OpenMC-based Parametric Neutronic Assessment of Fusion Breeding Blankets for Compact D-T Reactor Configurations

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Scope of work

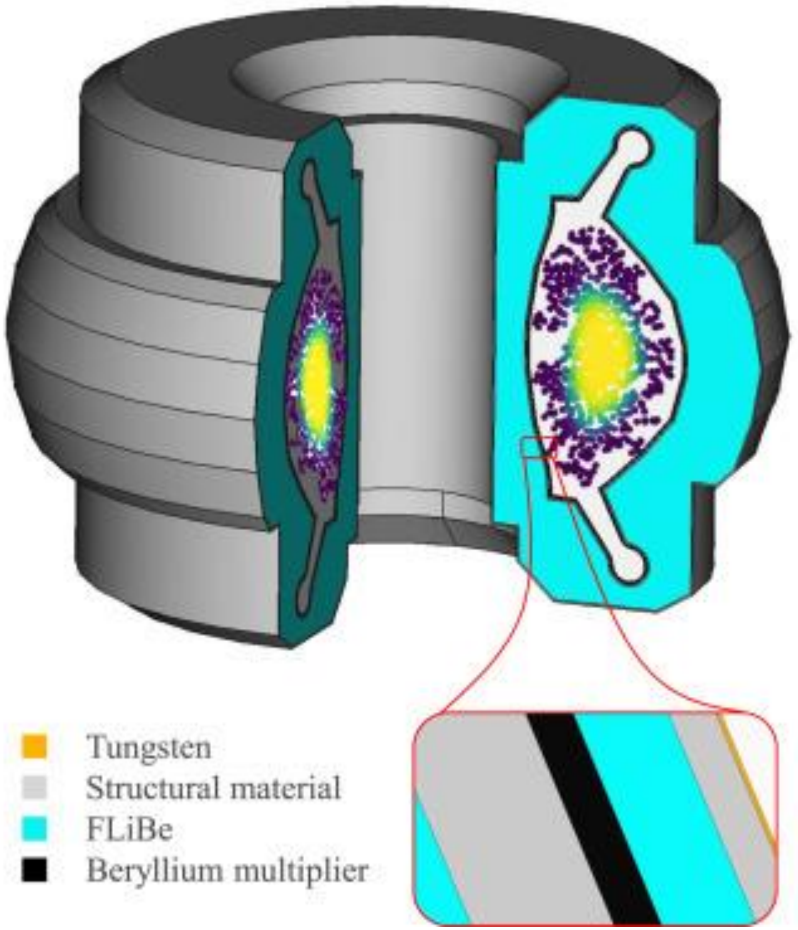
Pre-feasibility of the Breeding Blanket for high-field fusion reactor

Assess impact of breeding blanket design choices on key neutronic parameters:

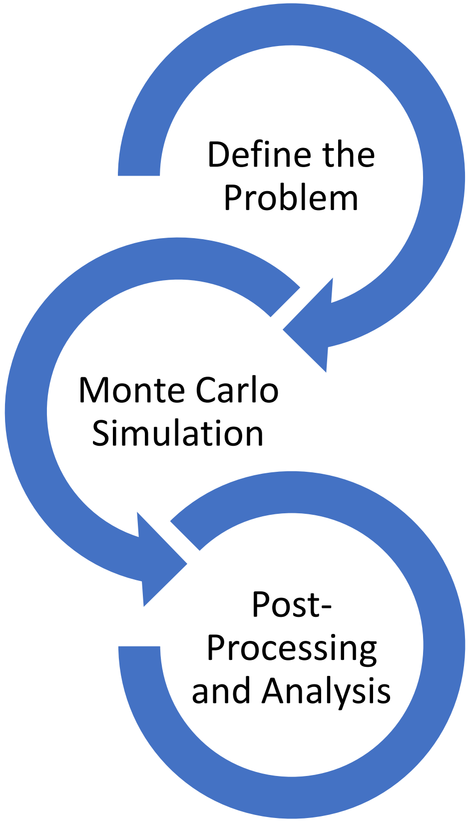
- Tritium self-sufficiency
- Structural integrity
- Shutdown dose rate

Methodology

- Open-source & reproducible workflow (OpenMC Monte Carlo)
- Constructive Solid Geometry (CSG) models for parametric studies
- Plasma chamber & external shielding kept constant
- Variation of internal blanket configuration within vacuum vessel



The OpenMC Monte Carlo Code



OpenMC is a community-developed Monte Carlo neutron and photon transport simulation code.

- Key Features
  - High-Fidelity Neutron Transport: Uses detailed physics models for accurate simulations.
  - Scalability: Can run on high-performance computing (HPC) clusters.
  - Python API: Provides easy scripting and automation capabilities.
- Applications of OpenMC
  - Nuclear reactor core design and analysis.
  - Radiation shielding and dose assessment.
  - Criticality safety evaluations.
  - Fusion reactor neutron transport studies.

github.com/openmc-dev/openmc

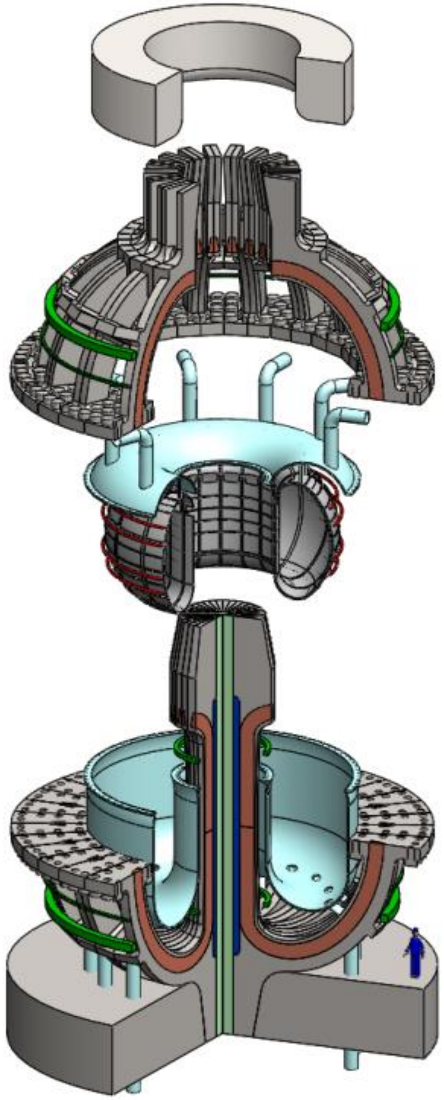
Breeding Blanket Concepts: An Overview

BB concept	First wall	Neutron Multiplier	Breeder	Coolant	Tritium carrier	Structures
Flibe LIB	Tungsten	Beryllium	Flibe	Flibe at low pressure and 850 K	Flibe	Inconel 718
PbLi LIB	Tungsten	Beryllium (optional)	PbLi	PbLi at 1070 K	PbLi	SiC/SiC
Liquid Li	Tungsten	None	Li	He	Li	V-5Cr-5Ti
WCLL	Tungsten	Pb.15.7Li	Pb.15.7Li	Water at 15.5 MPa, 295–328 °C	PbLi at 0.5MPa, 330-500 °C	Eurofer
HCPB	Tungsten	Beryllide (TiBe12 as reference material and CrBe12 as backup)	Advanced ceramic breeder (ACB), which is a solid solution of two-phase materials consisted of Li4SiO4 and about 35% mol. Li2TiO3.	Helium at 8 Mpa, 300-520°C	Helium at 0.2MPa, 450°C	Eurofer
WCCB	Tungsten	Beryllide (TiBe12)	Li2TiO3 pebbles	Water at 15.5 MPa, 280–325 °C	Helium (0.1%H2) at 0.1MPa	RAFM/CLAM

