development of new analytical tools for tritium transport modelling." *Fusion Engineering and Design* 177 (2022): 113083.

Urgorri, F. R., et al. "Theoretical evaluation of the tritium extraction from liquid metal flows through a free surface and through a permeable membrane." *Nuclear Fusion* 63.4 (2023): 046025.

Rader, Jordan D., M. Scott Greenwood, and Paul W. Humrickhouse. "Verification of modelica-based models with analytical solutions for tritium diffusion." *Nuclear Technology* 203.1 (2018): 58-65.

Now the code is open-source and some functions are extended (tritium inventory and outer partial pressure contribution)

Analytical solution for Liquid metal systems

$$c_{out} = c_{in} \cdot (1 - \eta)$$

η is the extraction efficiency

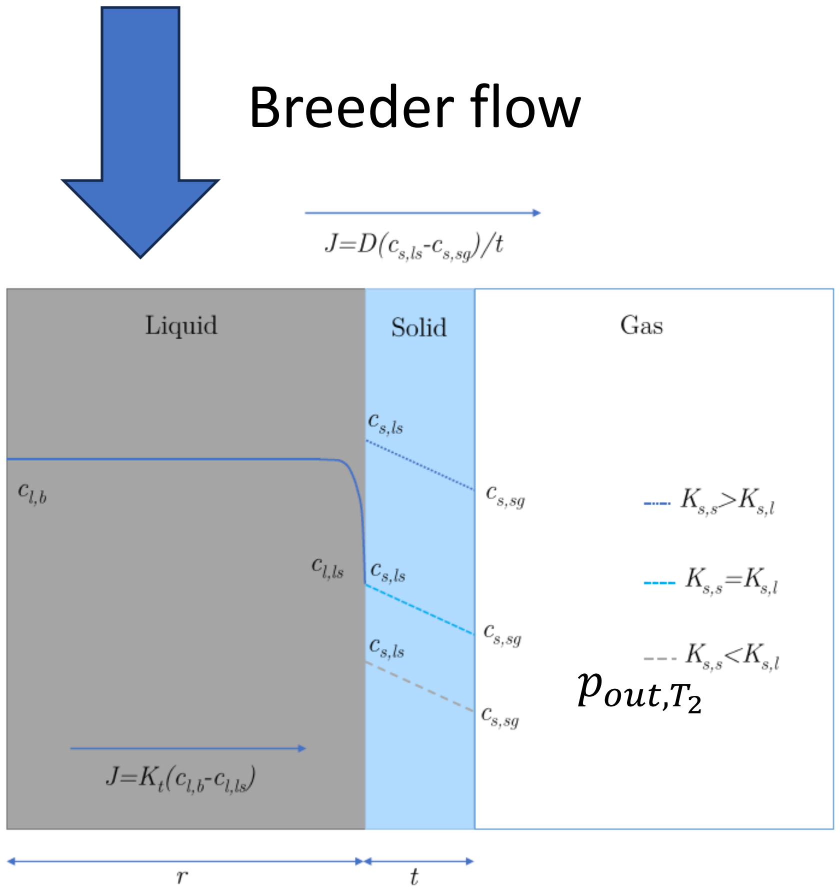
$$\tau = \frac{4 k_t L}{v d}$$

τ is the information of the residence time

$$\zeta = \frac{2 D_S}{d \cdot ln(\frac{d_o}{d}) \cdot k_t} \cdot \frac{K_{S,s}}{K_{S,l}}$$

ζ is the partition parameter

$$\eta(p_{out}) = (1 - e^{-\frac{\tau\zeta}{1+\zeta}}) \cdot \left(1 - \sqrt{\frac{p_{out}}{p_{in}}}\right)$$



. Alberghi, L. Candido, M. Utili, and M. Zucchetti. Development of new nalytical tools for tritium transport modelling. Fusion Engineering and esign, 177:113083, 2022.

Analytical solution for molten salts systems

$$\beta = \frac{\sqrt{\frac{1}{\xi} + 1 + \sqrt{\frac{K_H p_{\text{out}}}{\alpha}}}}{1 + 2\sqrt{\frac{K_H p_{\text{out}}}{\alpha}}} + \ln\left(\sqrt{\frac{1}{\xi} + 1 + \sqrt{\frac{K_H p_{\text{out}}}{\alpha}}} - 1 + 2\sqrt{\frac{K_H p_{\text{out}}}{\alpha}}\right)$$

$$\beta_\tau = \beta - \frac{\frac{4 \cdot k_t z}{v \cdot d}}{1 + 2\sqrt{\frac{K_H p_{out}}{\alpha}}} - 1$$

β_τ is the information of residence time

$$\alpha = \frac{1}{K_H} \cdot \left(\frac{\phi}{k_t \cdot d \cdot \ln\left(\frac{d_o}{d}\right)}\right)^2$$

ξ is the partition parameter for molten salts

$$\xi = \frac{\alpha}{c_0} = \frac{1}{K_H \cdot c_0} \cdot \left(\frac{\phi}{k_t \cdot d \cdot \ln \frac{d_o}{d}}\right)^2$$

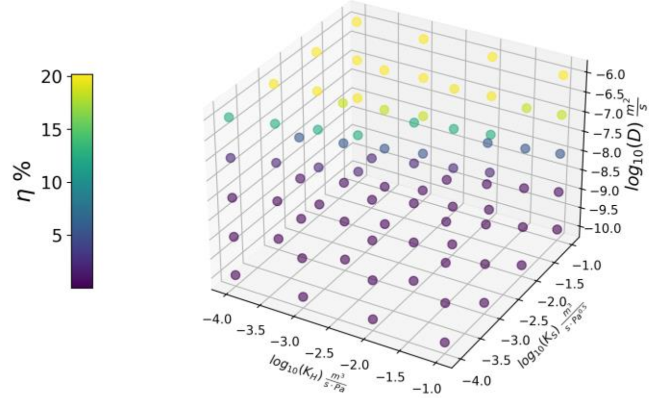
W is the real branch of the LambertW function

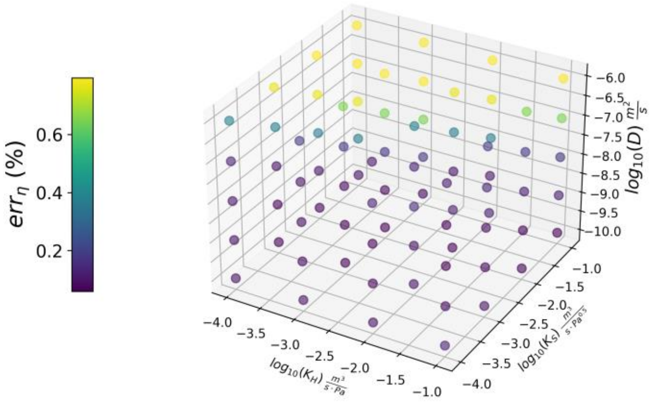
$$\eta = 1 - \frac{\xi}{4}\left(1 + 2\sqrt{\frac{K_H p_{\text{out}}}{\alpha}} + \left(2\sqrt{\frac{K_H p_{\text{out}}}{\alpha}} + 1\right) \cdot W\left(\frac{1}{2\sqrt{\frac{K_H p_{\text{out}}}{\alpha}} + 1} \cdot e^{\beta_\tau}\right)\right)^2 + \sqrt{\frac{K_H p_{\text{out}}}{\alpha}} \cdot \xi + \frac{\xi}{4}$$

PAV.get_efficiency()

PAV.get_inventory()

OFC.solve_circuit()





Less than 1% error wrt FEM

Packed tower extractors in TRIOMA

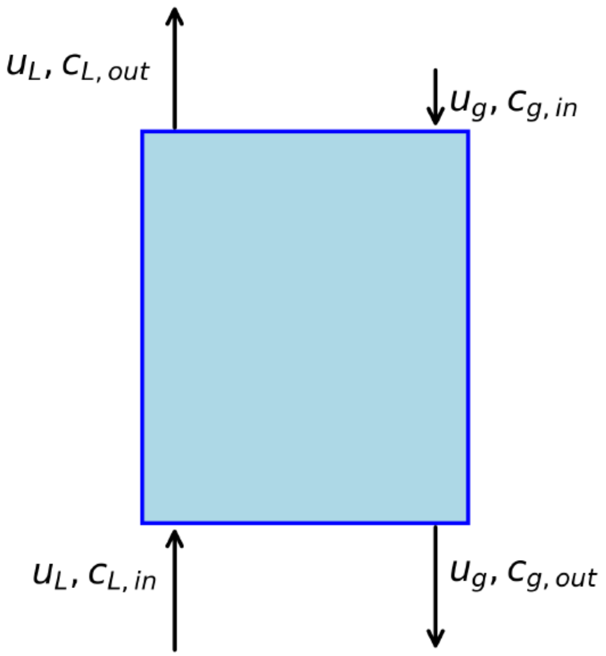
$$Z = HTU \cdot NTU$$

Z = height of the packed tower

$$HTU = \frac{u_L}{k_L a}$$

HTU= height of a transfer unit

NTU = number of transfer units



$$NTU_{MS} = \int_{c_{L,out}}^{c_{L,in}} \frac{dc_L}{c_L - K_H \frac{u_L}{u_G} RT \cdot \left(c_L - c_{L,out} + c_{g,in} \frac{u_G}{u_L} \right)}$$

$$NTU_{LM} = \int_{c_{L,out}}^{c_{L,in}} \frac{dc_L}{c_L - K_S \cdot \left(\frac{u_L}{2u_G} RT \cdot \left(c_L - c_{L,out} + c_{g,in} \frac{u_G}{2 \cdot u_L} \right) \right)^{1/2}}$$

