EUROfusion

International Atomic Energy Agency

Technical Meeting on Tritium Breeding Blankets and Associated Neutronics
2–5 Sept 2025
IAEA Headquarters, Vienna, Austria

Design status of the European DEMO Helium Cooled Pebble Bed breeding blanket

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Breeding Blanket Project in EUROfusion

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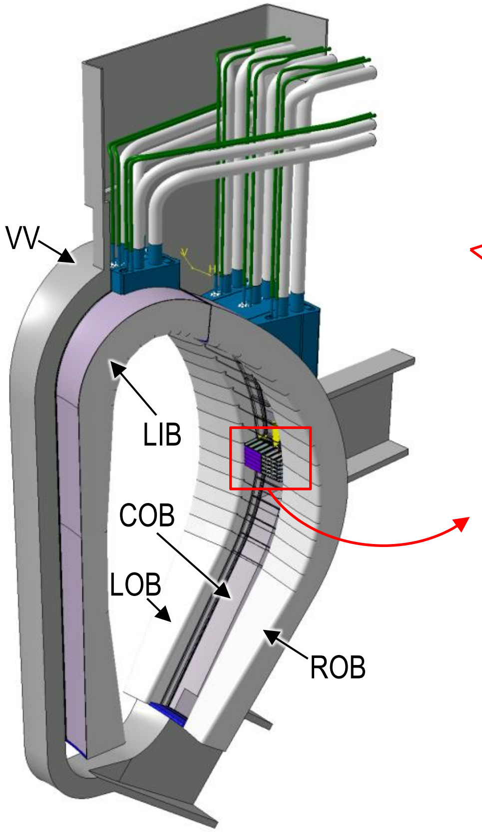
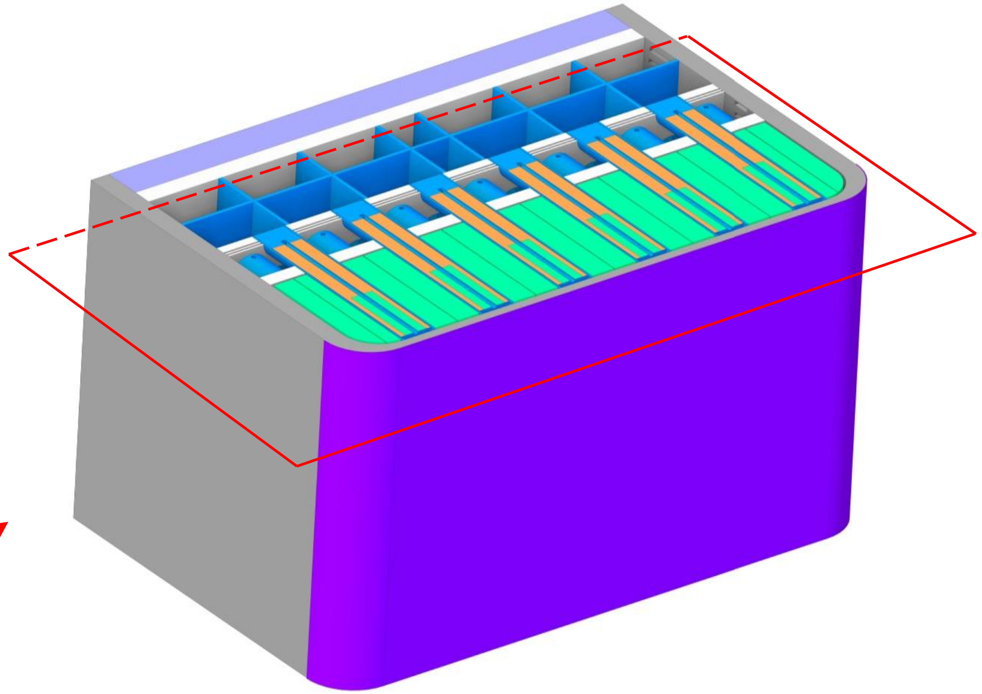
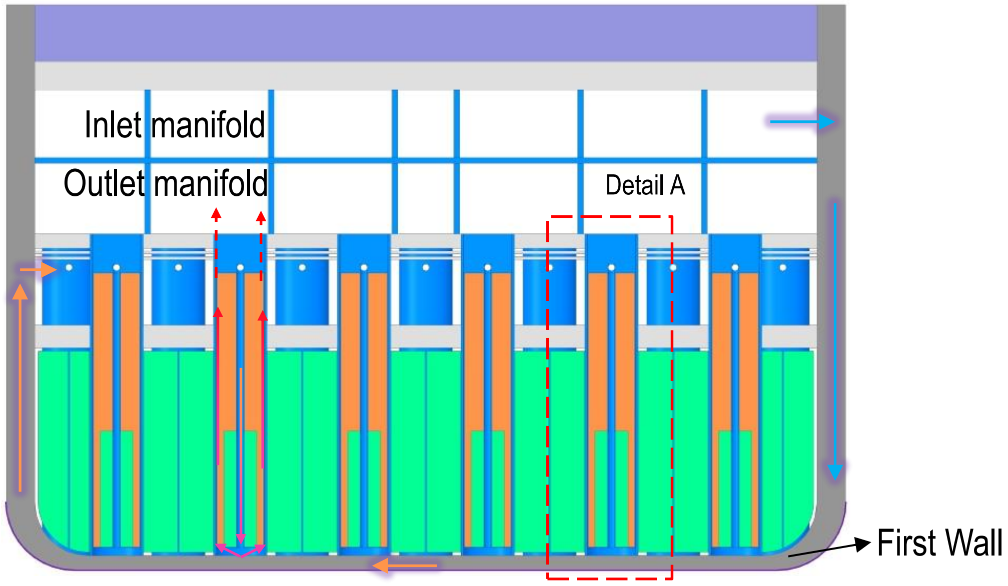
Outline

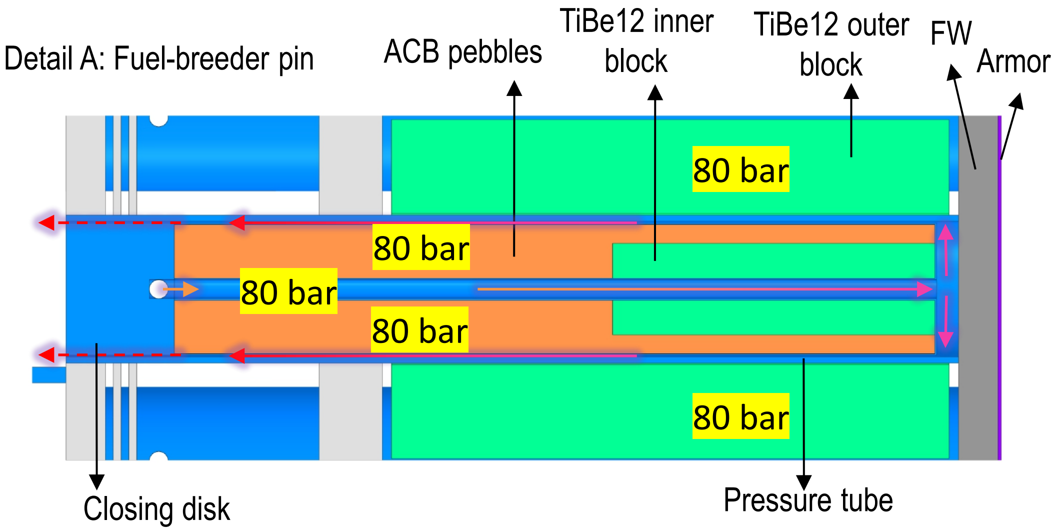
1. Current design of HCPB Breeding Blanket
2. Neutronics analysis
3. Thermal hydraulics analysis
4. Structural analysis
5. Reliability analysis
6. Design of HCPB Tritium Extraction and Recovery System
7. Conclusions

Design of high pressure purge gas HCPB (HCPB-BL2017-HP-v1)









- Coolant: He @80 bar, 300-520°C
- Structural steel: Eurofer97
- Fuel-breeder pins contain advanced Li-ceramic breeder (ACB) pebble
- T-extraction: He + 100 Pa H_2 @80 bar
- Inner beryllide block inside ACB pebble