Liquid Immersion Blanket: FLiBe

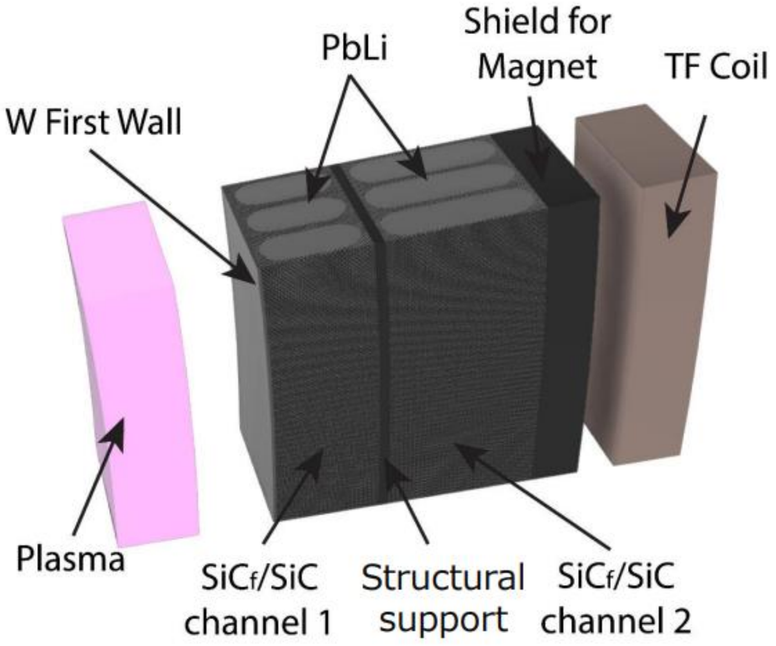
ARC LIB (Sorbom 2015)								
Radial Subdivision (%)	0.46%	1.83%	1.83%	0.91%	1.83%	91.32%	1.83%	
Material	FW	VV	Channel	Multiplier	Outer VV	Breeder	Tank outer	Total length
Thickness (mm)	5	20	20	10	20	1000	20	1095
Inconel 718 [%]		100			100		100	
Be [%]				100				
Flibe (90% Li) [%]			100			100		
Tungsten [%]	100							

https://doi.org/10.1016/j.fusengdes.2015.07.008



Liquid Immersion Blanket: PbLi SCLL

SCYLLA©: Advanced self-cooled blanket



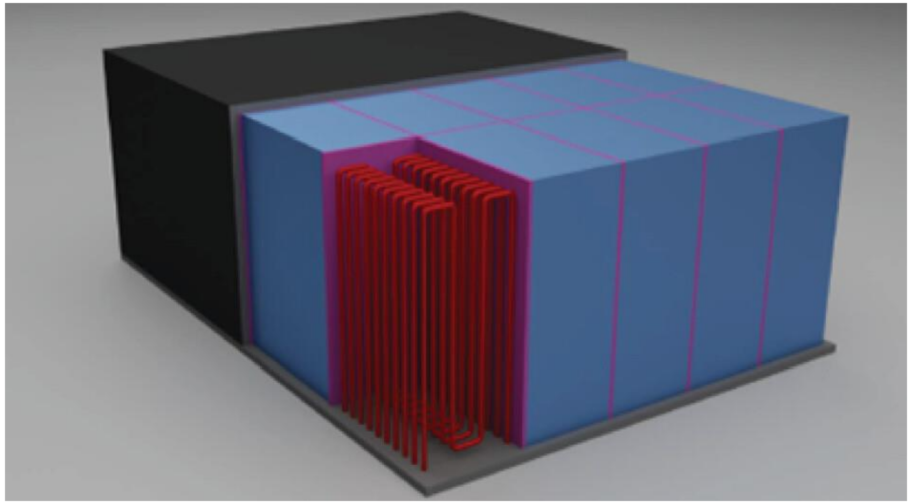
	PbLi SCLL (Pearson 2022)					
Radial Subdivision (%)	0.36%	2.42%	0.24%	84.85%	12.12%	100.00%
Material	FW	Structures	Multiplier	Breeder	Reflector	Total length
Thickness (mm)	3	20	2	700	100	825
SiC/SiC [%]		100		10		
Be [%]			100			
PbLi [%]				90		
Tungsten [%]	100					
Graphite					100	

https://doi.org/10.1109/TPS.2022.3211410

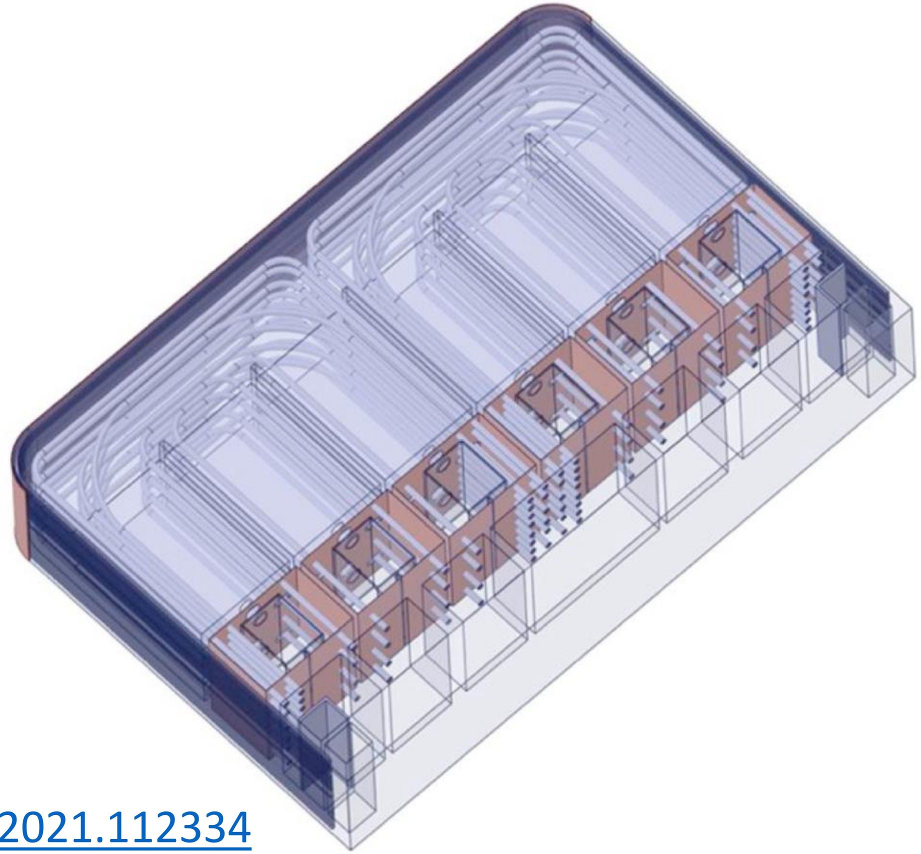
Liquid Li SCLL

Liquid Li SCLL (Lord 2024)					
Radial Subdivision (%)	0.36%	2.43%	85.05%	12.15%	100.00%
Material	FW	Structures	Breeder	Reflector	Total length
Thickness (mm)	3	20	700	100	823
V alloy [%]		100	6		
Be [%]					
Li [%]			65.7		
Tungsten [%]	100				
Void (vacuum) [%]					
He [%]			28.3		
Graphite				100	

https://doi.org/10.1098/rsta.2023.0410



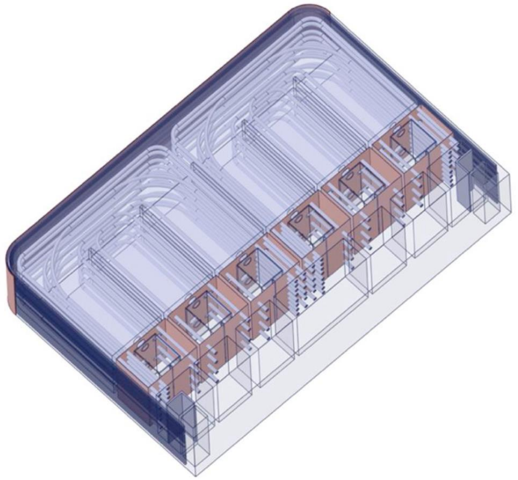
Water-Cooled Lead Lithium



https://doi.org/10.1016/j.fusengdes.2021.112334

Water-Cooled Lead Lithium

WCLL OB (Candido, 2021)								
Radial Subdivision (%)	0.88%	11.01%	19.82%	8.81%	6.61%	8.81%	44.05%	100.00%
Material	FW armour	FW structures	Breeding zone	Back-plate	PbLi manifold	Water Manifold	BSS	Total length
Thickness (mm)	2	25	45	20	15	20	100	227
Eurofer [%]		86.1	16.13	97.2	44.9	44.9	100	
Water [%]		13.9	1.46	0.91	44.1	44.1		
PbLi (90% Li) [%]			82.41	1.89				
Tungsten [%]	100							
Void (vacuum) [%]								