Other components in TRIOMA

Connection pipes are extremely inefficient PAVs

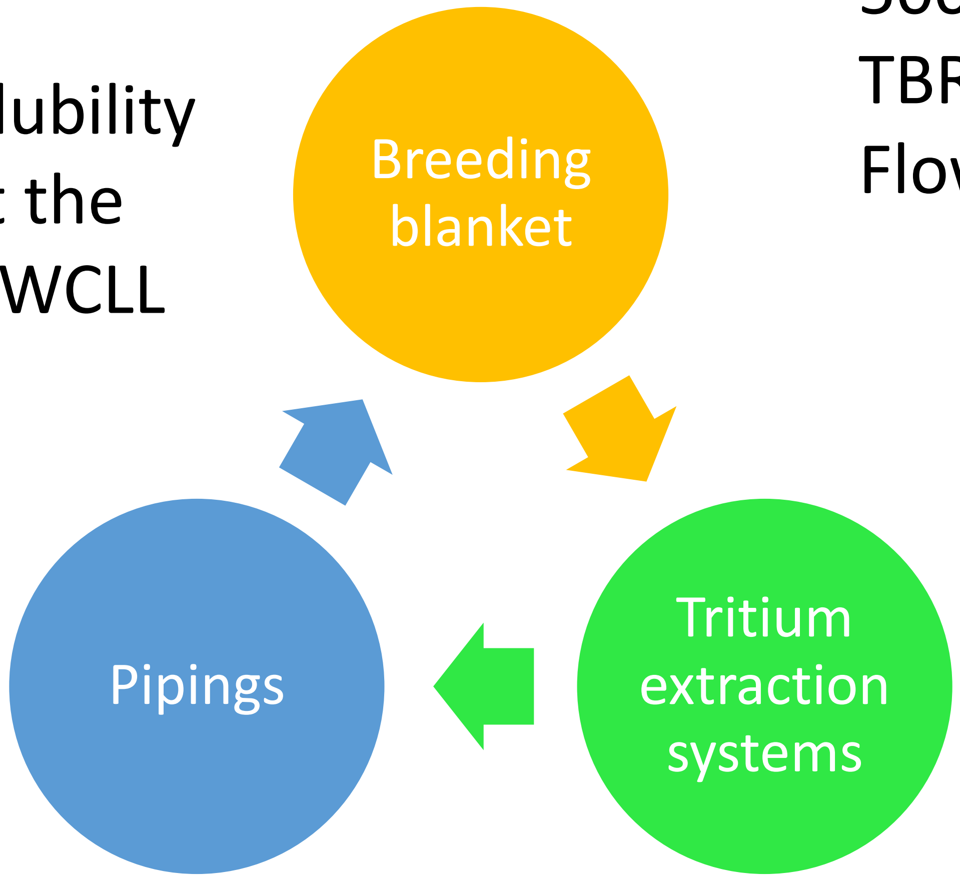
Heat exchangers can be described as multiple segments of pipes (PAVs) each with different temperature (nodalization)

Saturators, for experimental facilities, can be pipes where hydrogen permeates from the external atmosphere (rich of hydrogen) to the fluid.

Simulation of different OFC configurations

Fuel cycle for FLiBe (molten salt) and PbLi (liquid metal)
High solubility and low solubility
Breeder conditions reflect the operational conditions of WCLL and ARC-class reactors

500 MW plasma power
TBR =1.08-1.2
Flowrate=2000 kg/s



Heat exchanger / Heat removal system

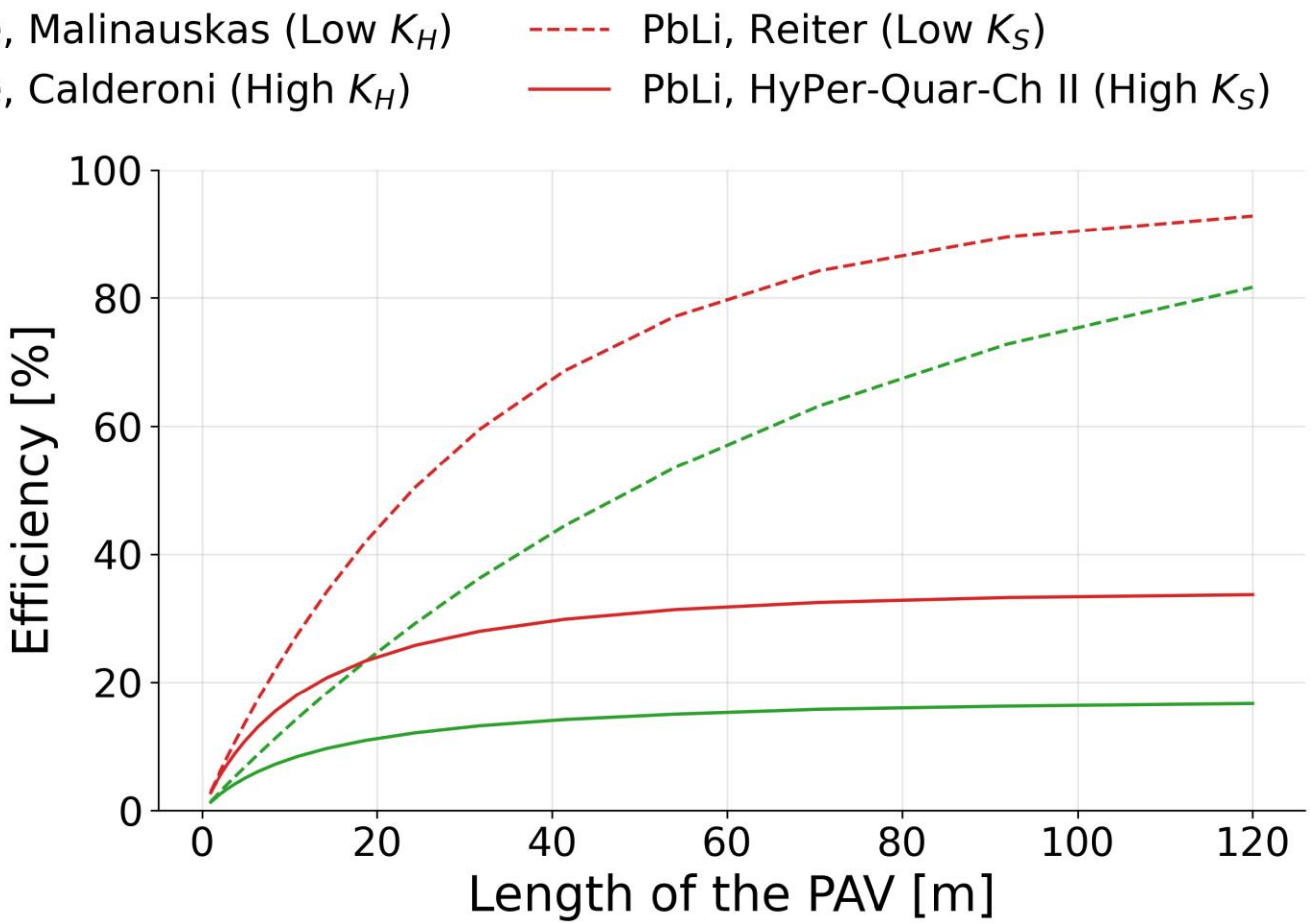
700 pipes, hydraulic diameter=1 in. , L=10 m

PAV and GLC technology are simulated

PAV extractor results

$p_{T_2,out} = 0\ Pa$

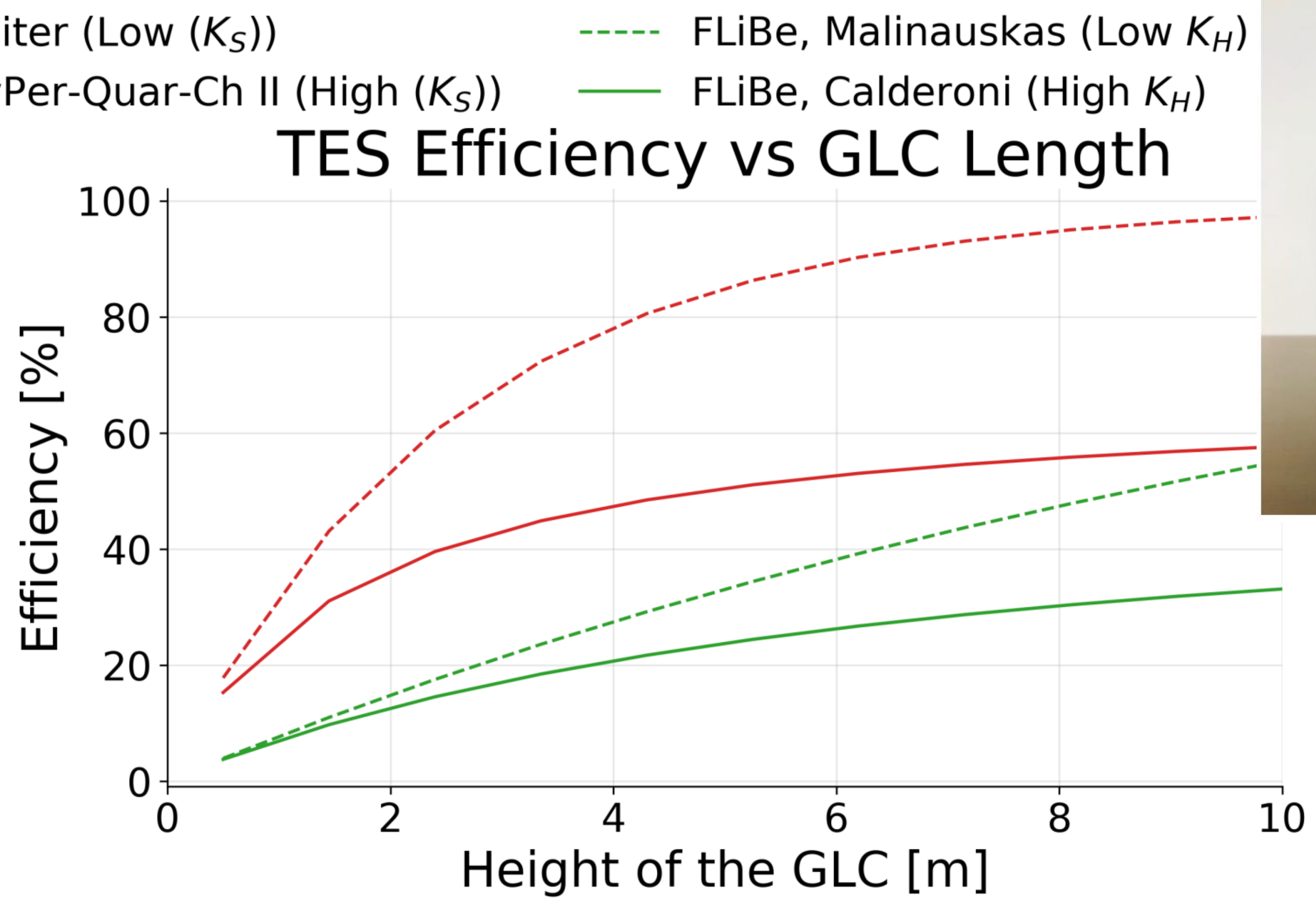
Parameter	Value
Hydraulic diameter	0.5 in.
Pipe thickness	3 mm
Fluid velocity	2.2 m/s
Number of pipes PbLi	734
Number of pipes FLiBe	3600