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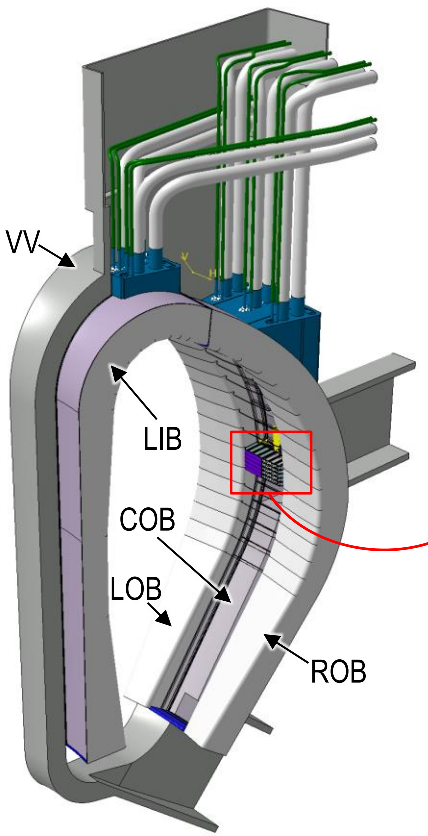
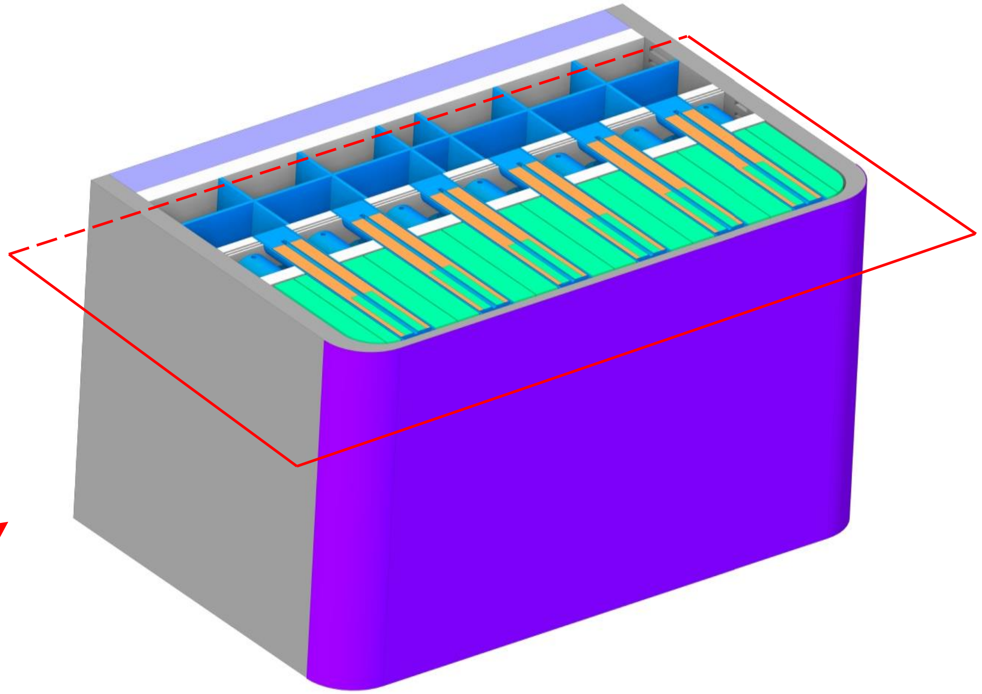
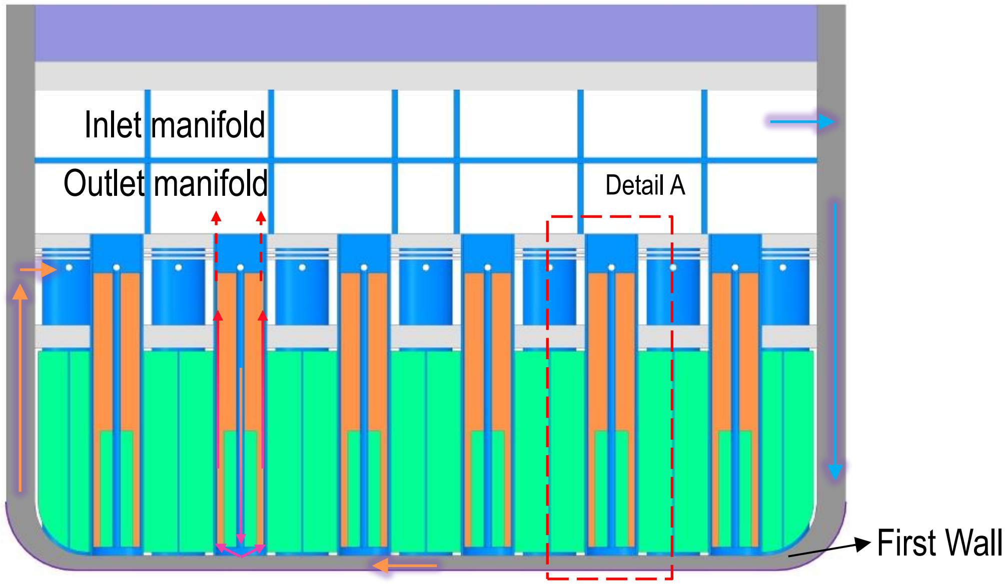
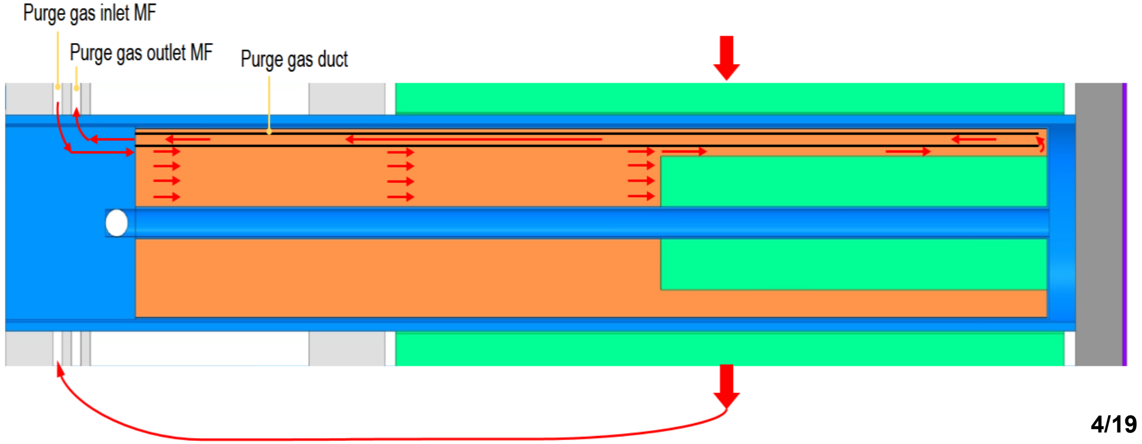






Detail A: Fuel-breeder pin



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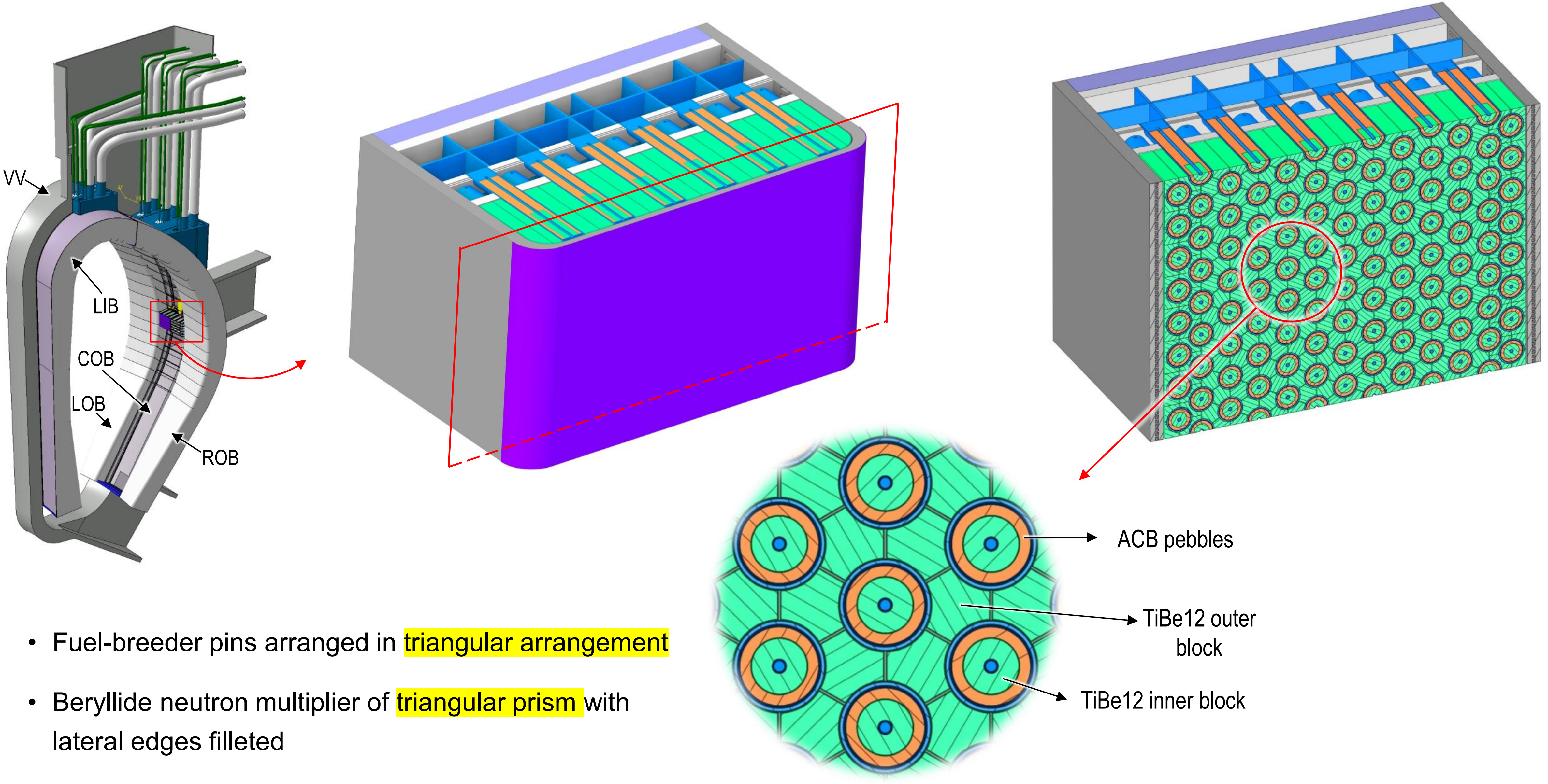
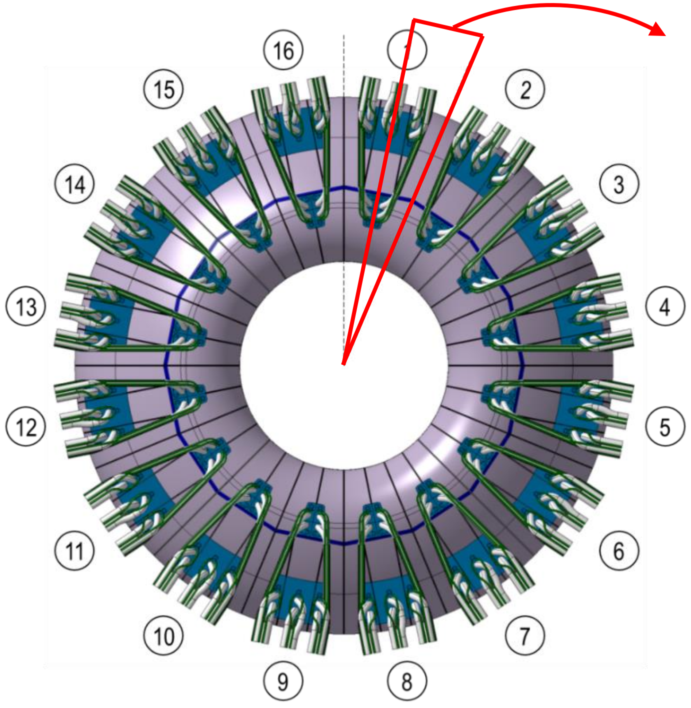