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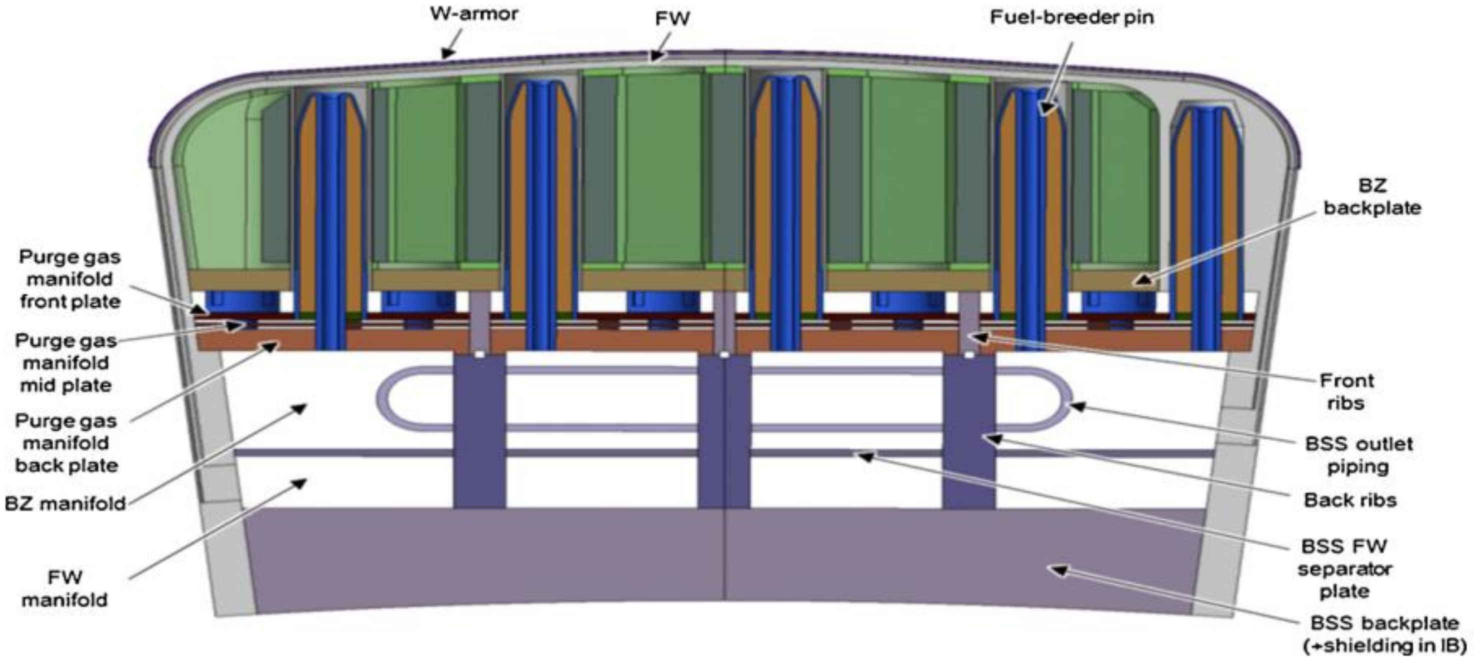
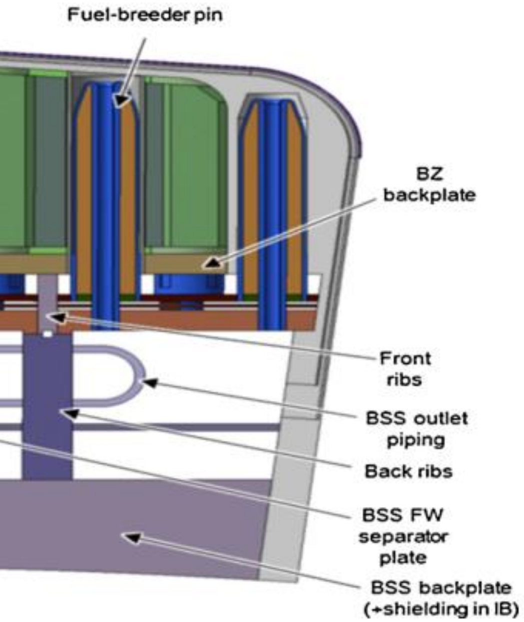
Helium-Cooled Pebble Bed



https://doi.org/10.1016/j.fusengdes.2021.112428

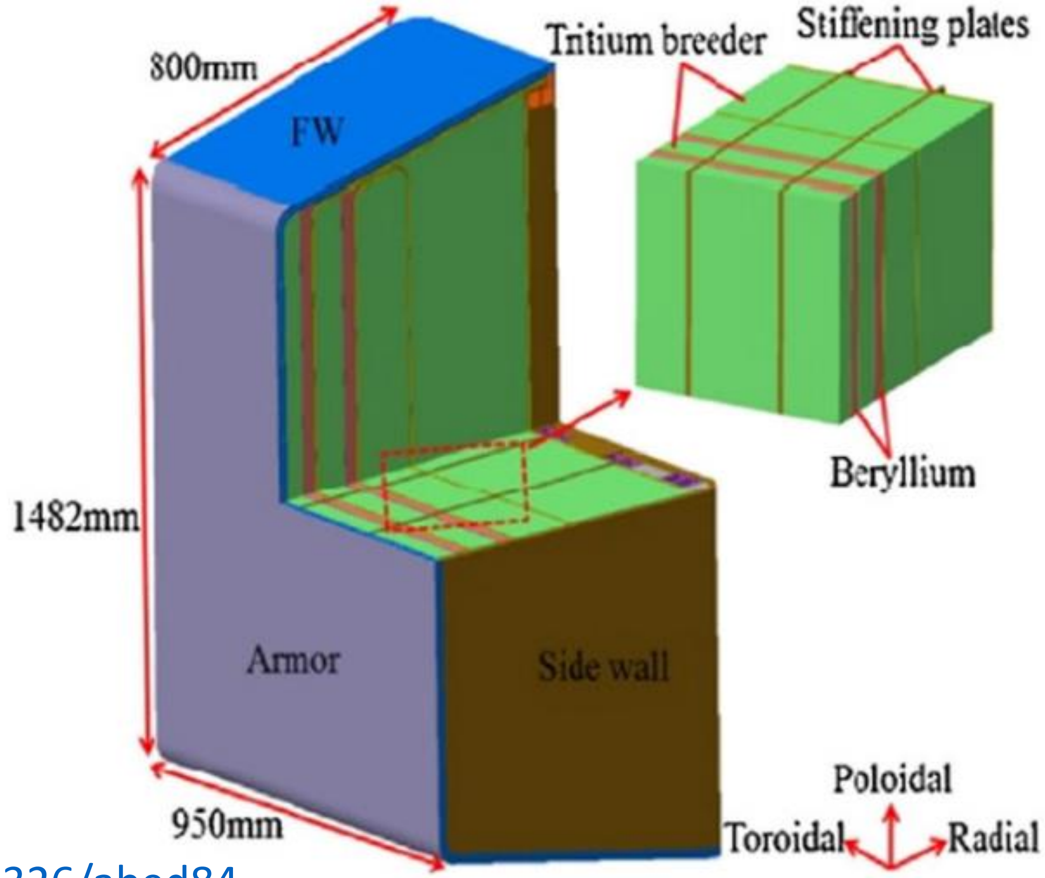
Helium-Cooled Pebble Bed



HCPB OB (Noce, 2021)							
Radial Subdivision (%)	0.20%	2.01%	51.51%	3.02%	8.85%	34.41%	100.00%
Material	FW armour	FW structures	BZ	Back-plate	Purge gas manifold	BSS manifold	Total length
Thickness (mm)	2	20	512	30	88	342	994
Eurofer [%]		57.3	14.3	80.2	37.9	46.7	
Helium [%]		42.7	26.1	9	56	52.1	
PbLi (60% Li) [%]							
Tungsten [%]	100						
TiBe12 [%]			49.3				
ACB [%]			10.3	10.8	6.1	1.2	