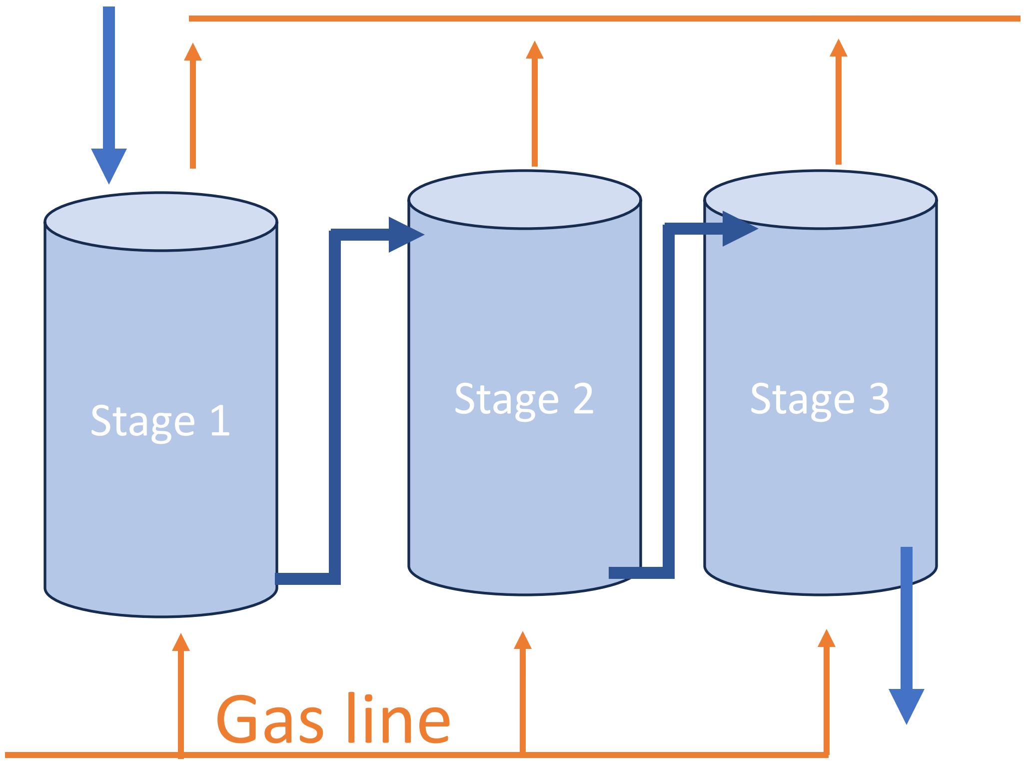
The high solubility case is sensible to the outer partial pressure

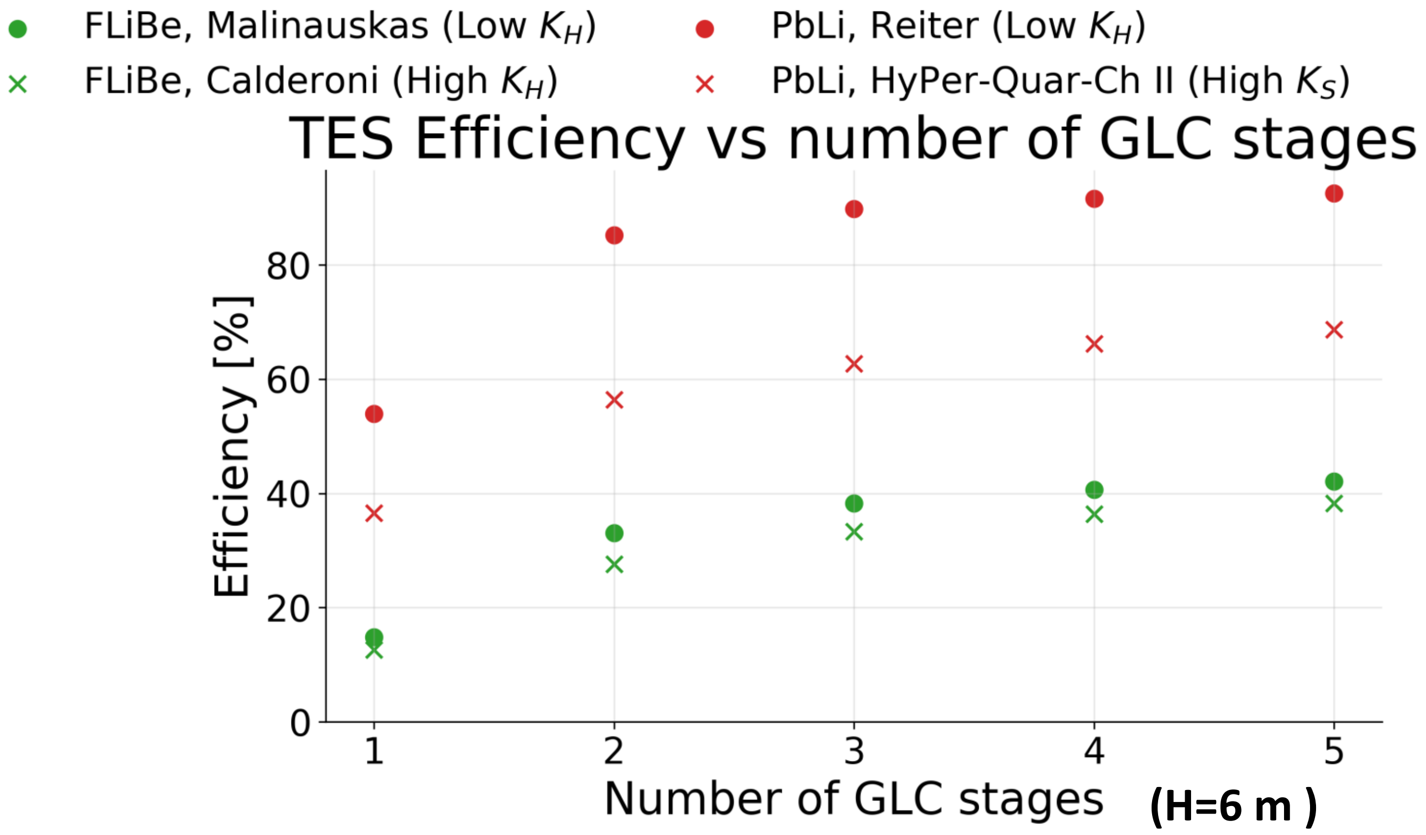
Packed tower column results

Parameter	Value
Mass transfer coefficient kla	$5 \cdot 10^{-3}$ 1/s
Number of loops	8
Pressure	1 bar
Gas flowrate	0.0974 Nl/s
Hydraulic diameter	1.6 m



Breeder





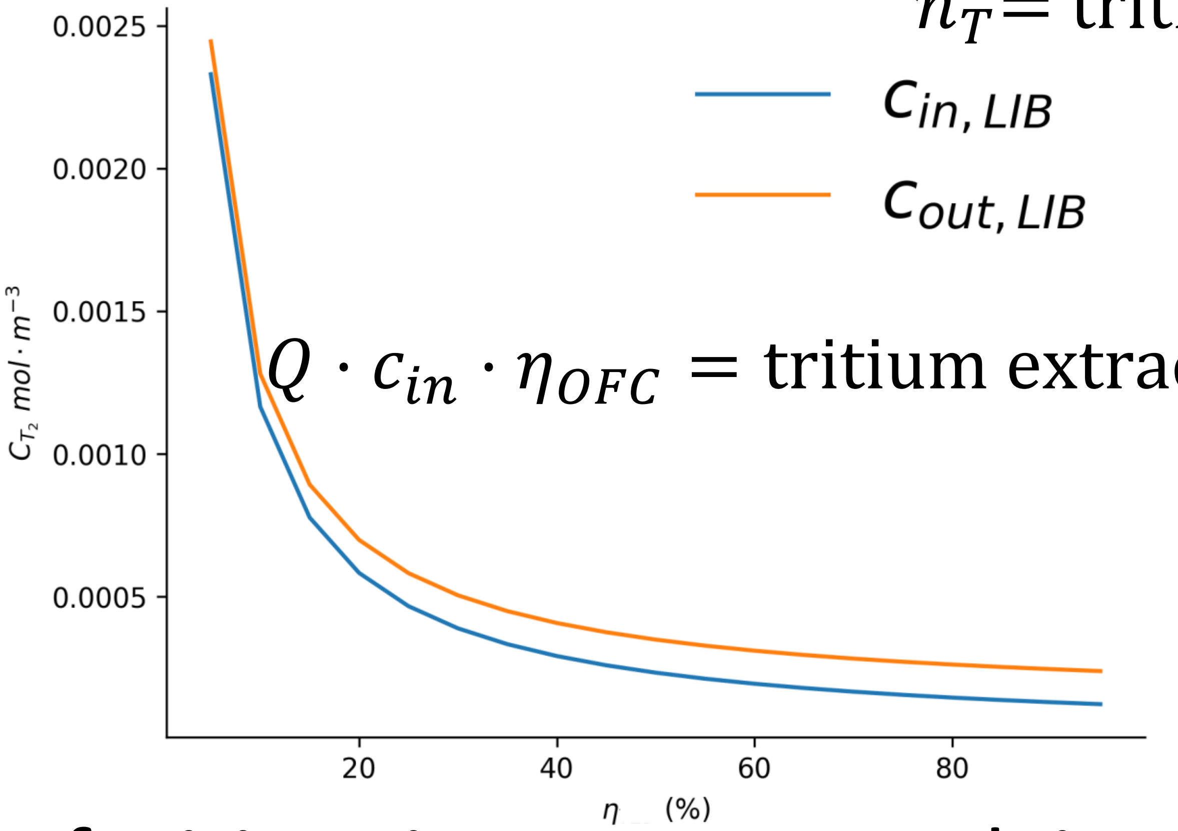
Two extraction stages increase **significantly** the extraction efficiency with same extraction length