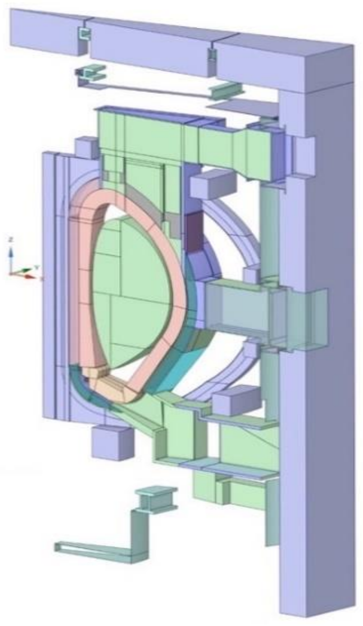
- Fuel-breeder pins arranged in triangular arrangement
- Beryllide neutron multiplier of triangular prism with lateral edges filleted

Tritium breeding assessment

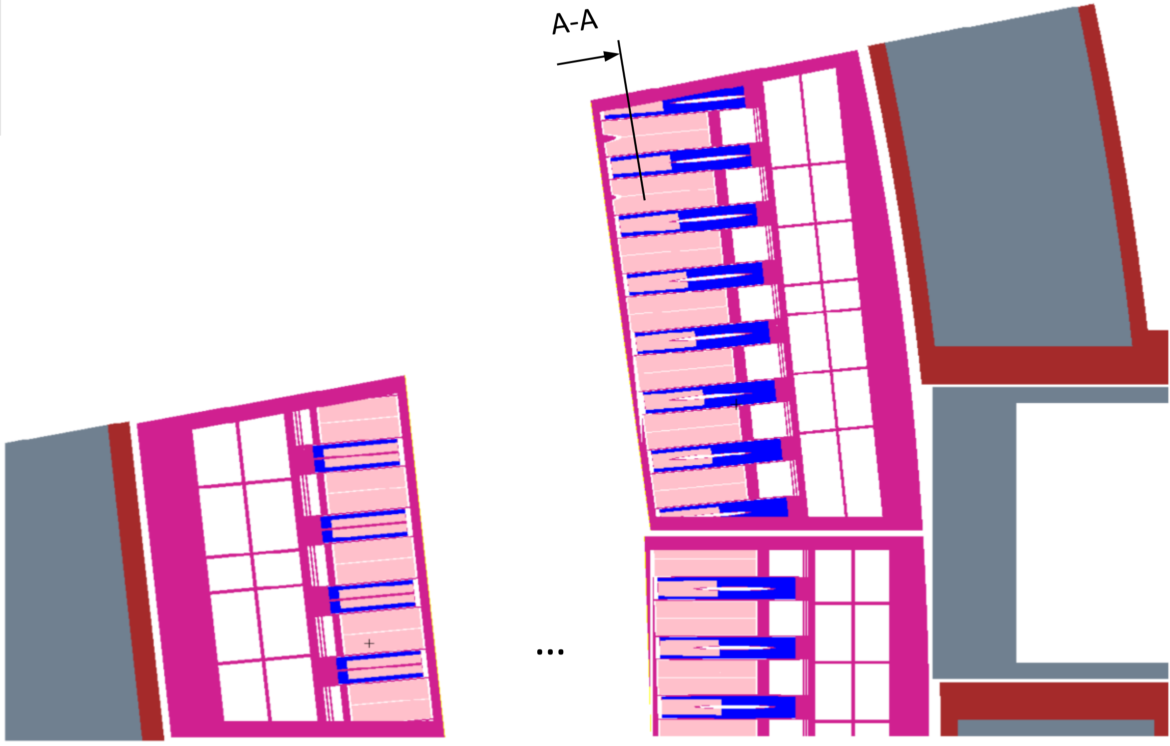
- **Without considering cut-outs**
  - 3D heterogenous model calculated using MCNP6.2 and JEFF-3.3
  - 11.25°: half of a sector of reactor