https://doi.org/10.1016/j.fusengdes.2021.112428

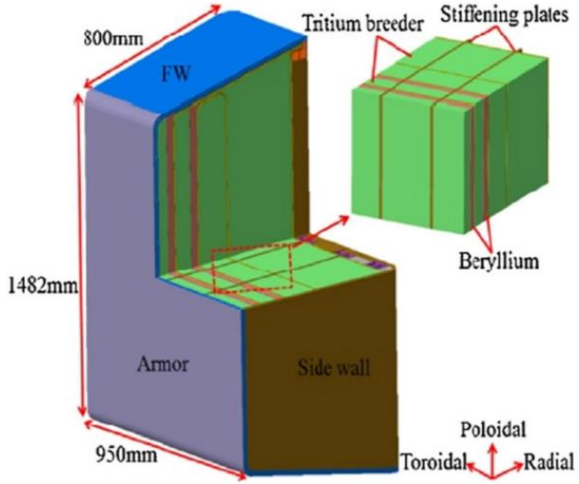
Water Cooled Ceramic Breeder



http://dx.doi.org/10.1088/1741-4326/abed84

Water Cooled Ceramic Breeder

WCCB (Zhu, 2021)									
Radial Subdivision (%)	1.07%	10.66%	7.25%	26.65%	5.86%	10.66%	31.98%	5.86%	100.00%
Material	FW armour	FW structures	Breeder	Multiplier	Cooling plate	Breeder	Multiplier	Cooling plate	Total length
Thickness (mm)	2	20	13.6	50	11	20	60	11	187.6
RAFM [%]		70.9			71.6			71.6	
Water [%]		29.1			28.4			28.4	
Li2TiO3 (80% Li) [%]			14.4			14.4			
Be12Ti			65.6	80		65.6	80		
He			20	20		20	20		
Tungsten [%]	100								



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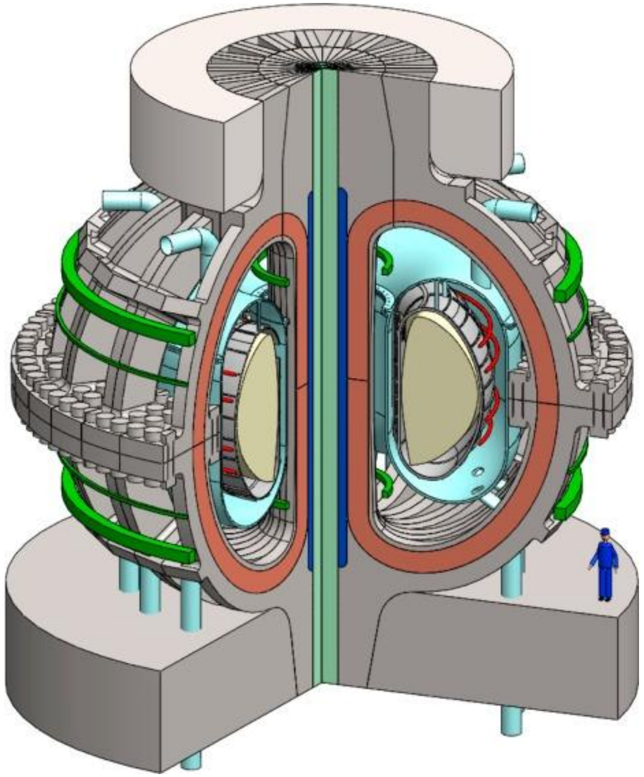
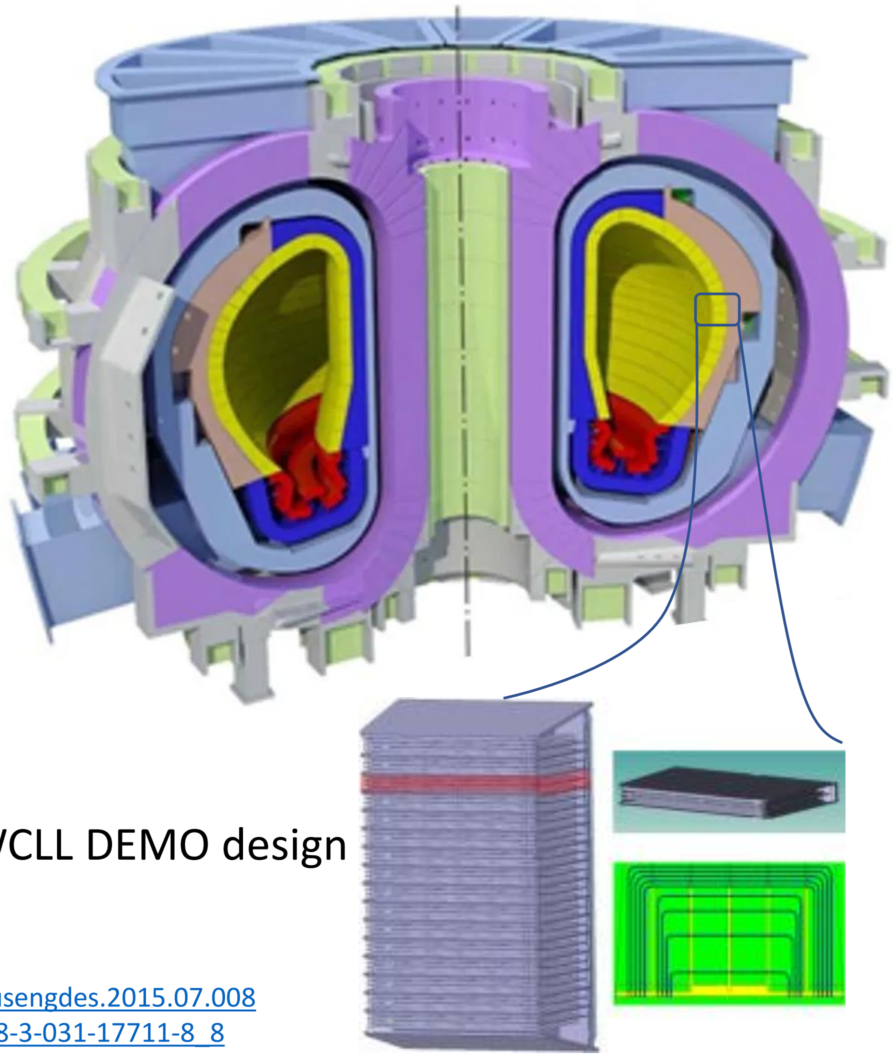
Design Options for Blanket



Liquid Immersion Blanket ARC-class reactor design

Several different designs to analyze (e.g. liquid immersion blanket, solid blankets,…)

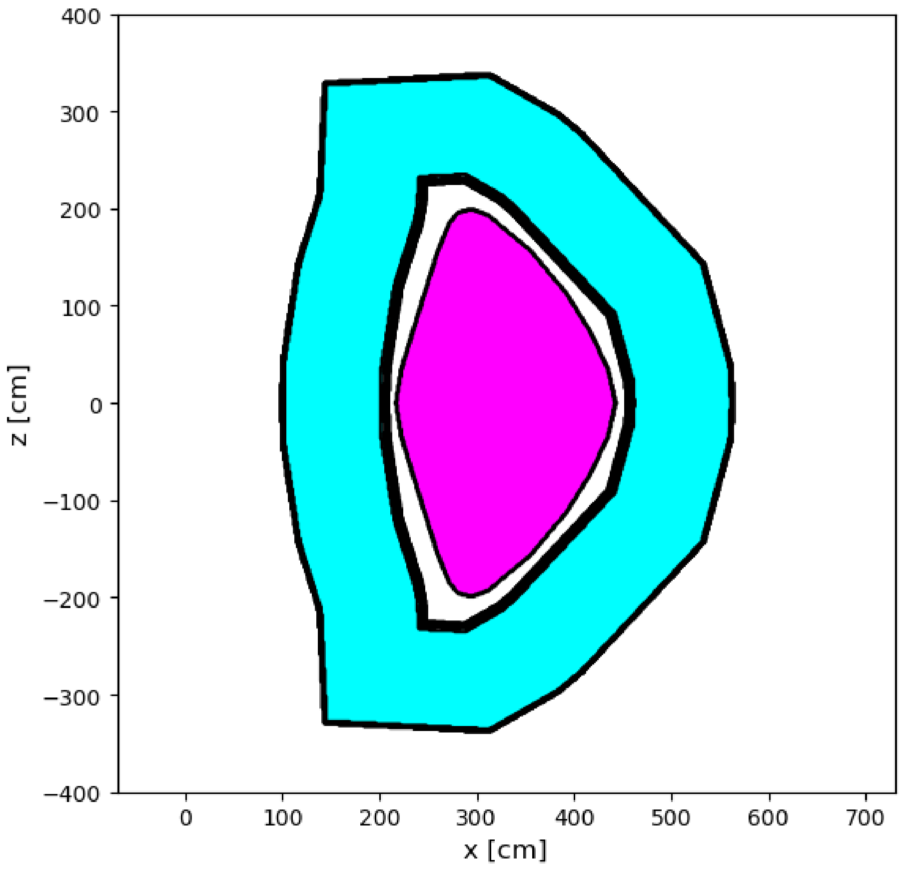
How can they be analyzed using a single neutronic model?