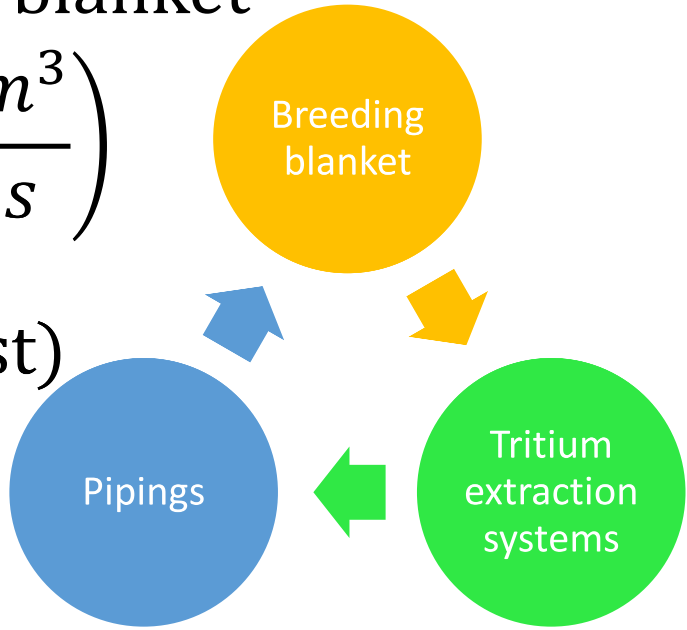
Efficient extractors do not extract more

$\dot{n}_T$ = tritium produced in the blanket

$$Q = flowrate \left(\frac{m^3}{s}\right)$$

$$Q \cdot c_{in} \cdot \eta_{OFC} = \text{tritium extracted (retrieved + lost)}$$





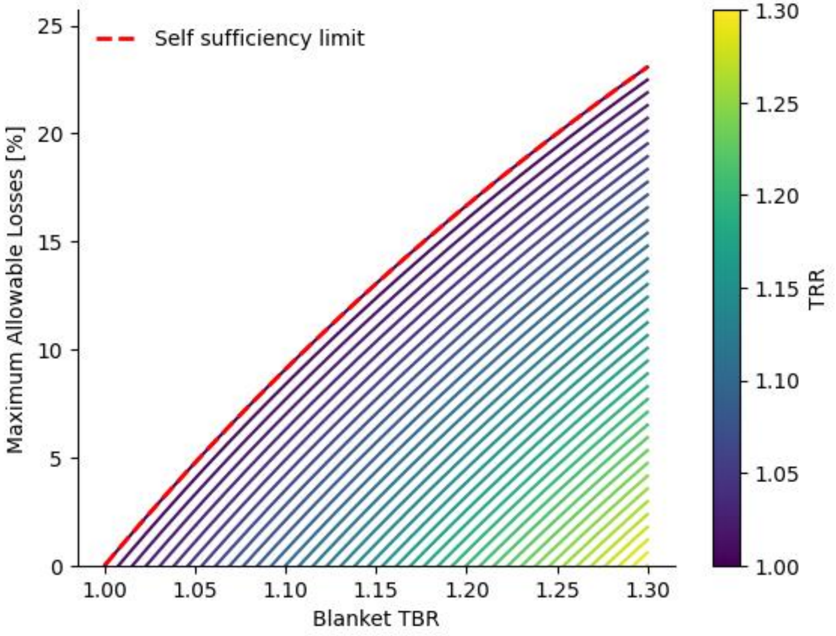
$$\dot{n}_T = Q \cdot c_{in} \cdot \eta_{OFC}$$

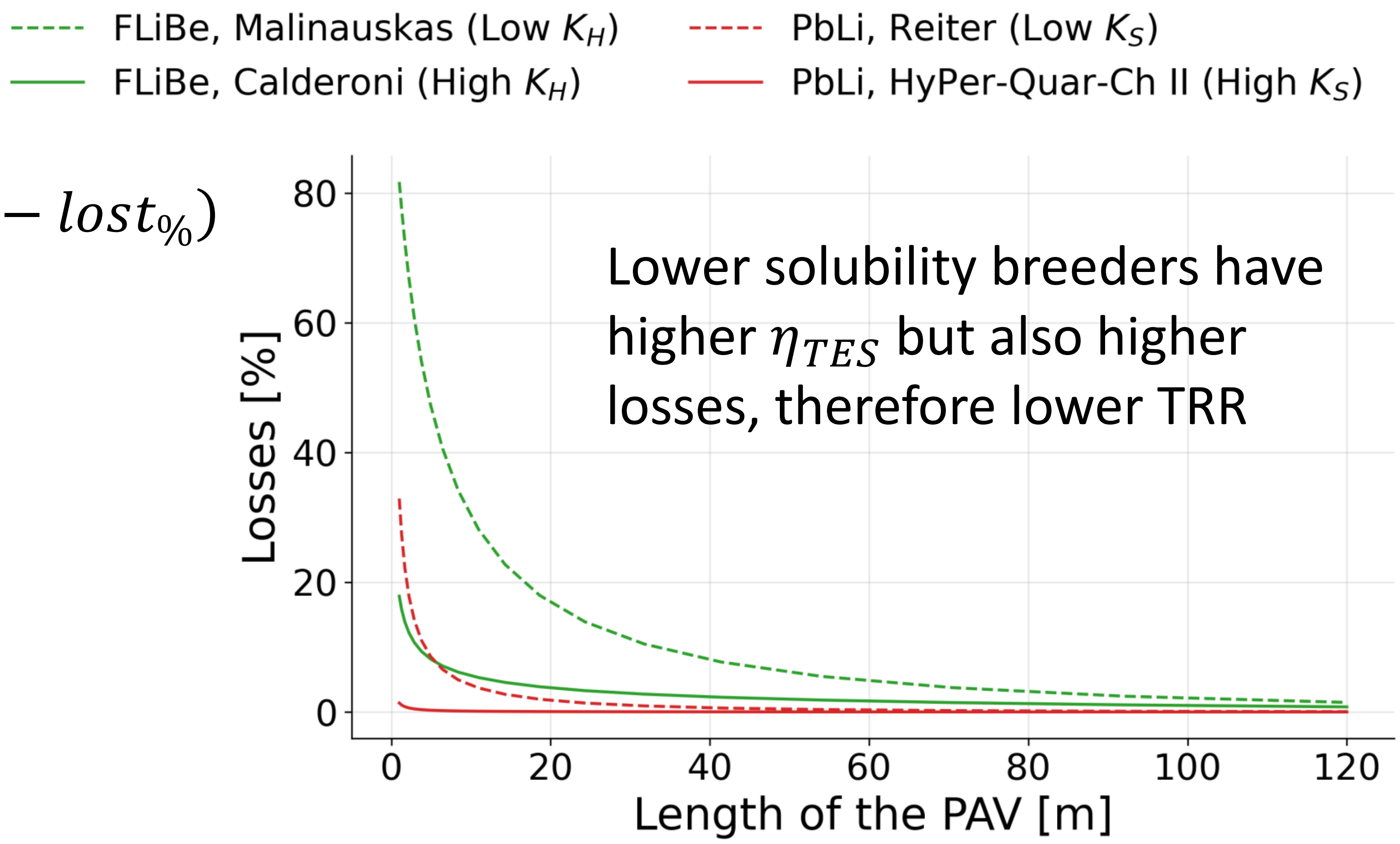
If tritium is not extracted, it re-enters the Breeding blanket and recirculates in the loop, until c_{in} builds up enough to extract as much tritium as it is produced (steady state)