360° Model

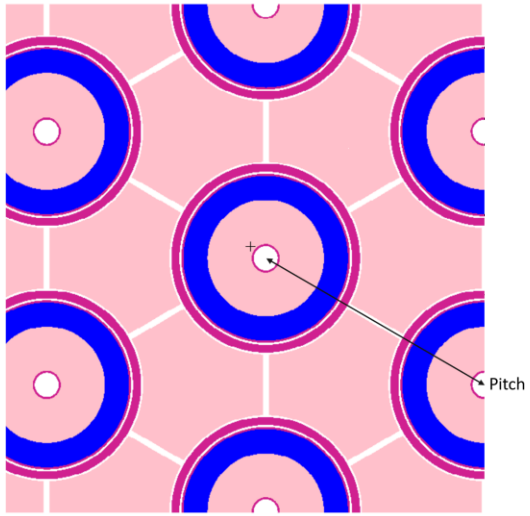


11.25° Model



Radial-toroidal cut view - inboard

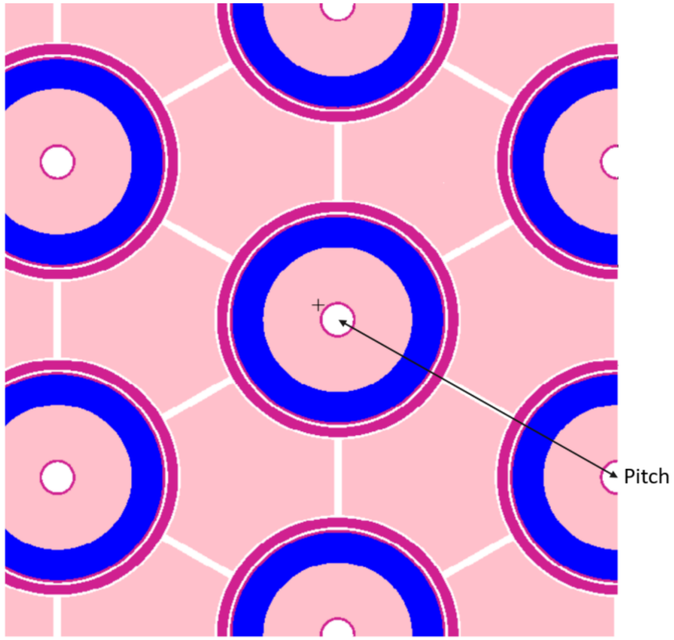
Radial-toroidal cut view - outboard



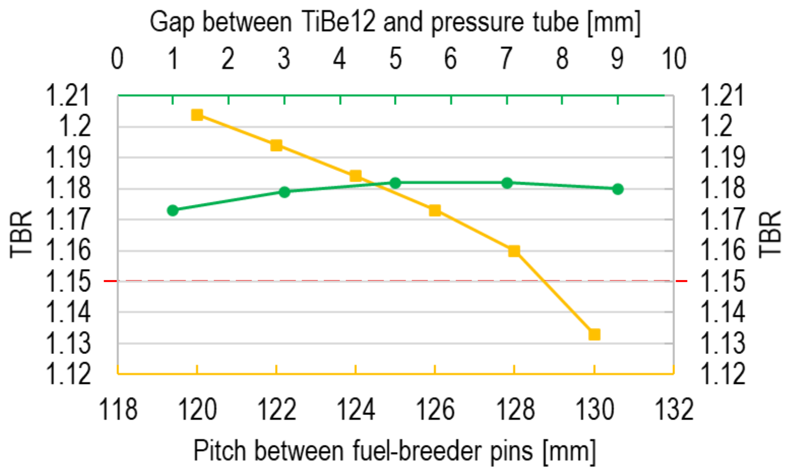
A-A: Poloidal-toroidal view

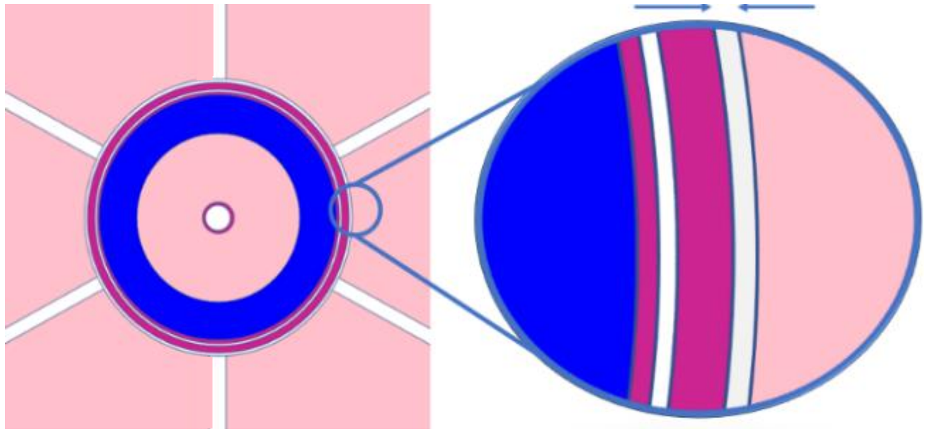
Tritium breeding assessment

- **Without considering cut-outs**
  - The smaller the pitch, the higher TBR (TBR=1.16~1.20 ±0.01%)
  - Larger gap facilitates neutron streaming



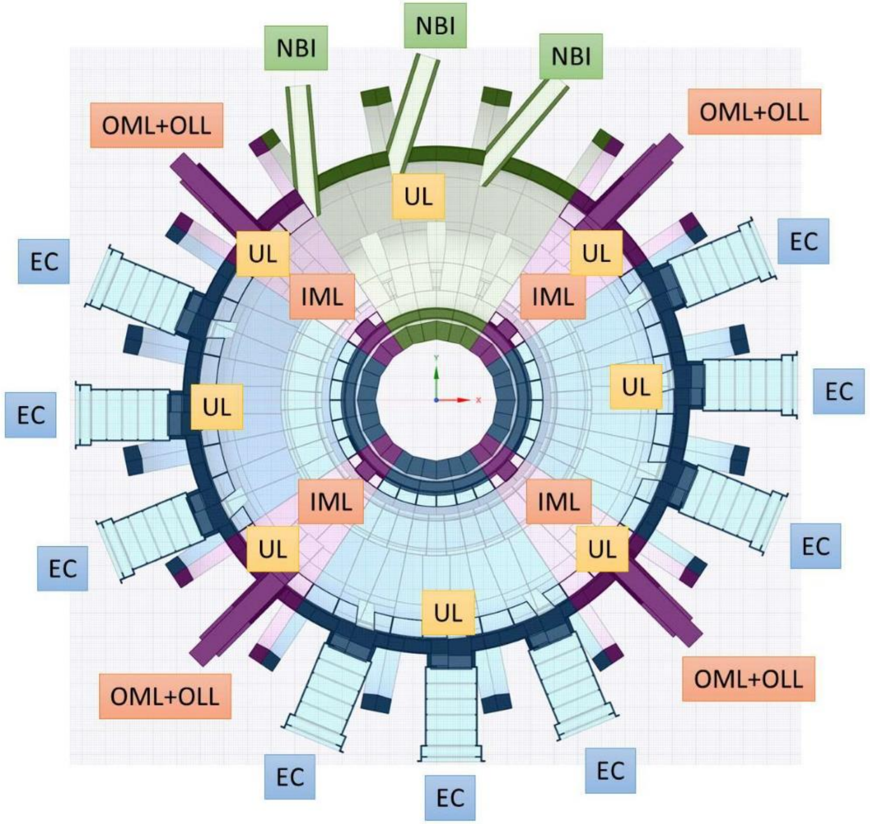
Pitch between two pins

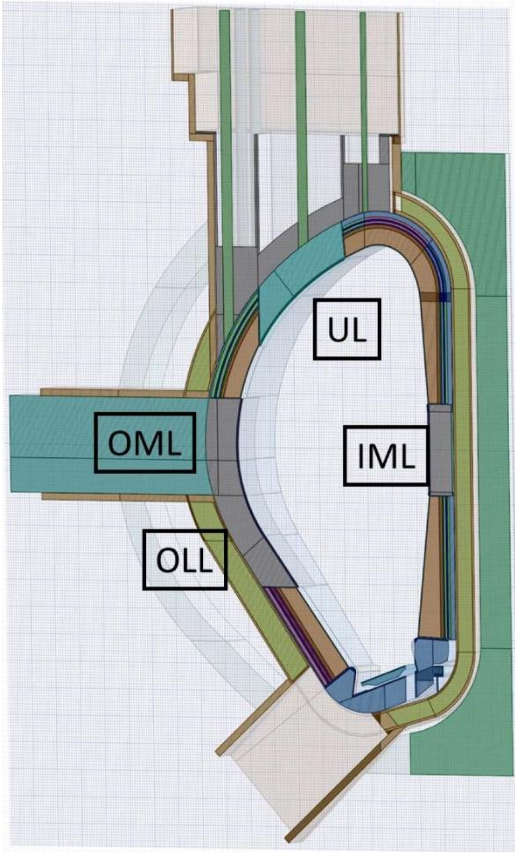




Without considering cut-out, TBR=1.16~1.20

Global tritium breeding assessment considering heating systems & limiters





Systems that cut breeding blanket

	ΔTBR Single IVC	Amount of systems in whole reactor	ΔTBR 360° Reactor
EC	0.22%	9	1.97%
NBI	0.22%	3	0.66%
UL	0.52%	8	4.14%
IML	0.19%	4	0.77%
OML	0.37%	4	1.49%
OLL	0.37%	4	1.49%
Total TBR reduction			**10.51%**

TBR=1.16~1.20 (Without cut-out)

TBR=1.04~1.07 (With cut-out)

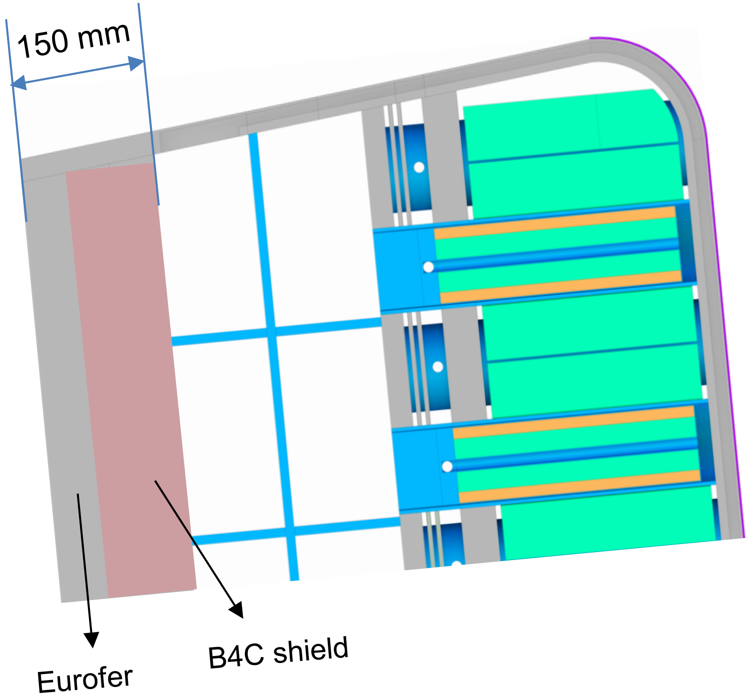
Shielding assessment

- Parametric neutronics analysis

Shield materials: B4C, WC, WB and hydrides

- ***Baseline***: 150 mm Eurofer
- ***v1***: 10 mm B_4C, 140 mm Eurofer
- ***v2***: 20 mm B_4C, 130 mm Eurofer
- ***v3:*** 30 mm B_4C, 120 mm Eurofer
- …
- ***v10***: 100 mm B_4C, 50 mm Eurofer