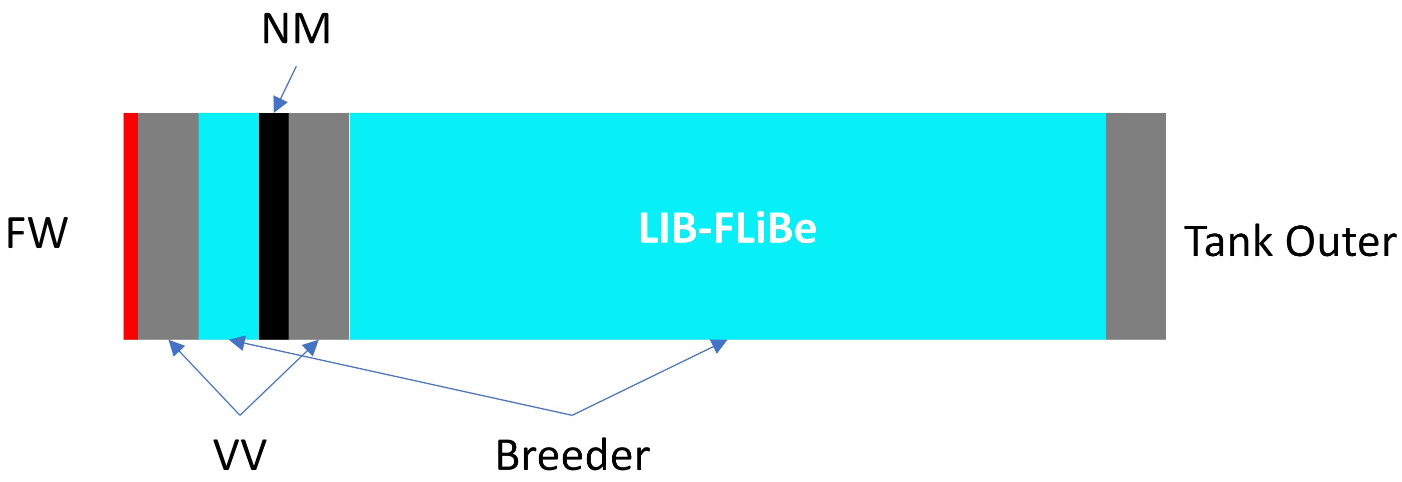
WCLL DEMO design

https://doi.org/10.1016/j.fusengdes.2015.07.008
https://doi.org/10.1007/978-3-031-17711-8_8

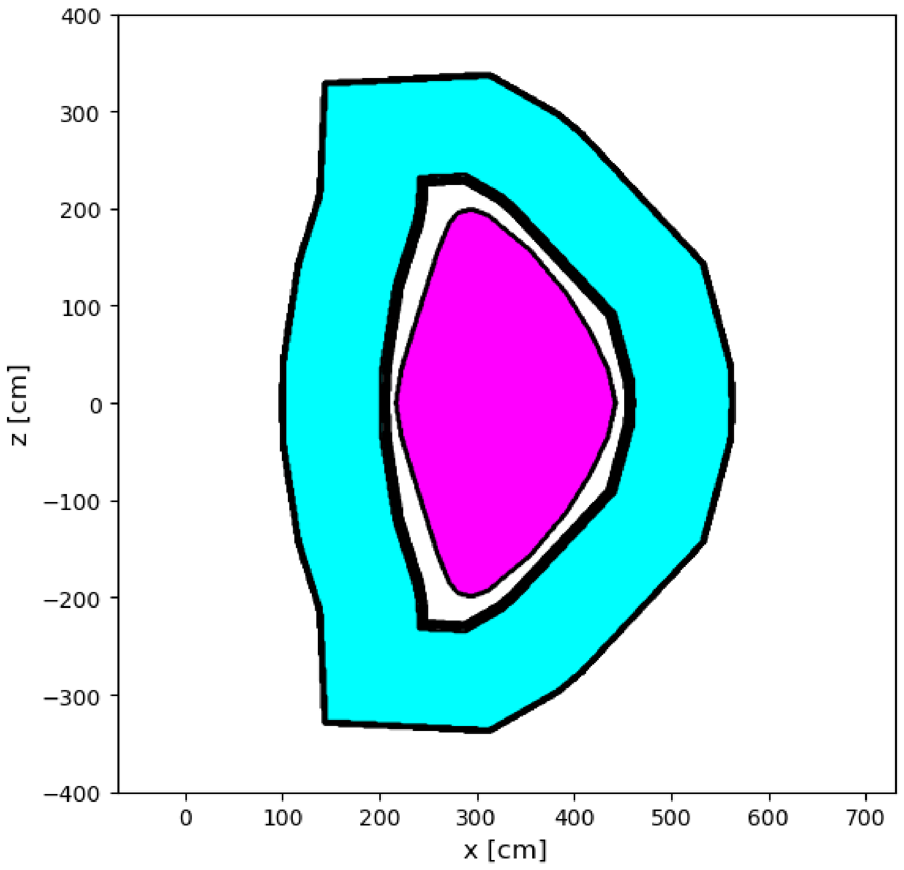
Parametric model



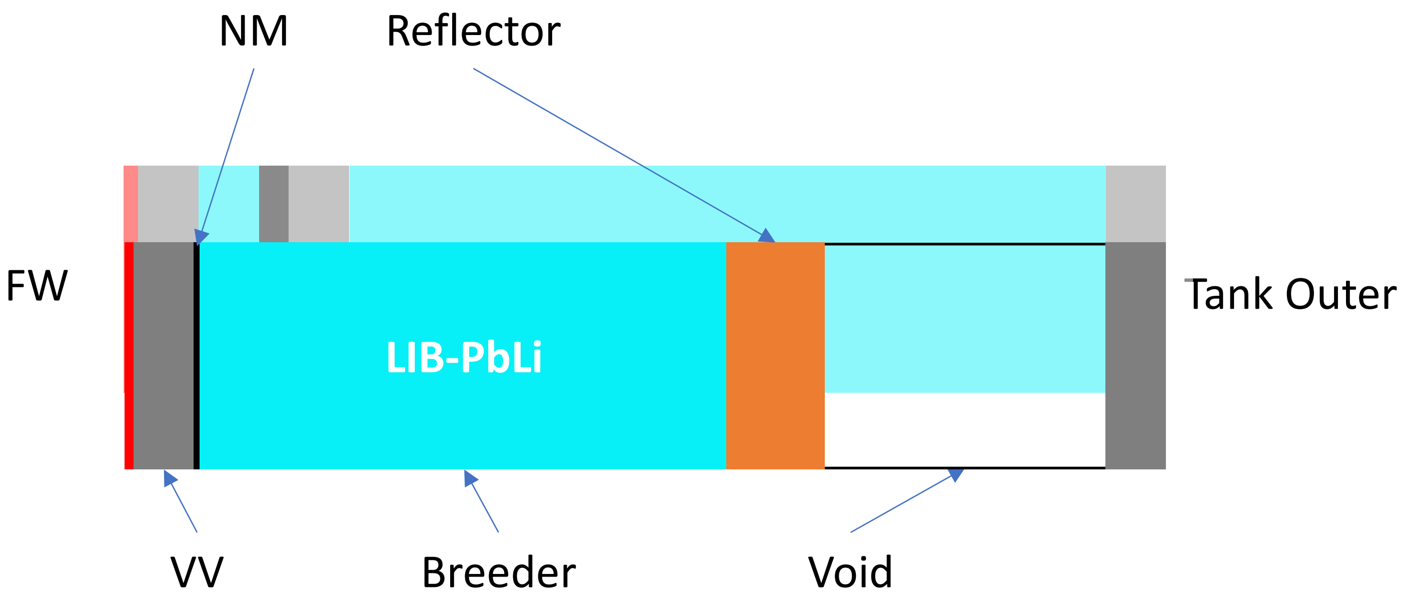
- CSG geometry
- Simple D-T plasma source
- Fusion power: 1000 MW
- Neutron source: $3.55 \cdot 10^{20}$ n/s