Good extraction ≠ good fuel cycles

$$lost_{\%} = \frac{lost_T}{produced_T}$$

$$TRR = \frac{retrieved_T}{burned_T} = TBR \cdot (1 - lost_{\%})$$

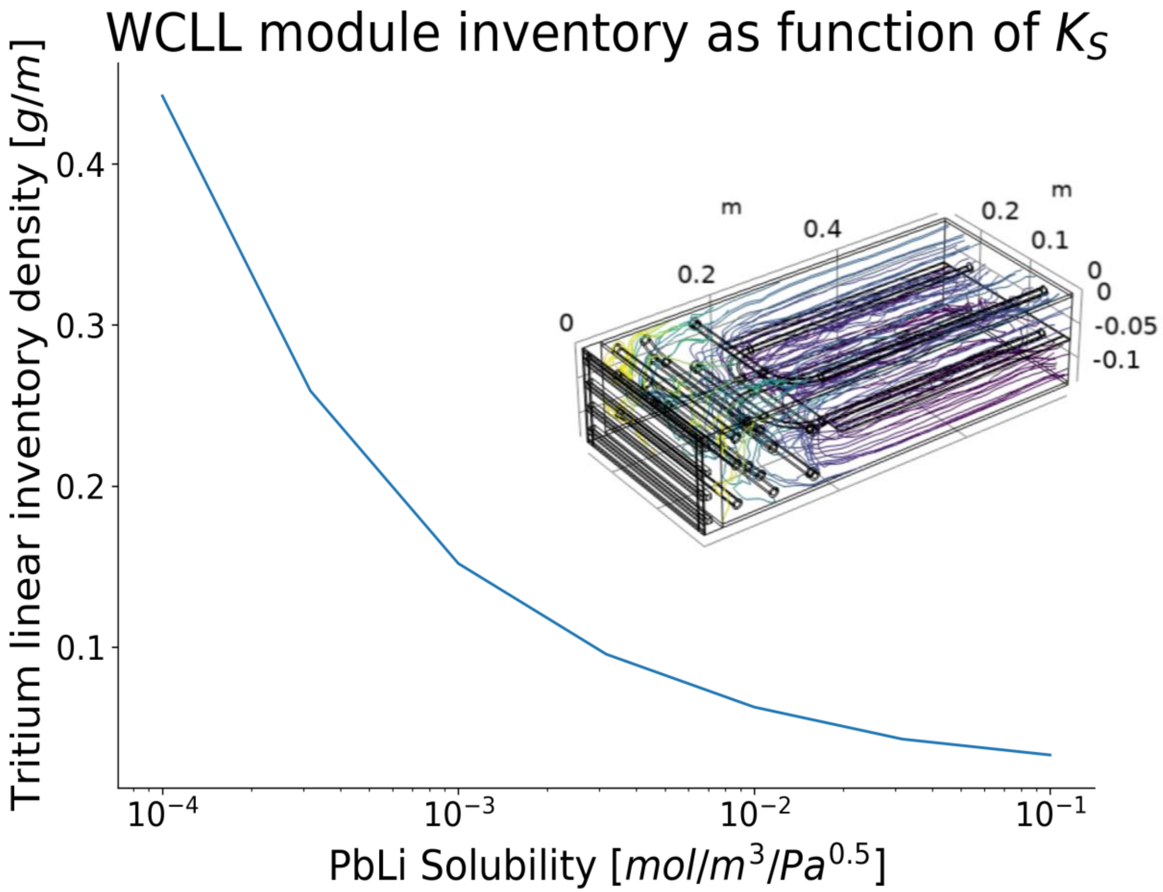


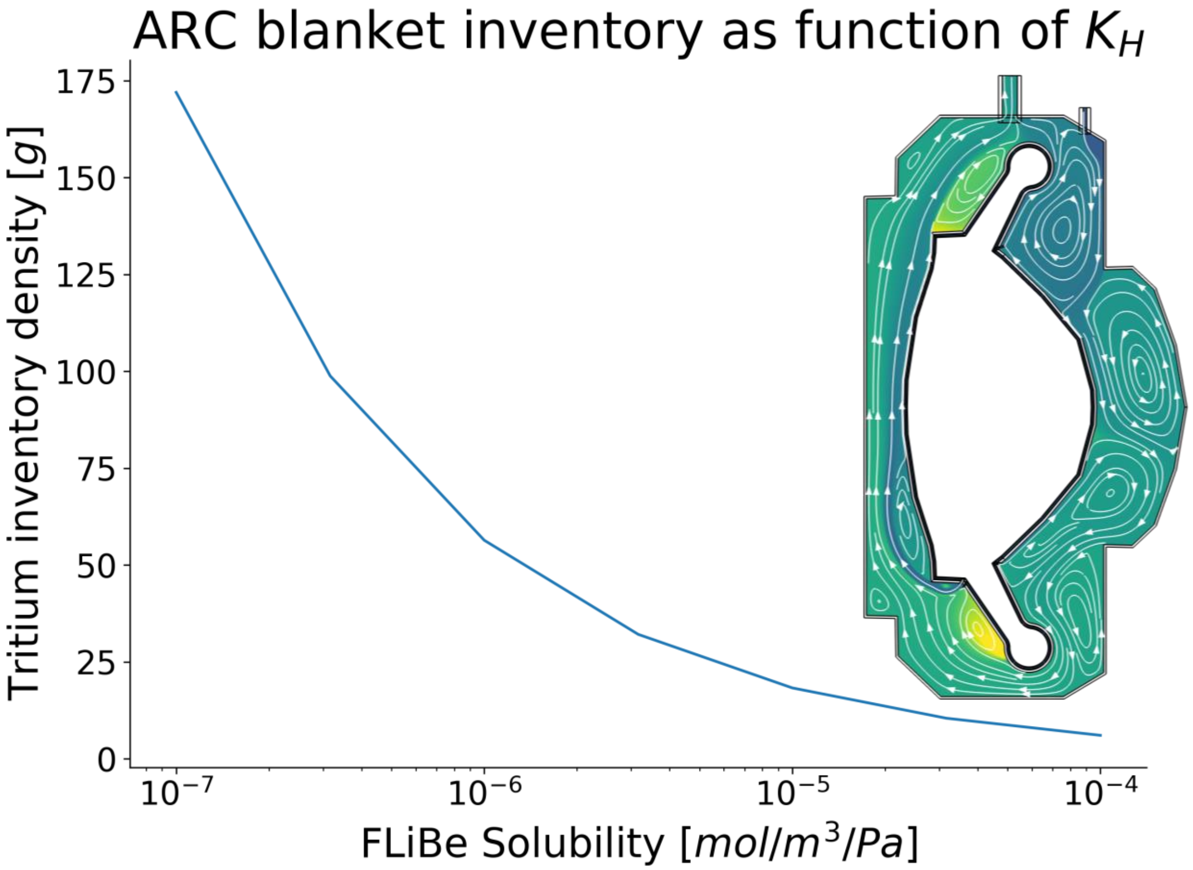


Lower solubility breeders have higher η_{TES} but also higher losses, therefore lower TRR

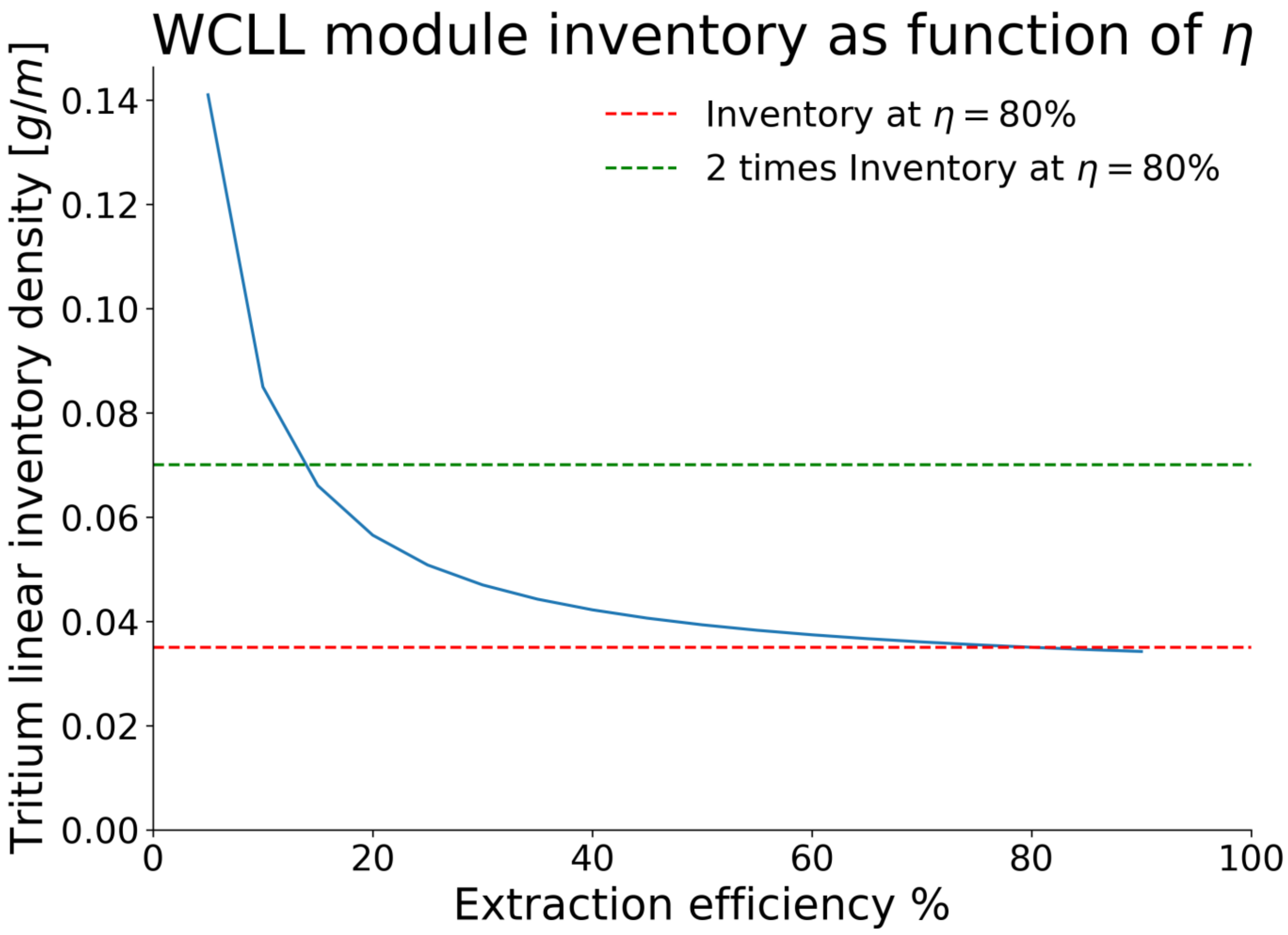
Lower solubility → more tritium in BB

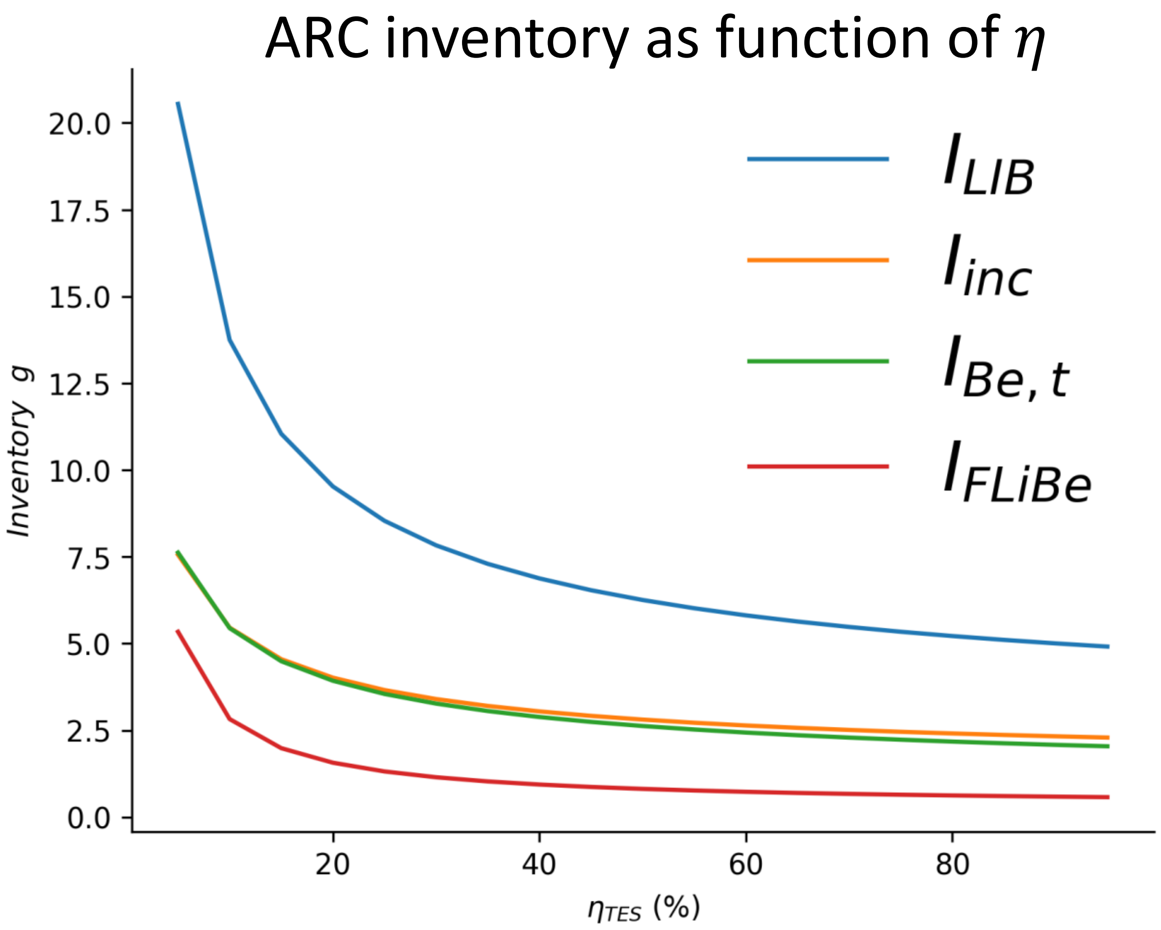
For low solubility breeders, tritium escapes from the breeder and accumulates in structural material