Shoshin A et al., 2021 *Fusion Eng Des* 168, 112426



HCPB inboard blanket

- Tritium and helium production in B_4C

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{3}_{1}T + 2^{4}_{2}He$$

Shielding assessment

- Results

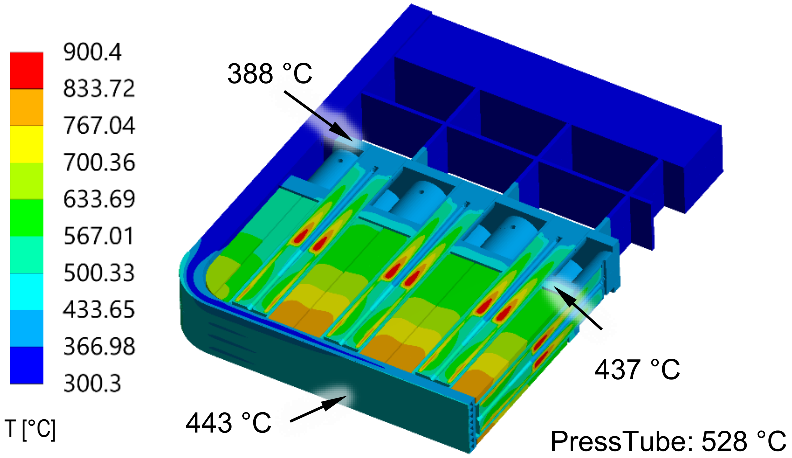
Cases	Nuclear heating at 1st cm of TFC (limit: 5e-5)	Neutron flux at 1st cm of TFC (limit: 1e9)	dpa/fpy at 1st cm of TFC (limit: 1.6e-5)	dpa/fpy at 1st cm of VV (limit: 4.5e-1)	He product. at 1st cm of VV (limit: 0.16)
	W/cm^3	$n/cm^2/s$	appm/fpy	appm/fpy	appm/fpy
Baseline	8.69e-5	2.21e9	1.81e-5	1.53e-1	0.56
v1	7.36e-5	2.07e9	1.69e-5	1.28e-1	0.42
v2	6.83e-5	2.29e9	1.24e-5	9.27e-2	0.35
v3	5.37e-5	1.82e9	1.42e-5	9.43e-2	0.29
v4	5.16e-5	1.74e9	1.50e-5	8.58e-2	0.27
v5	4.72e-5	1.66e9	1.40e-5	7.70e-2	0.24
v6	4.16e-5	1.57e9	1.41e-5	6.94e-2	0.22
v7	3.69e-5	1.47e9	1.41e-5	6.29e-2	0.18
v8	3.32e-5	1.43e9	1.24e-5	5.76e-2	0.17
v9	3.30e-5	1.41e9	1.27e-5	5.52e-2	0.16
v10	3.24e-5	1.40e9	1.24e-5	5.27e-2	0.15
v5_inverted	4.06e-5	1.65e9	1.28e-5	7.46e-2	0.19
v10_inverted	2.81e-5	1.33e9	1.16e-5	5.07e-2	0.14

- Maximum T and He production is in v10: 1.84 mol (5.52 g) T per FPY, 500 mol (2 kg) Helium per FPY in EU-DEMO

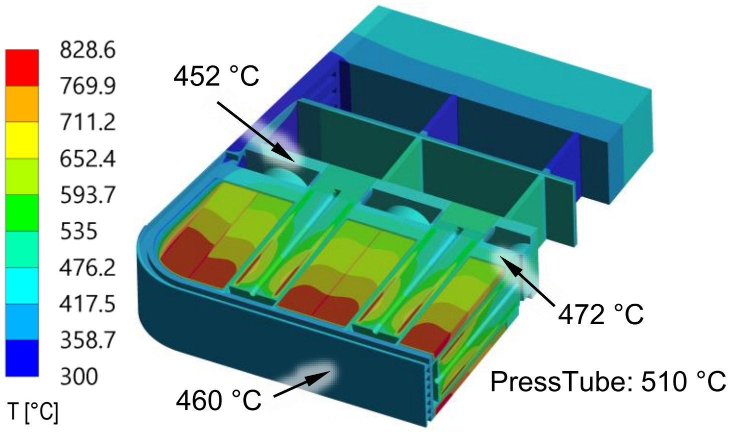
  Negligible, 117 kg T/fpy in EU-DEMO → 1e-28 [$Pa \cdot m^3/(s \cdot m^2)$] << Outgassing limit 1e-11

- 90 mm B_4C is needed for meeting all the requirements
- ITER-like solution seems feasible