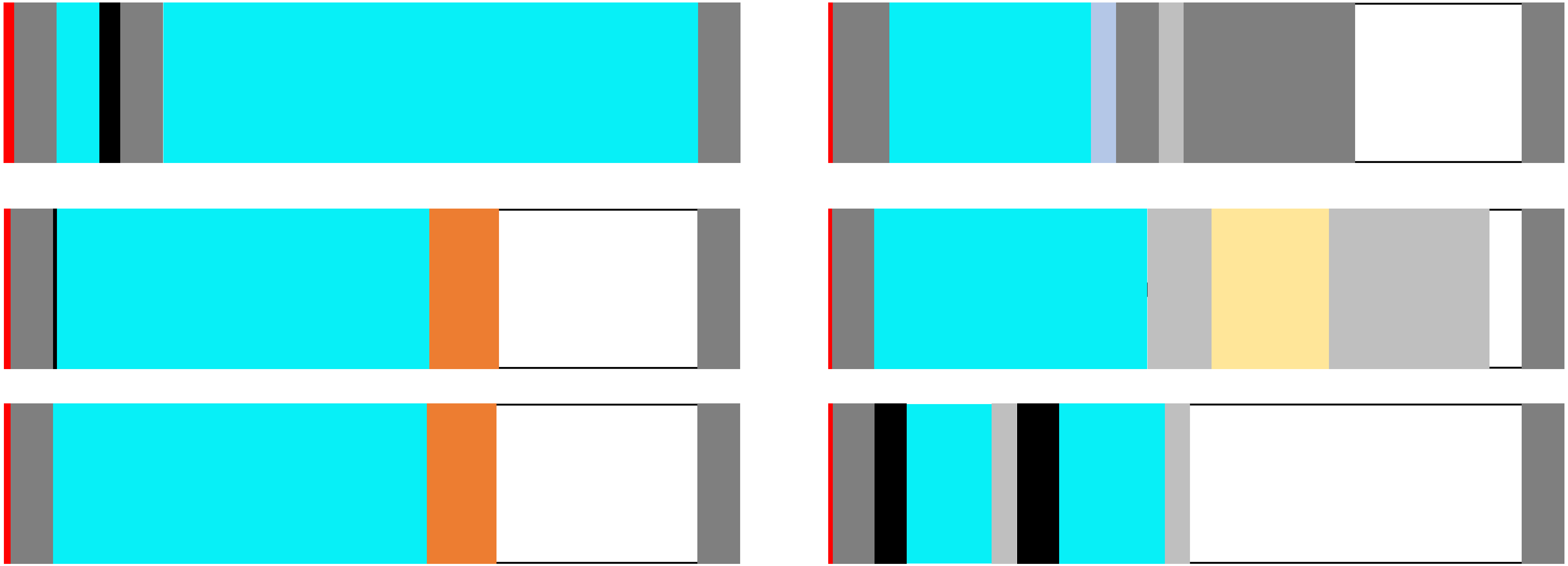
Parametric model



Each layer is modeled as a **homogeneous** material that includes all the elements present in the different sub-layers of the various configurations.
An **average** density is assigned, with the aim of obtaining preliminary neutronics results.



Section view



Tritium Breeding Ratio - TBR

TBR = 1 is achieved when for every tritium atom consumed in the fusion process, a new tritium atom is produced.

$$\mathrm{TBR} = \frac{\text{Tritium Bred}}{\text{Tritium Burnt}} > 1.1$$

- Depends on the choice of the breeder and **structural materials**
- The two major tritium breeding reactions are from $^{6}Li(n,Xt)$ $^{7}Li(n,Xt)$

Breeding Blanket	TBR
LIB-FLiBe	1.08
LIB-PbLi	0.96
Liquid Li SCLL	1.22
WCLL	1.17
HCPB	1.39
WCCB	0.52

Energy Multiplication Factor - EM

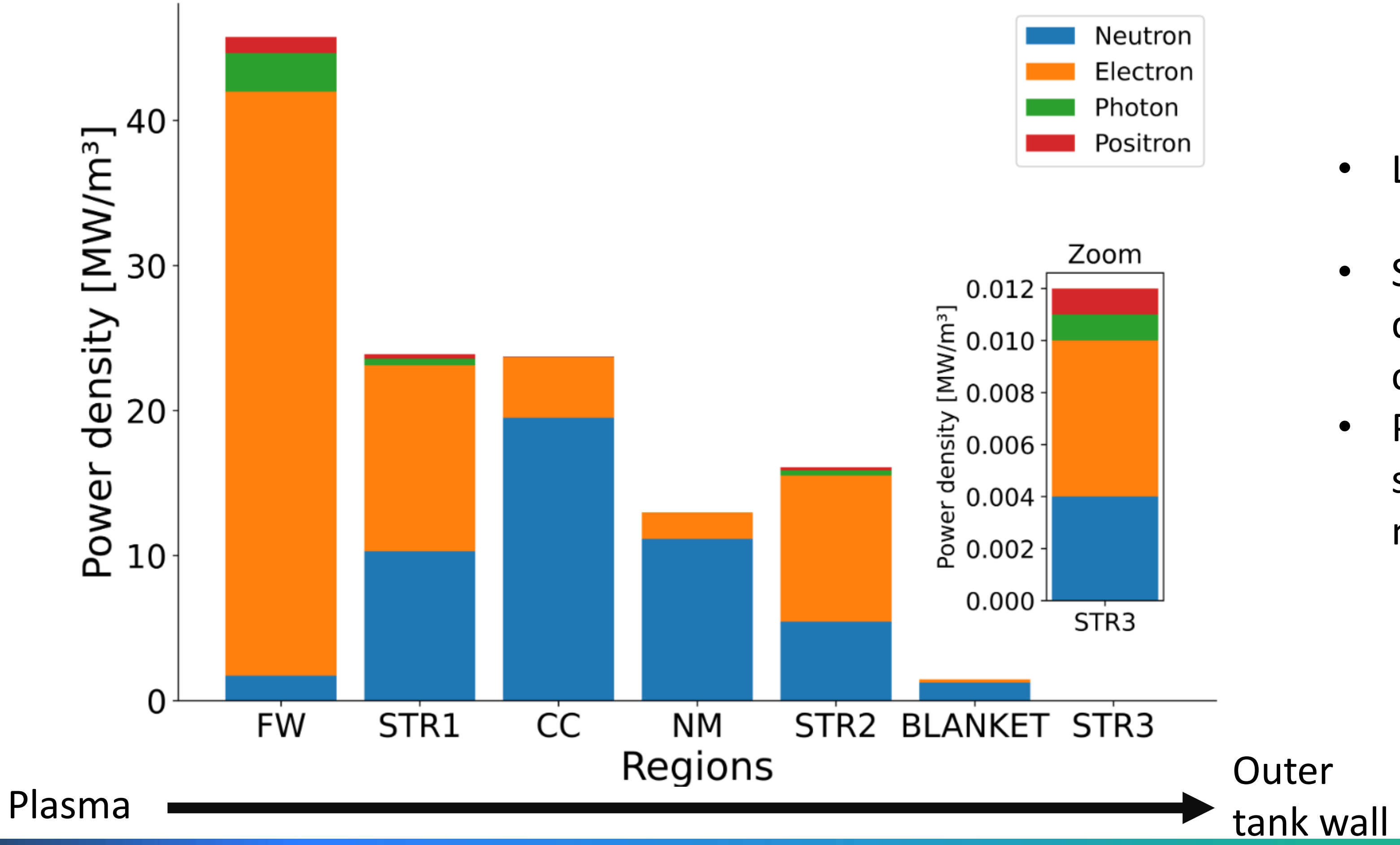
Indicates how efficiently neutron energy is converted into **heat** inside the reactor.

$$\text{EM} = \frac{\text{Energy absorbed}}{\text{Fusion n energy}} > 1.0$$

- Accounts for **secondary contributions**, e.g.:
  - Photon interactions from **radiative capture**
  - **Inelastic scattering** processes
- Key parameter for evaluating **blanket performance** and overall energy balance of the system.