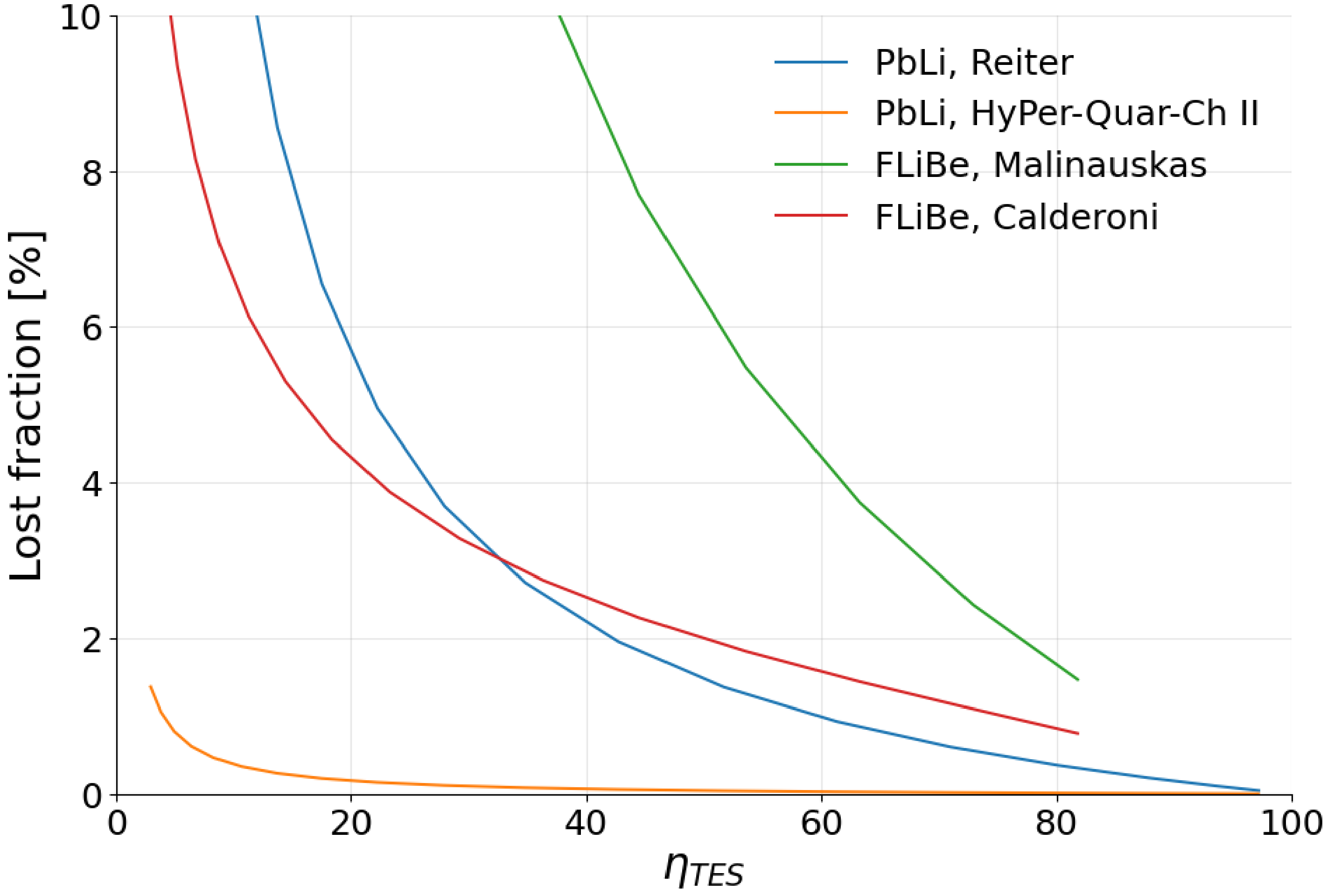


BB tritium inventory depends on TES





Tritium losses also depend on TES



Efficient extraction is needed to reduce tritium losses.

If there are anti-permeation coatings or mitigation strategies, the extraction efficiency can be reduced

Conclusions

Tritium self-sufficiency is a hard challenge.

The TRIOMA code offers a fast and simple tool to analyze and design the OFC of future fusion reactors and hydrogen characterization experiments.

The OFC is a loop with non-trivial interaction. It needs an holistic vision to make an efficient design. This requires multiple tools.