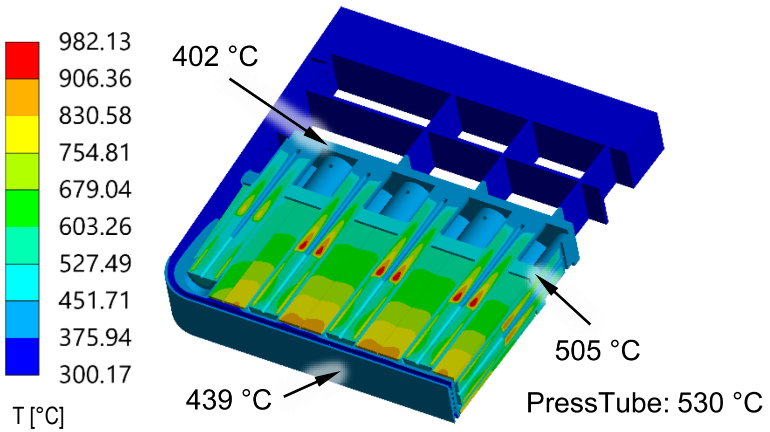
Thermal hydraulics: Temperature



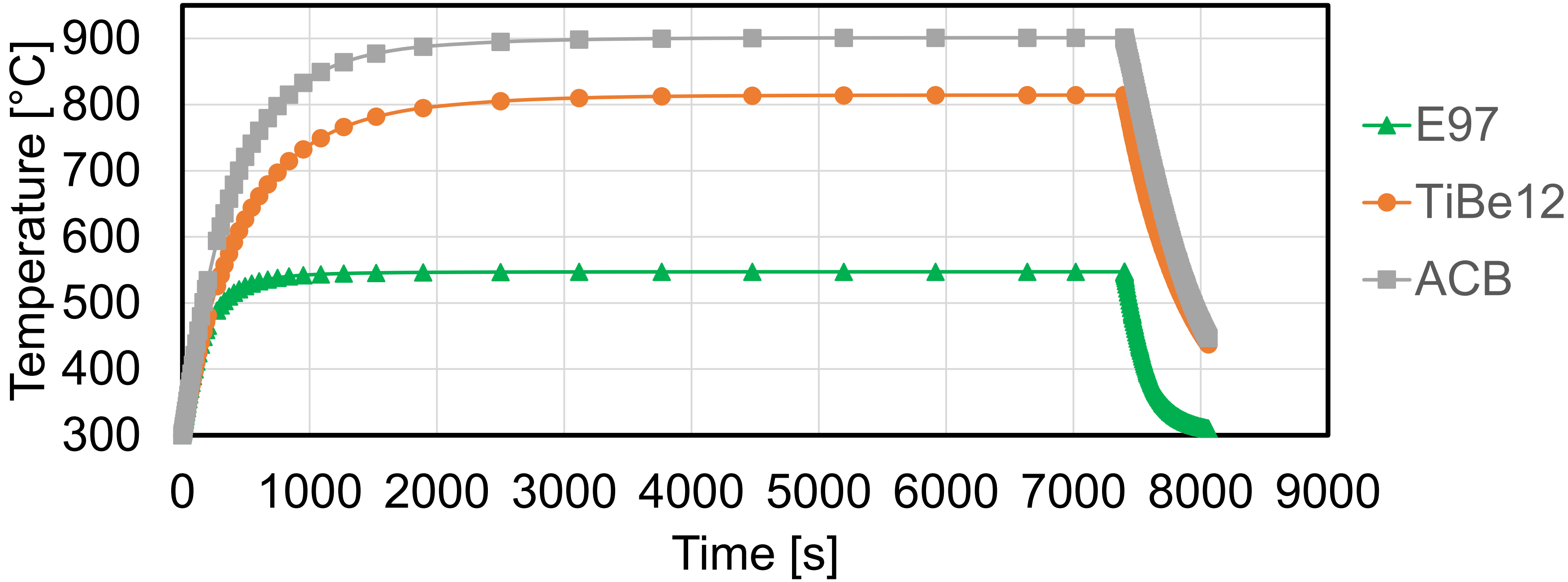
Temp. field of half unit-slice of COB



Temp. field of half unit-slice of LIB



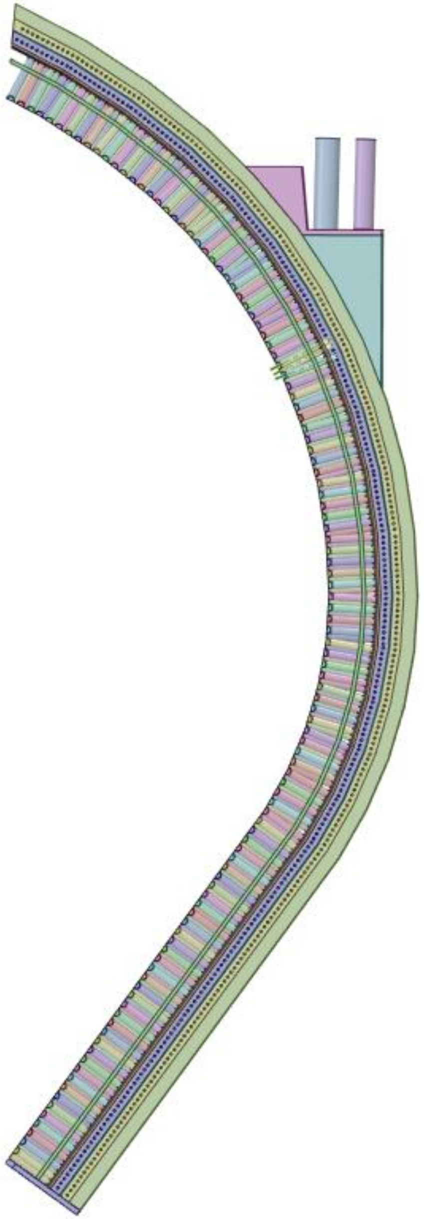
Temp. field of half unit-slice of LOB



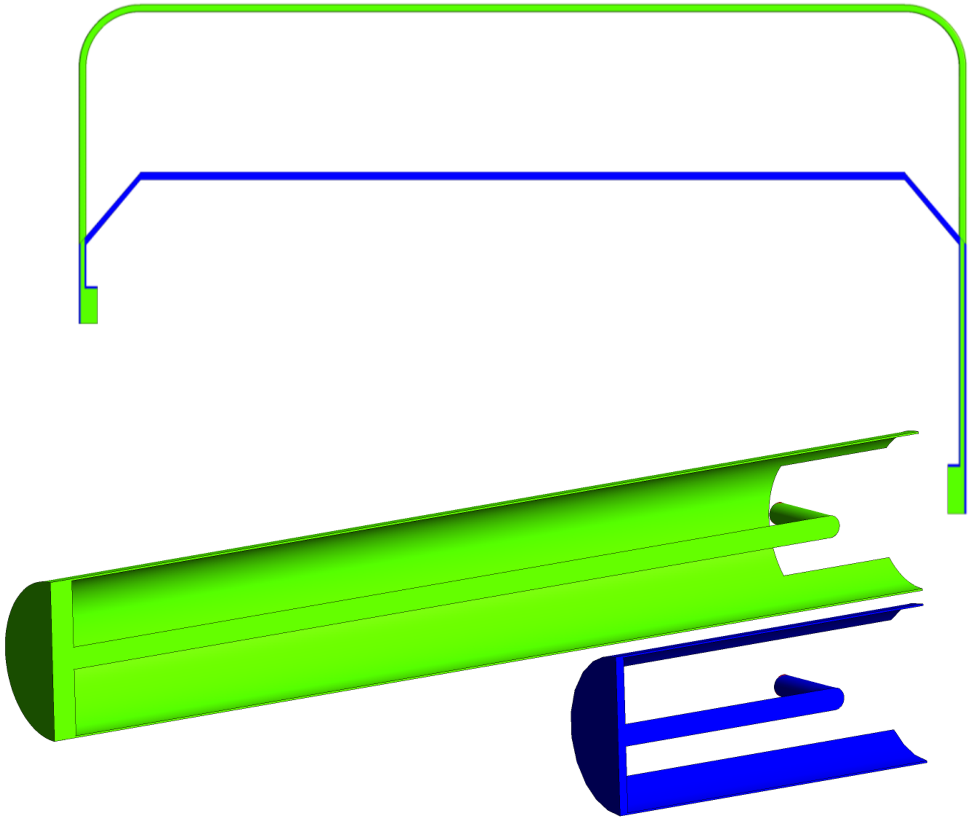
Temperatures of three unit slice within design limits

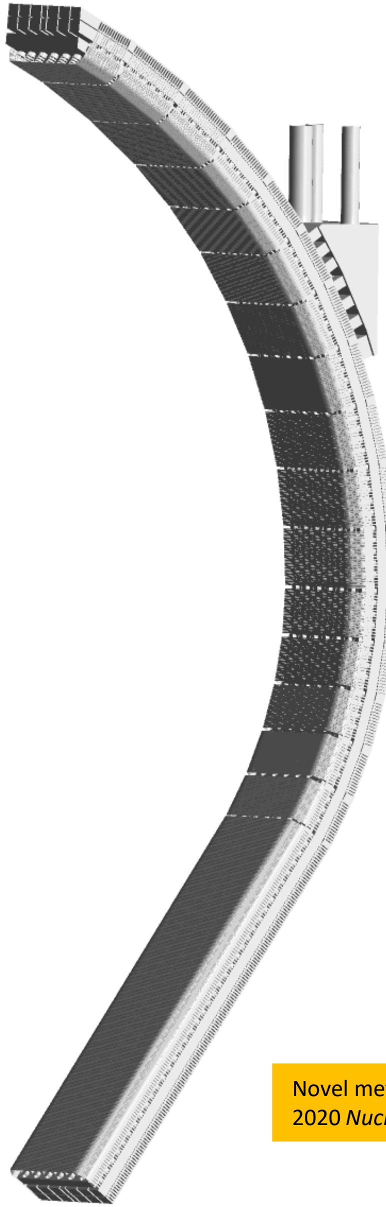
Transient thermal analysis shows that there is a thermal inertial in the blanket, especially in functional materials.

Thermal hydraulics: Flow distribution



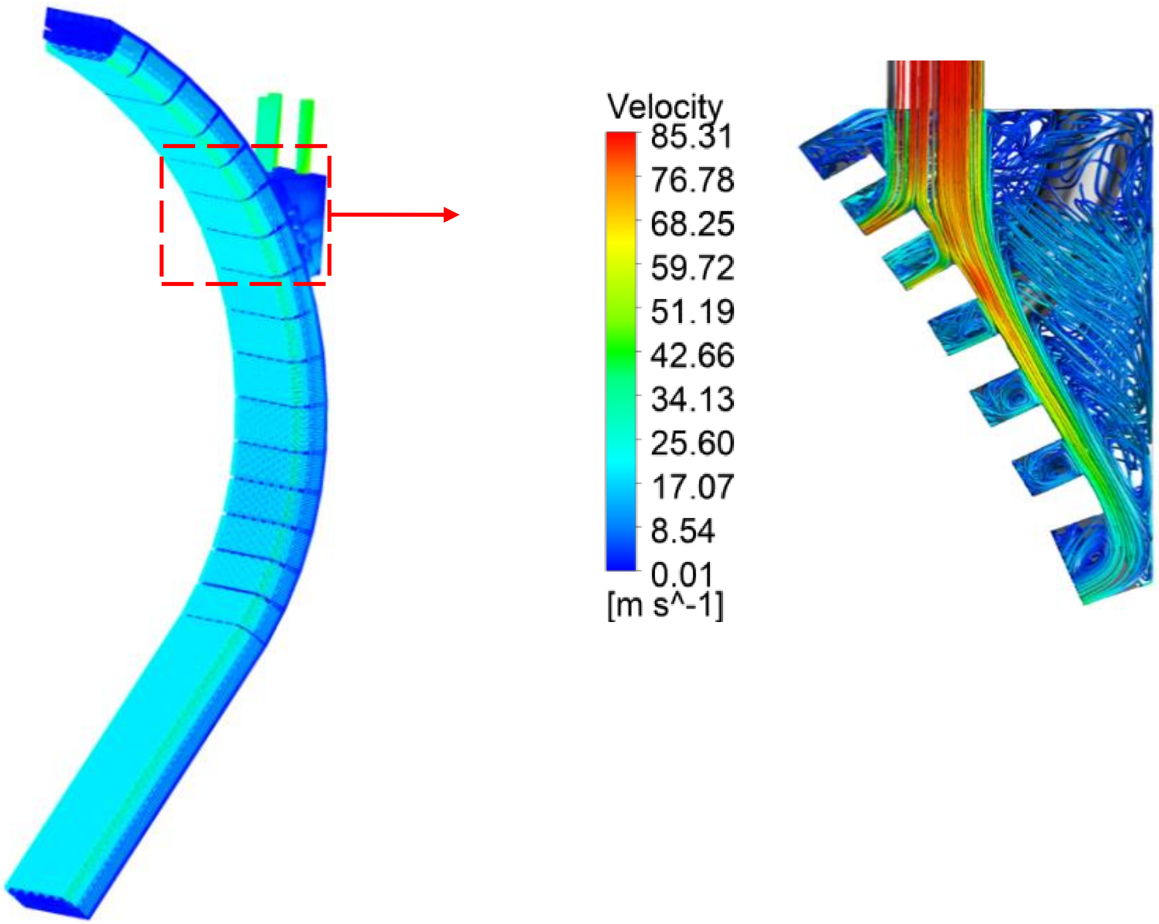
Porous media approach to reduce meshing and computing time



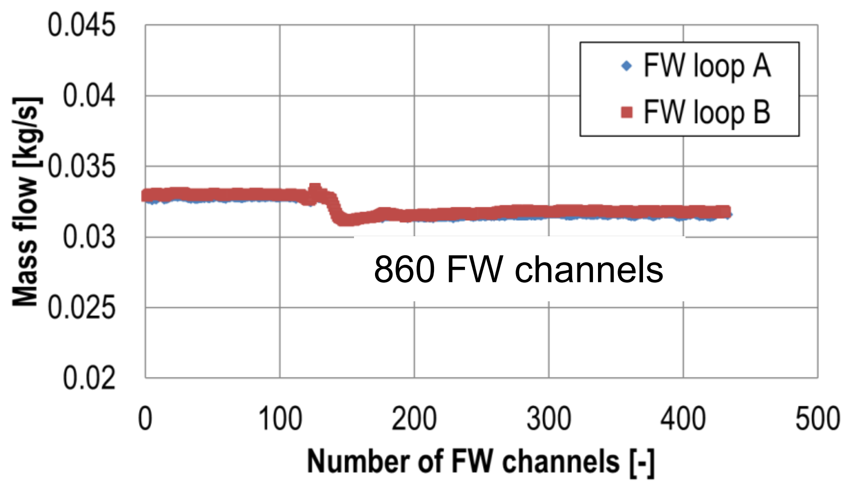


Novel method: Zhou G et al., 2020 *Nucl Fusion* 60, 096008.