Breeding Blancket	EM
LIB-FLiBe	1.14
LIB-PbLi	1.09
Liquid Li SCLL	1.03
WCLL	1.16
HCPB	1.34
WCCB	0.85

Power deposition



- LIB – FLiBe

- Significant impact of neutron power deposition, especially in areas closest to the plasma
- Power-depositing electrons are secondary electrons generated by nuclear interactions

Layer	LIB-FLiBE [MW/m³]	LIB-PbLi [MW/m³]	Liquid Li SCLL [MW/m³]	WCLL [MW/m³]	HCPB [MW/m³]	WCCB [MW/m³]
First wall	46.98	88.49	50.94	76.30	71.12	83.28
Structures	23.22	20.68	13.68	24.05	13.83	25.82
Breeder	24.69		3.19	5.55	6.47	34.64
Back-plate				0.58	1.03	
PbLi manifold				3.11		
Water manifold				1.01		
Multiplier	12.54	22.75				10.29
Cooling						16.88
Structures	16.07					
Breeder	1.53	3.23				20.40
Multiplier						5.15
Cooling						1.08
Reflector		0.22	1.12			
Purge gas manifold					0.31	
BSS				0.52	0.07	
Structures	0.01	0.98	1.87	0.13	0.03	0.05

Displacement per Atom - DPA

DPA quantifies the extent of atomic displacements in materials subjected to neutron radiation.

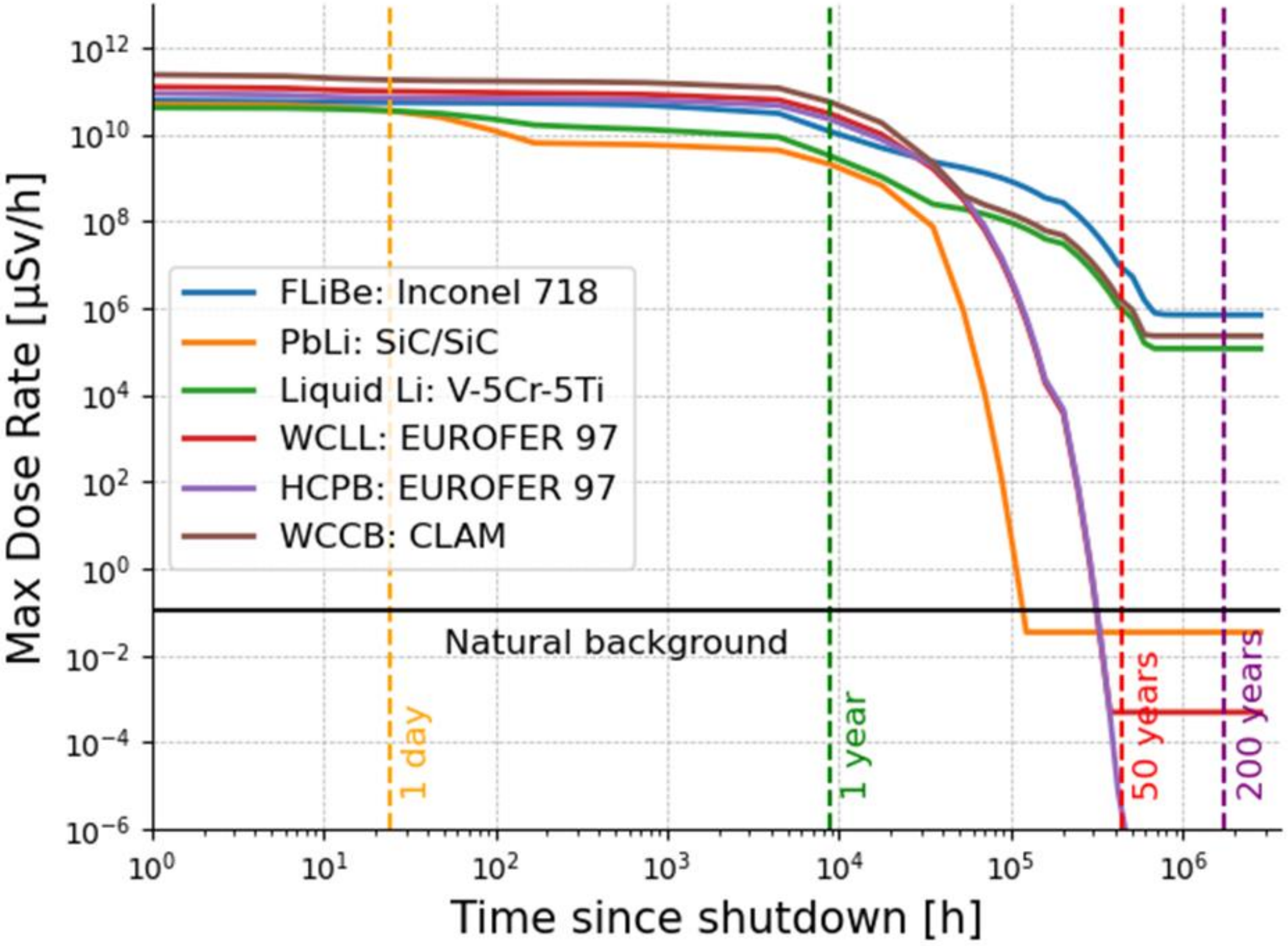
- Damage energy deposited per source neutron
- Threshold displacement energy
- The damage-energy represents the kinetic energy available for creating atomic displacements.
- Assuming that about 20% recombine with the original lattice locations

Breeding Blancket	Material	DPA
LIB-FLiBe	Inconel 718	23.61
LIB-PbLi	SiC/SiC	56.70
Liquid Li SCLL	V-5Cr-5Ti	25.52
WCLL	EUROFER 97	22.21
HCPB	EUROFER 97	24.04
WCCB	CLAM	16.25

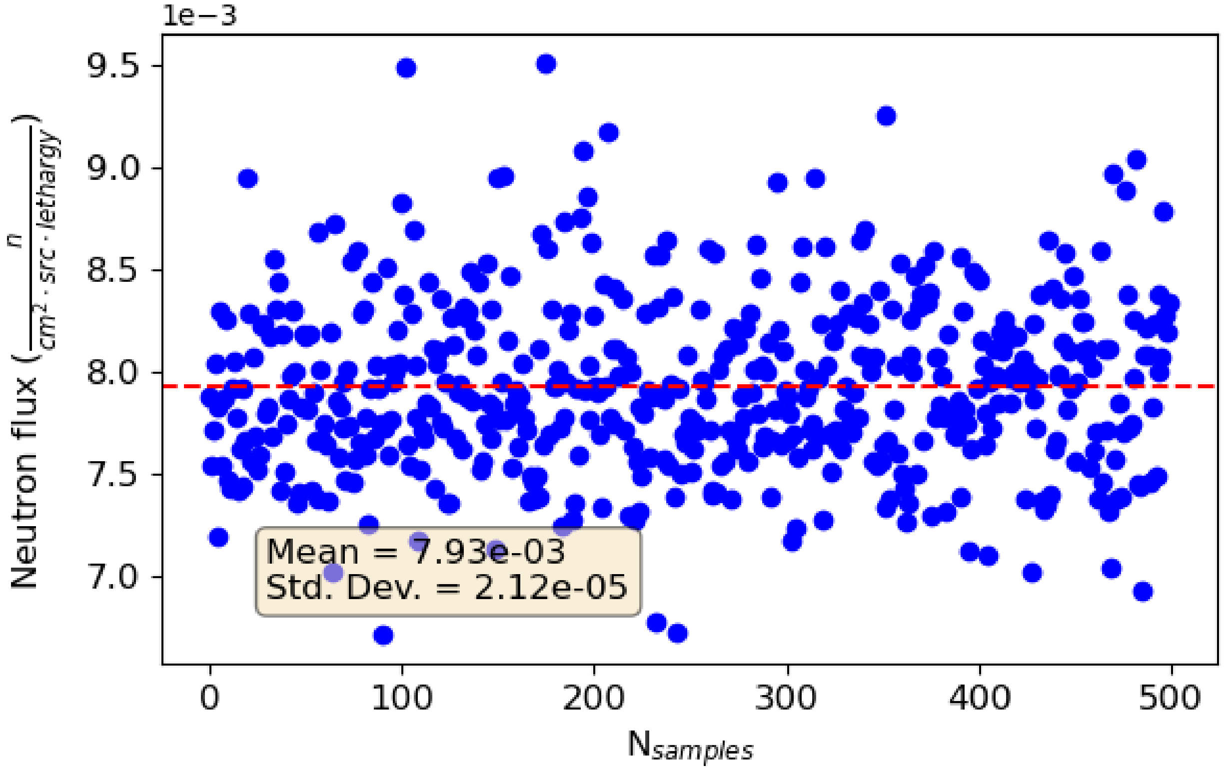
Evaluated on the first layer of structural material