Thank you for your attention

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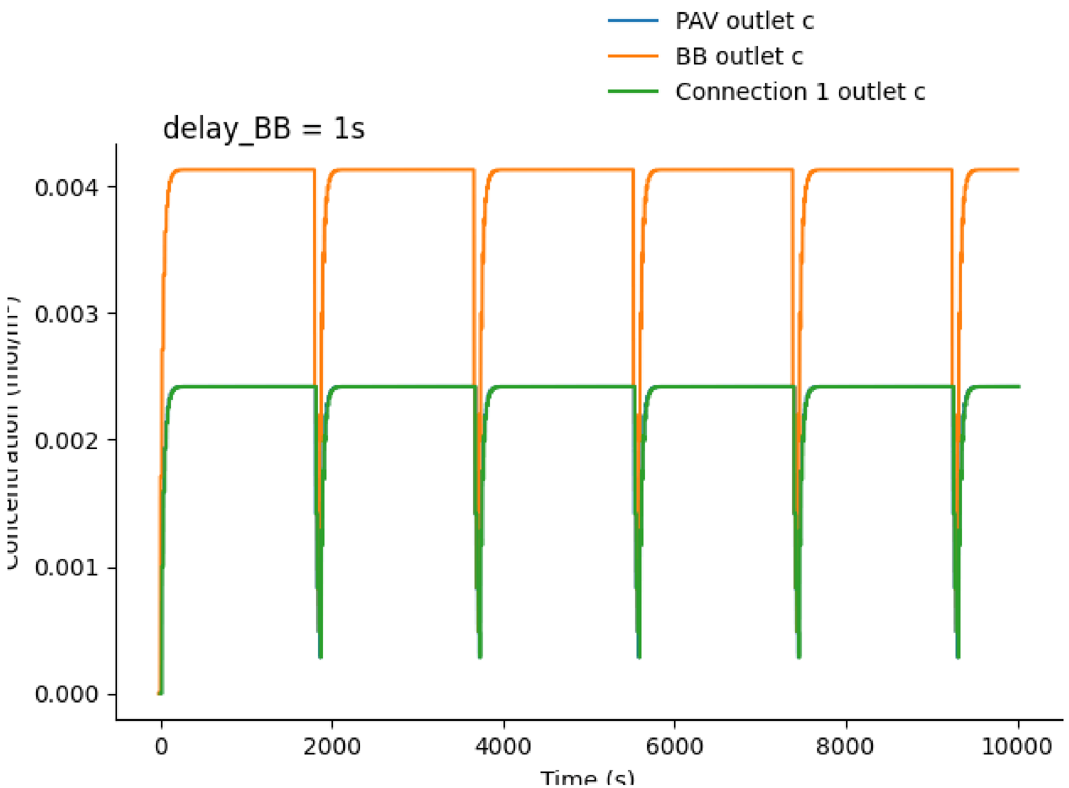
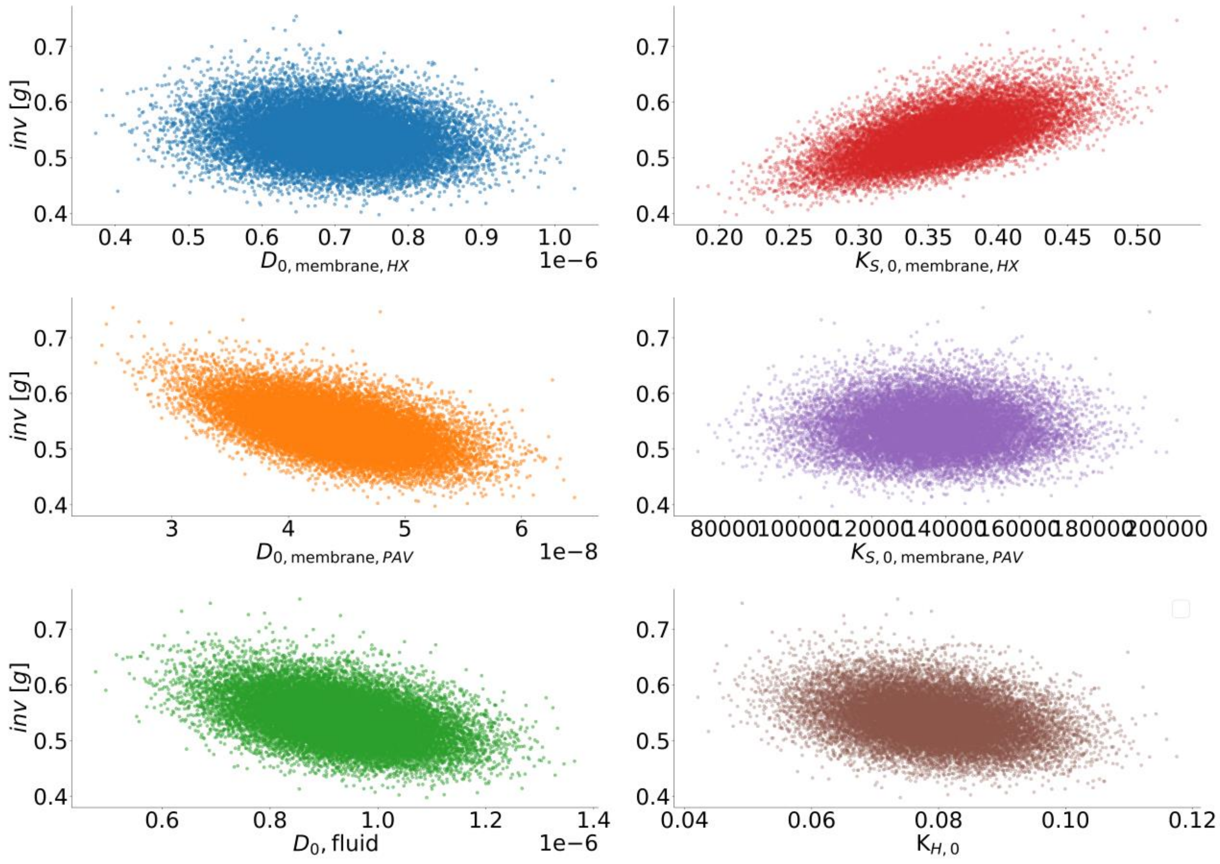
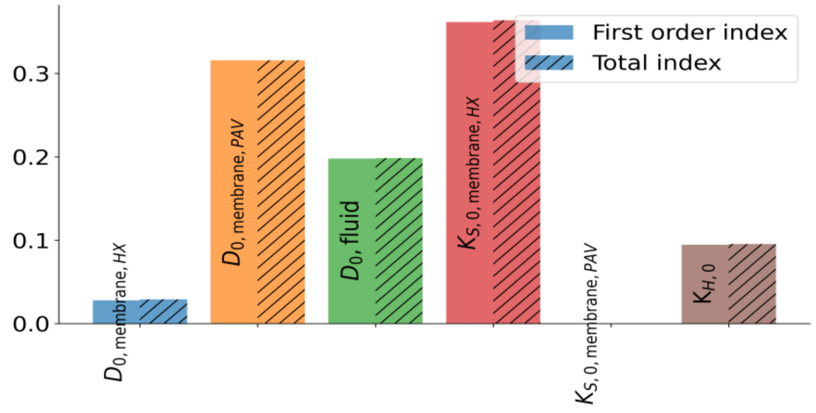
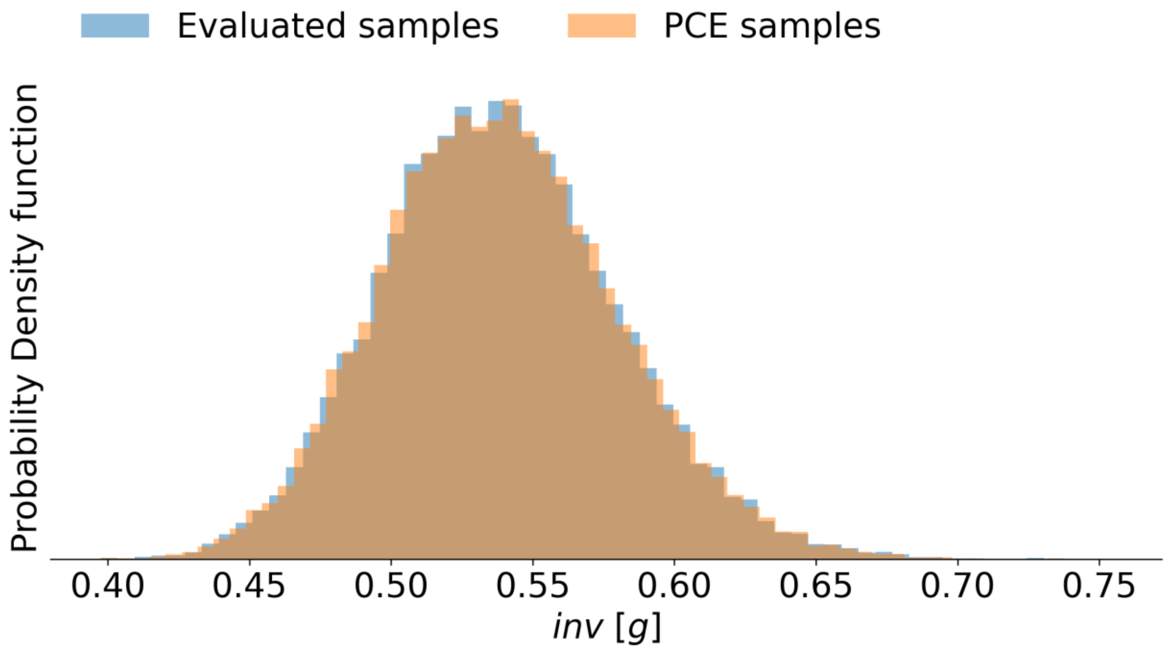
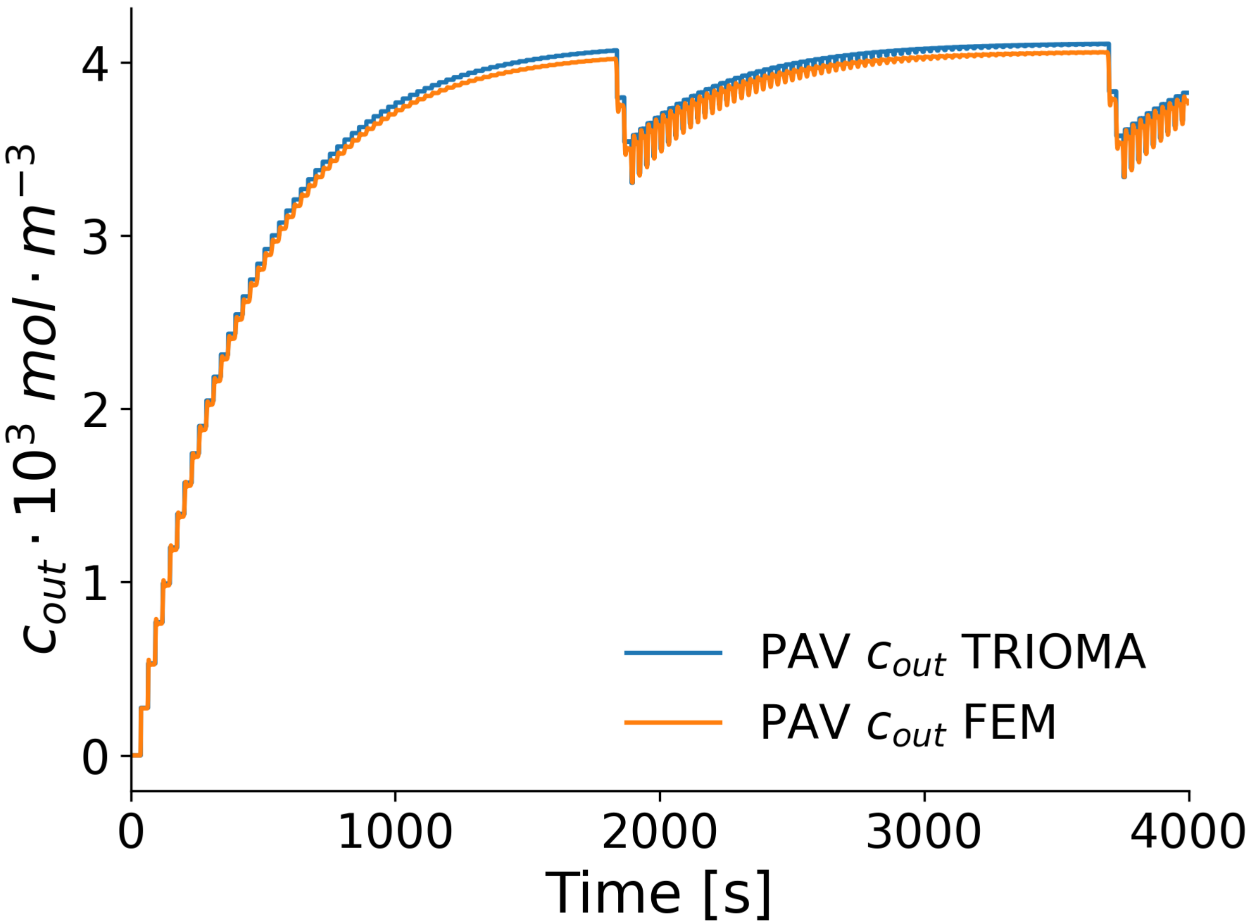

PAV outlet c
BB outlet c
Connection 1 outlet c
delay_BB = 1s
0.004
0.003
0.002
0.001
0.000
0
2000
4000
6000
8000
10000
Time (s)

20K simulations in 2 h









$c_{out} \cdot 10^3\ mol \cdot m^{-3}$
0
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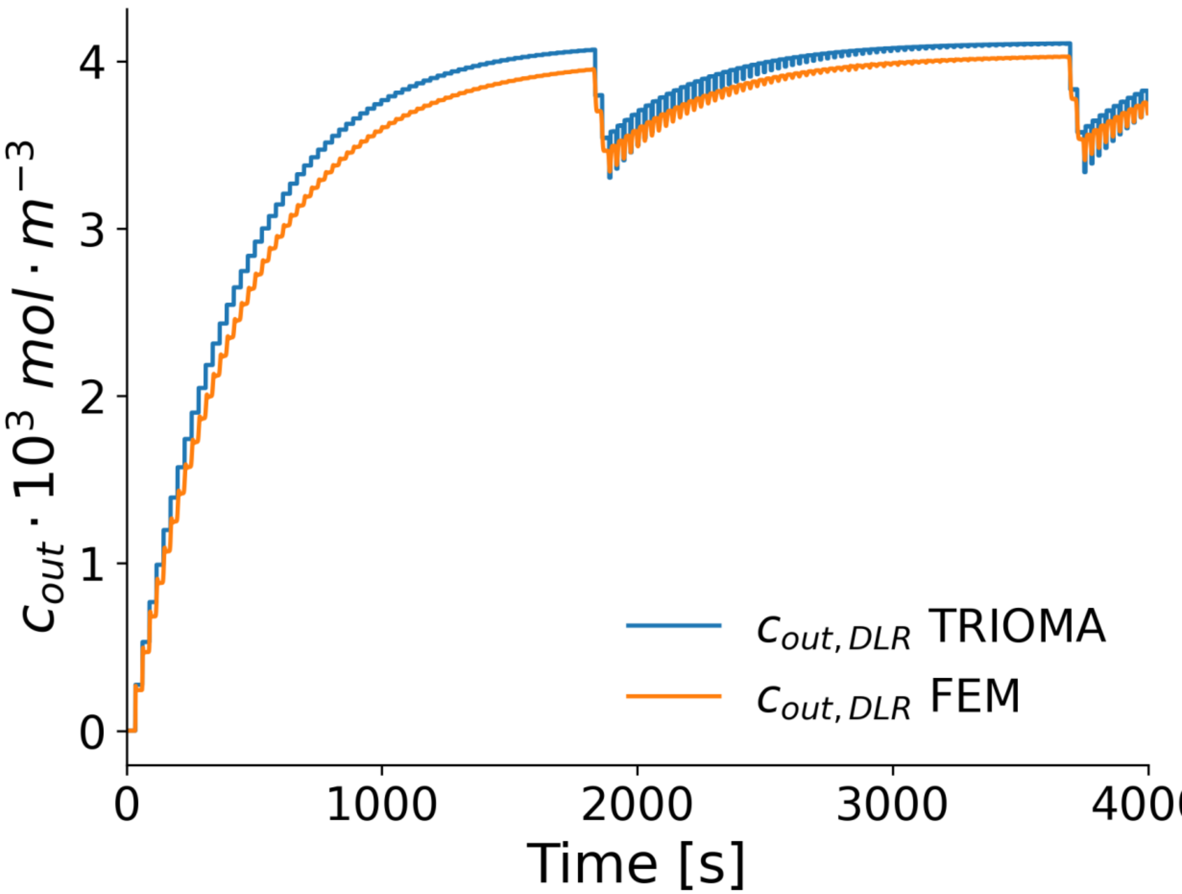
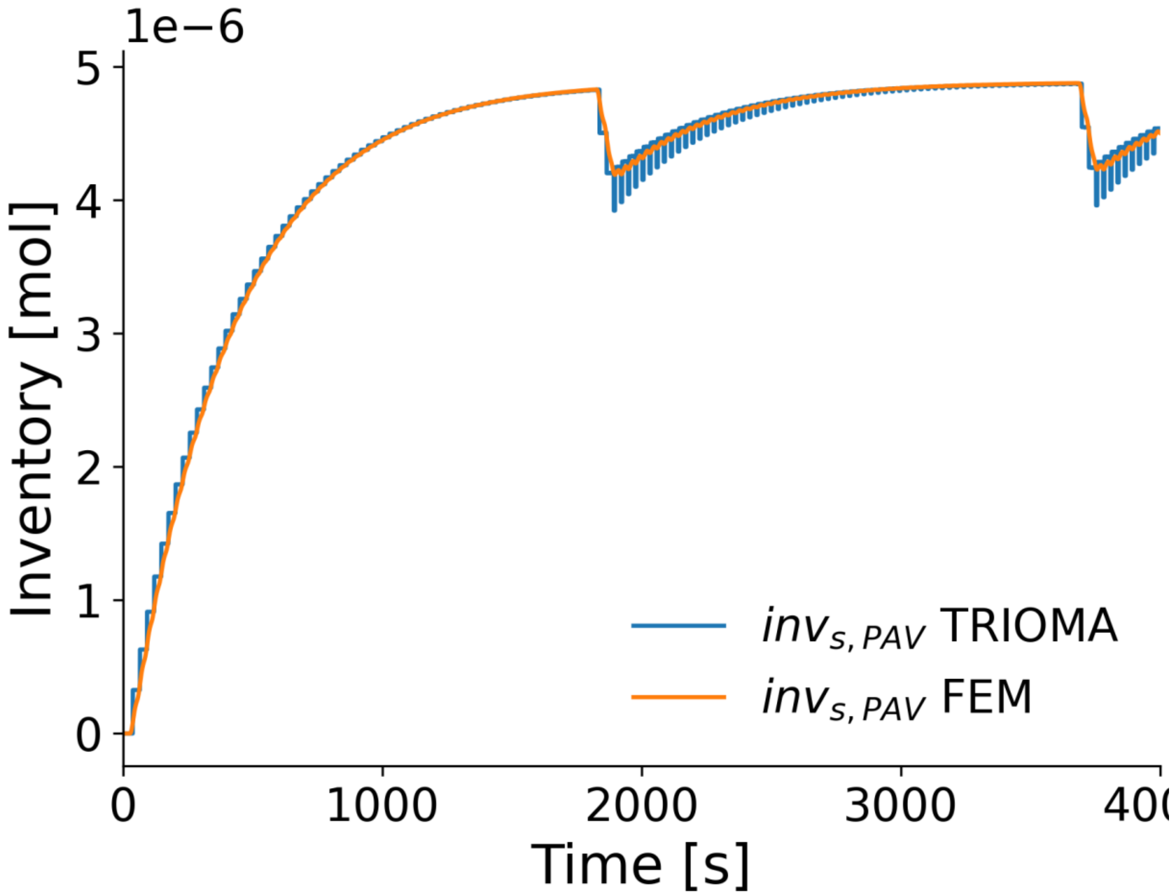
2
3
4
0
1000
2000
3000
4000
Time [s]
PAV c_{out} TRIOMA
PAV c_{out} FEM



$c_{out} \cdot 10^3\ mol \cdot m^{-3}$
0
1
2
3
4
0
1000
2000
3000
4000
Time [s]
$c_{out,DLR}$ TRIOMA
$c_{out,DLR}$ FEM



1e−6
5
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Inventory [mol]
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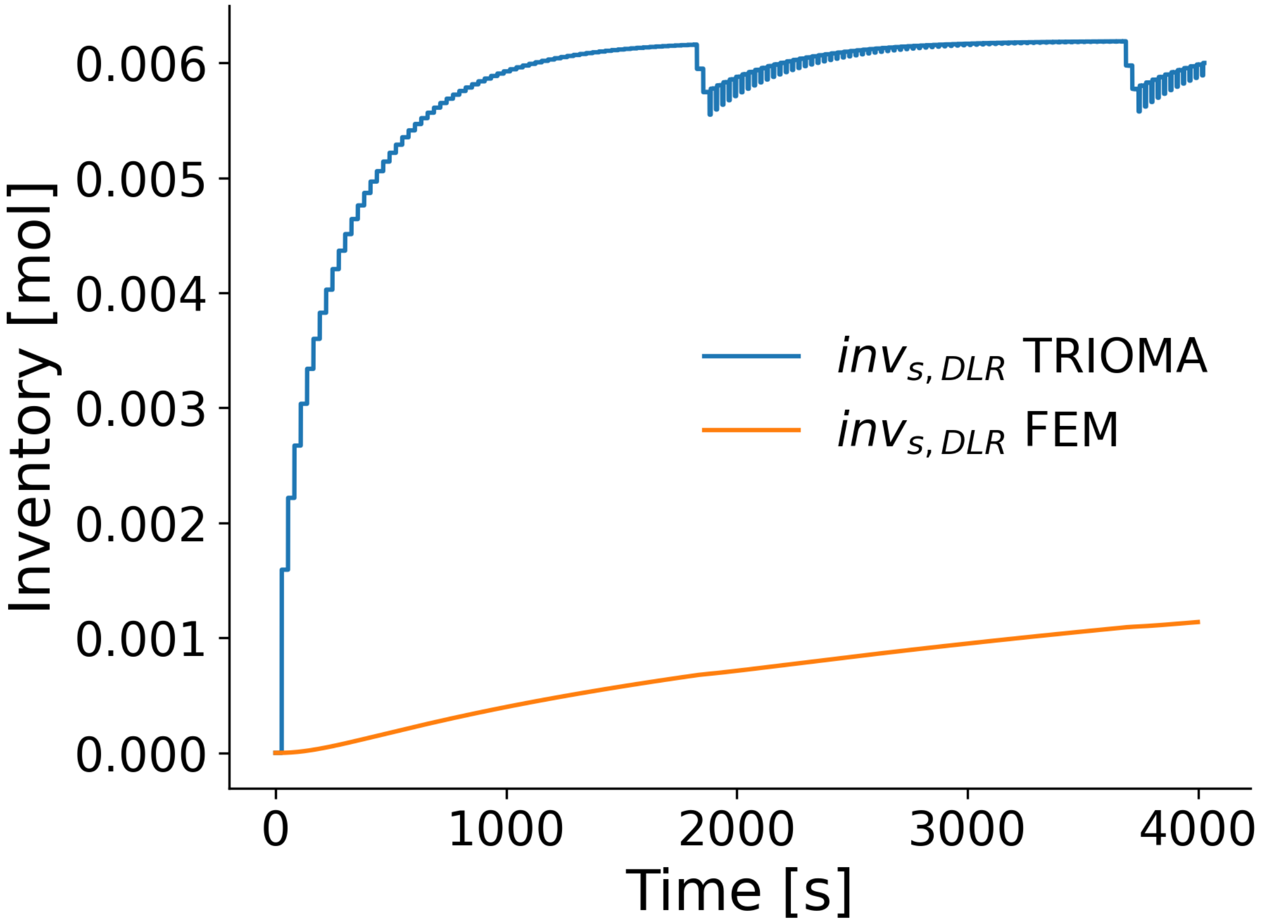
Time [s]
$inv_{s,PAV}$ TRIOMA
$inv_{s,PAV}$ FEM



0.006
0.005
0.004
0.003
0.002
0.001
0.000
Inventory [mol]
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Time [s]
$inv_{s,DLR}$ TRIOMA
$inv_{s,DLR}$ FEM