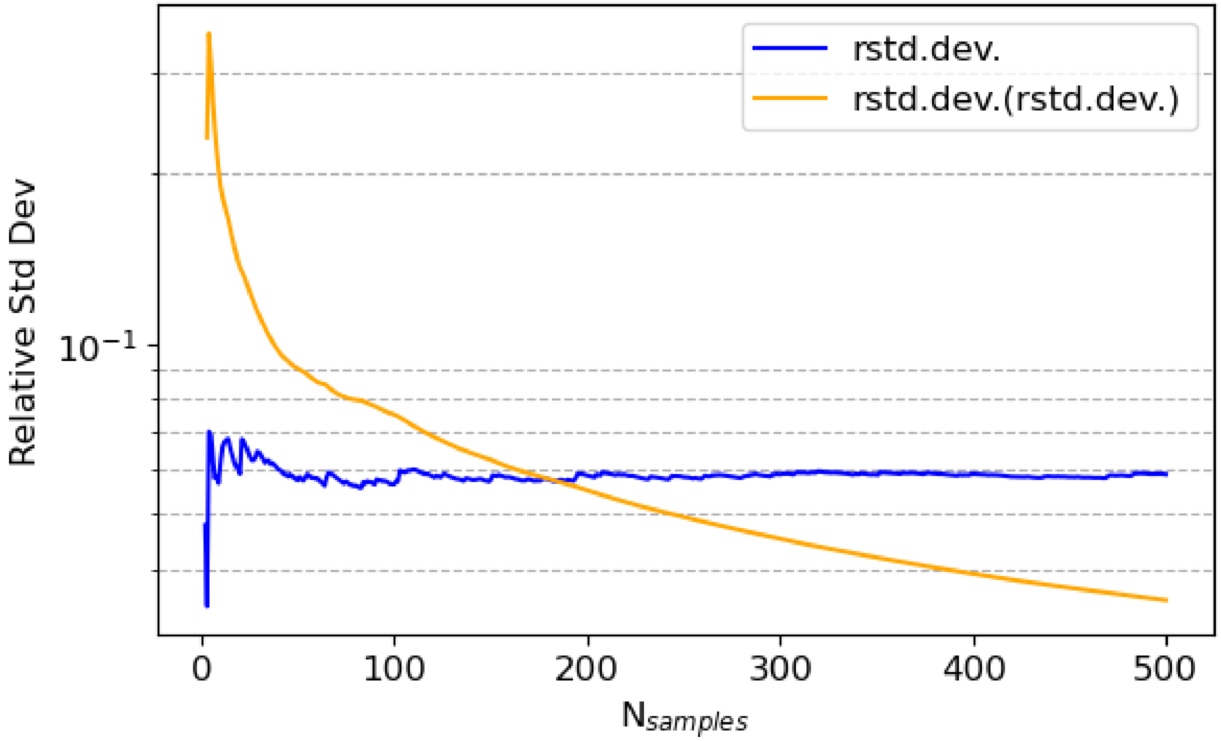
Shutdown Dose Rate

- OpenMC implements the Direct 1-Step (**D1S**) method.
- A coupled neutron–photon transport is performed where prompt photons are replaced by decay photons from activated materials.
- **1 year** of full-power irradiation simulated.
- Post-irradiation dose rate evaluated at multiple time steps (cooling times).



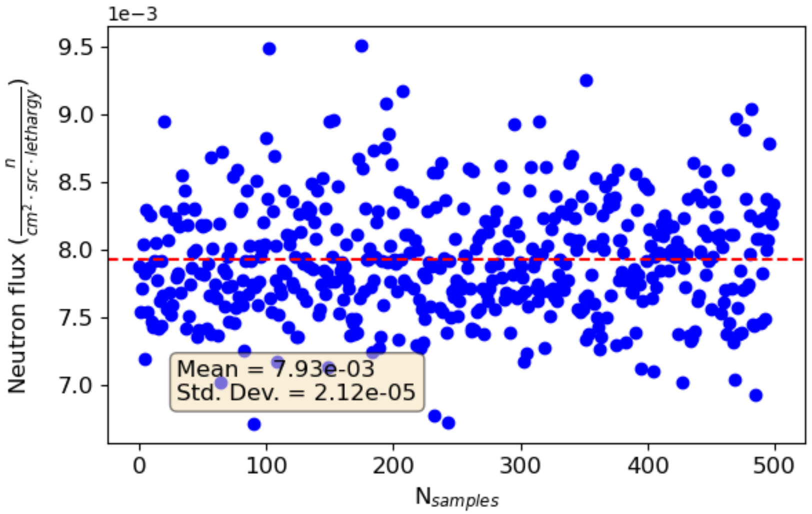
Uncertainty Quantification - UQ

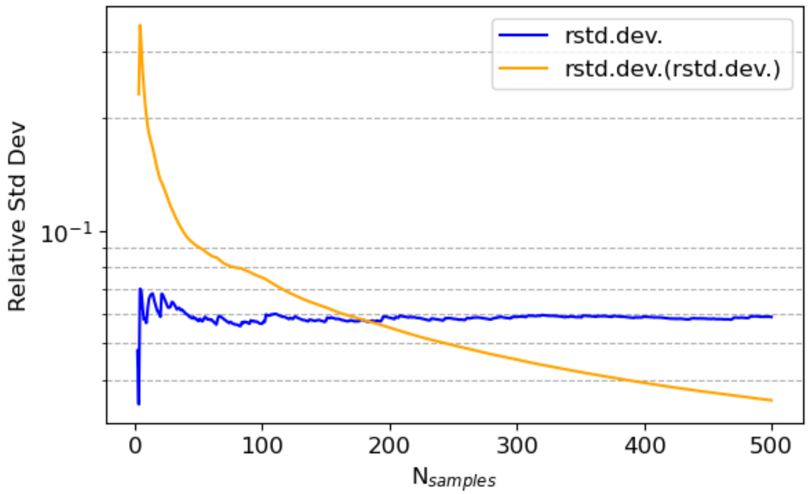




Uncertainty Quantification - UQ

- Fast Total Monte Carlo
- UQ was performed using 500 perturbed Be-9 cross sections from ENDF/B-VIII.0 to evaluate the impact of input cross-sections data uncertainties on the simulation results.





- Left: 500 sampled results of the leakage tally. The blue dots represent the 500 means, while the dashed red line indicates the mean of the means.

- Right: Progressive relative standard deviation of the means (blue) and relative standard deviation of the standard deviations (orange),used for convergence analysis.

https://github.com/luca-fiorito-11/sandy.git

Conclusions

- **HCPB** → Best overall performance: high TBR & EM, low DPA, dose rate < background < 50 years.
- **WCCB** → Lowest performance: TBR < 1, EM < 1, high breeder load, long-term activation.
- **WCLL** → Balanced performance, but higher activation and long-term dose rate persistence.
- **FLiBe** → Acceptable TBR/EM, but suffers from long-lived activation (Inconel 718).
- **PbLi** → Fast decay of activation, dose rate close to background in ~1 year, but TBR < 1.
- **Liquid Li** → Promising compromise: good neutronics, relatively fast activation decay, manageable DPA.

- The analysis highlights the need for further optimization and the transition to realistic **CAD-based** models for validation.

Thank you for your attention

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