Thermal hydraulics: Flow distribution

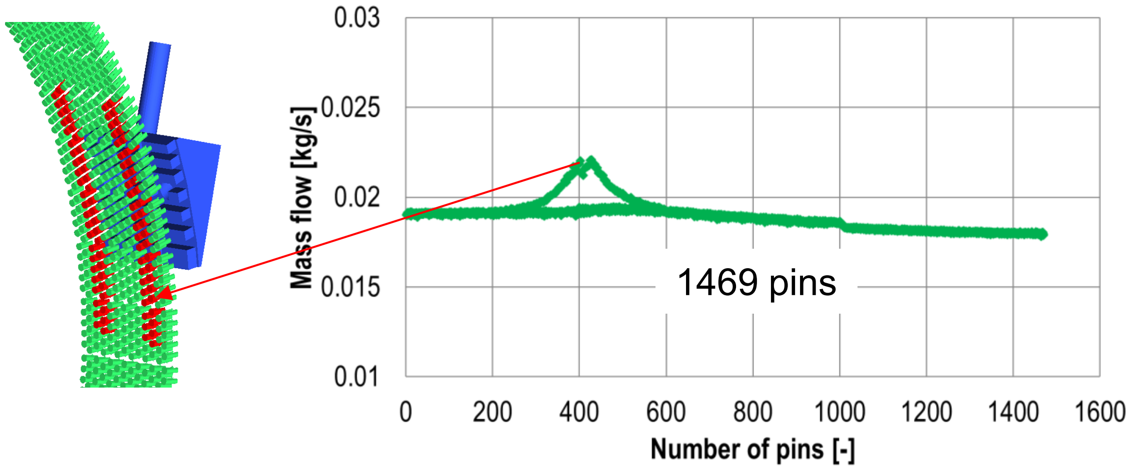


Flow streamline of blanket segment



Mass flow rate distribution in FW

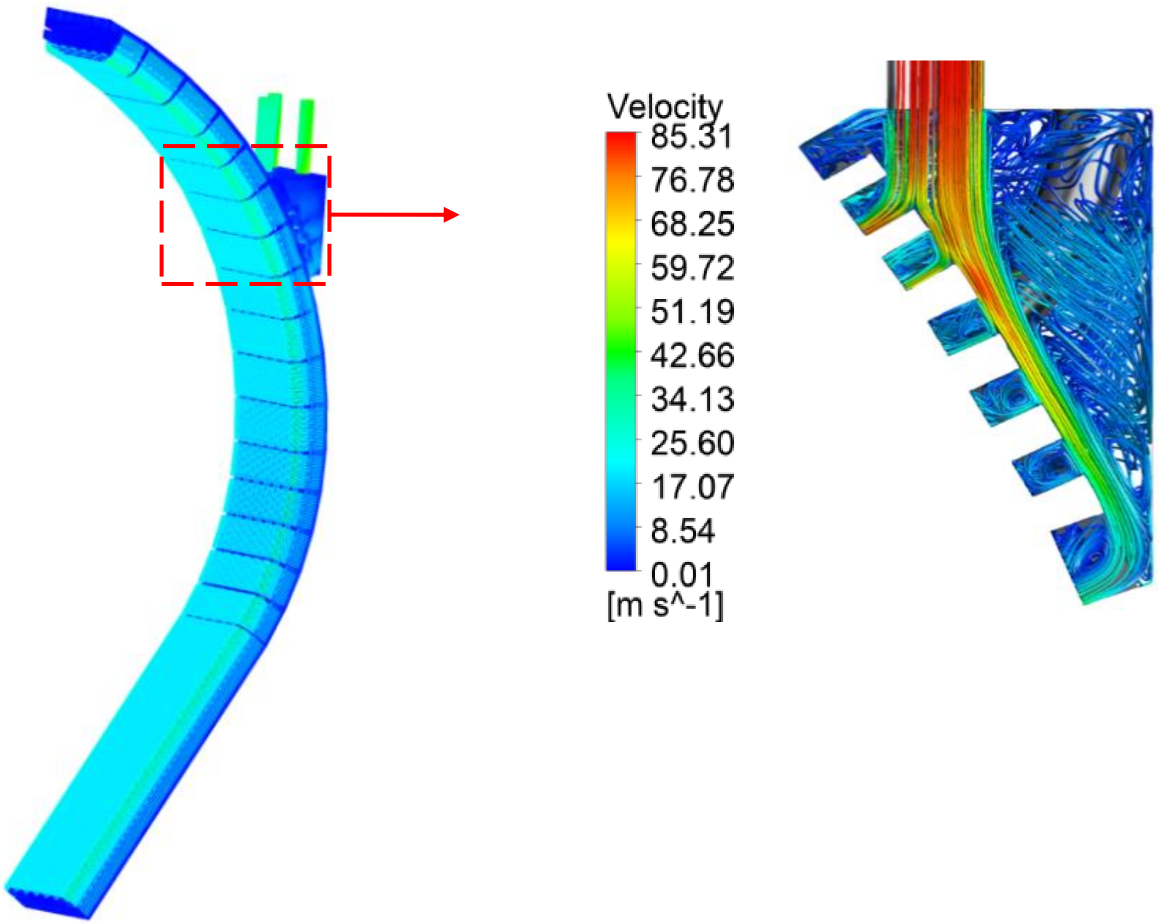
- Max deviation from target value: 4.4%



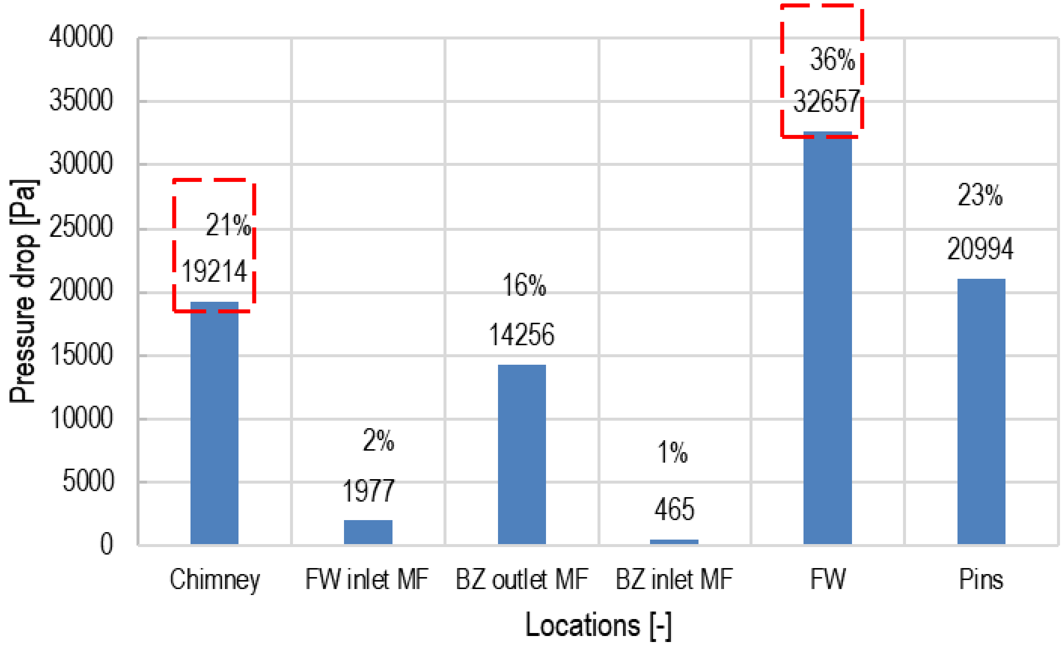
Mass flow rate distribution in pins

- Max deviation from target value: 17.3%

Thermal hydraulics: Pressure drop



Flow streamline of blanket segment

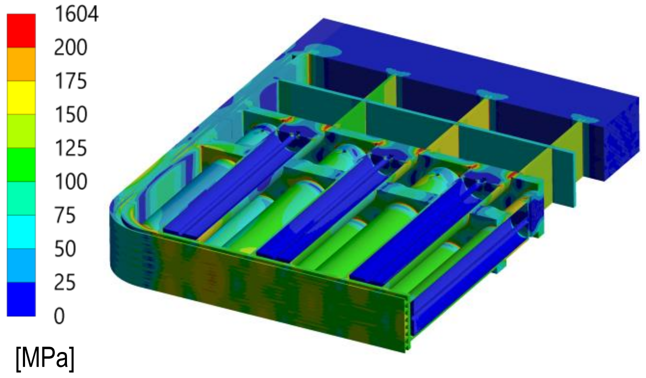


Pressure drop distribution

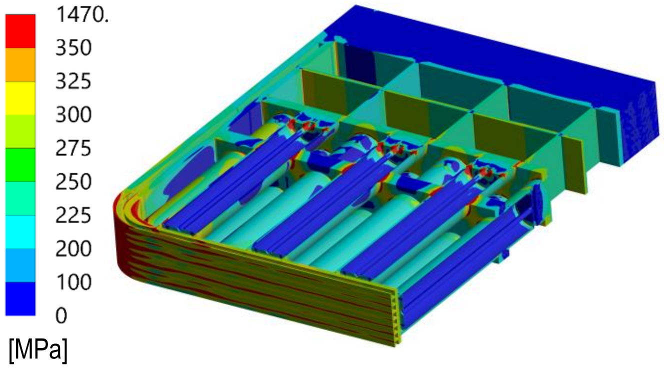
- Total pressure drop: 0.89 bar

Thermal mechanical assessment

- **Stress assessment using plane strain**

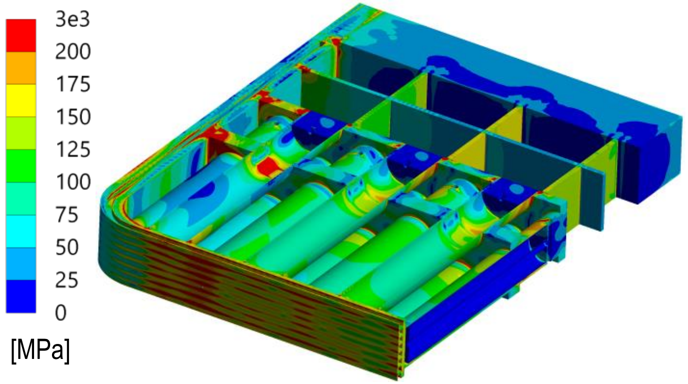


Primary stress of COB

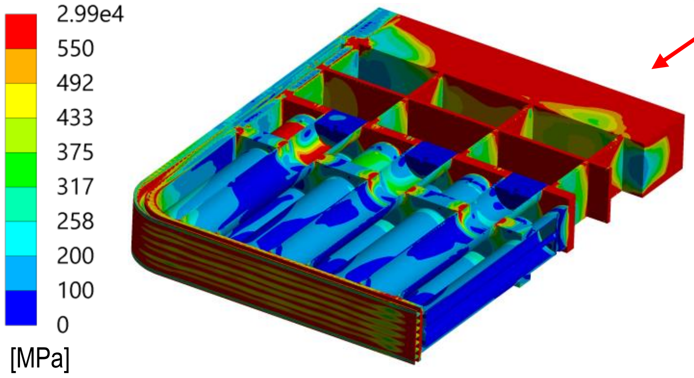


Primary+Secodary stress of COB

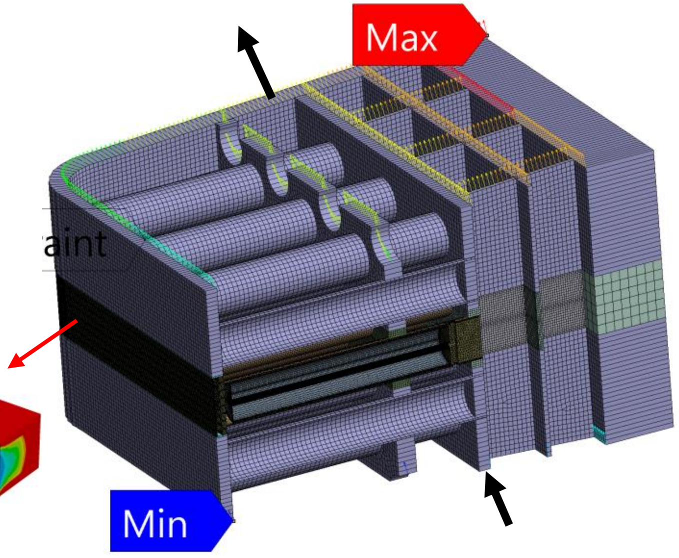
- **Stress assessment using submodelling technique**



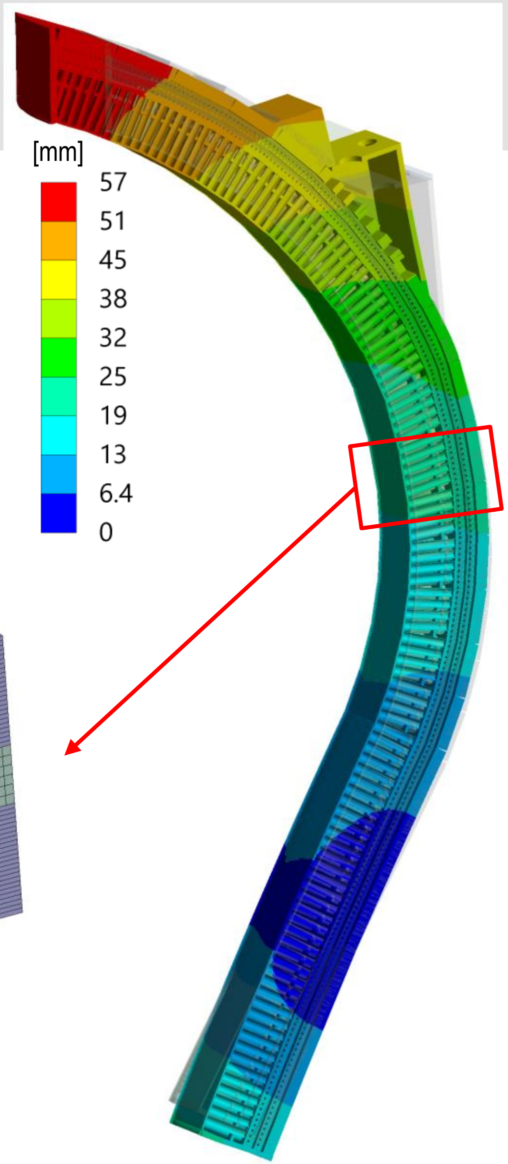
Primary stress of COB



Primary+Secodary stress of COB



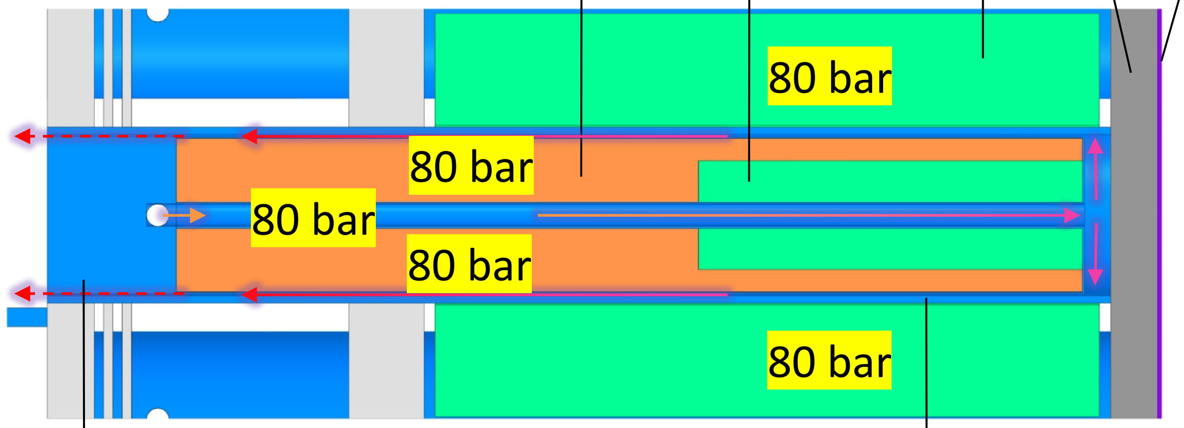
Submodel



Displacement of global model

- Developed a sub-modelling technique to transfer the global displacement to submodel
- Generalized or plane strain boundary conditions not conservative
- Most critical regions met the immediate plastic instability, plastic collapse and thermal creep damage modes

RAMI (Reliability, Availability, Maintainability, Inspectability) analysis



BB	HCPB-2020 [1]	HCPB-2025-v1	HCPB-2025-v2	EU-DEMO Req. [1]
Operating availability	14.66%	**42.05%**	**36.01%**	>=30%
Inherent availability	23.23%	**66.66%**	**57.08%**	>=48%
Uptime (h)	3630	**10414**	**8918.5**	>=7430
Total Downtime for corrective maintenance (h)	11994	**5209**	**6705.5**	<=8194
Total Downtime for preventive maintenance (h)	9144	**9144**	**9144**	9144

- Leak from the pressure tube and fuel-breeder pin will not lead to in-box LOCA event, no immediate shutdown is required.
- Availability increases 2.9x (v1) and 2.4x (v2).

IA = ∑ Up times / (∑ Up times + ∑ Down times for corrective maintenance)

OA = ∑ Up times / Total time

OA: operational availability
IA: inherent availability

[1] T. Pinna et al., Fusion Engineering and Design, Volume 161, December 2020, 111937

Tritium Extraction and Recovery (TER) system

▪ Previous design

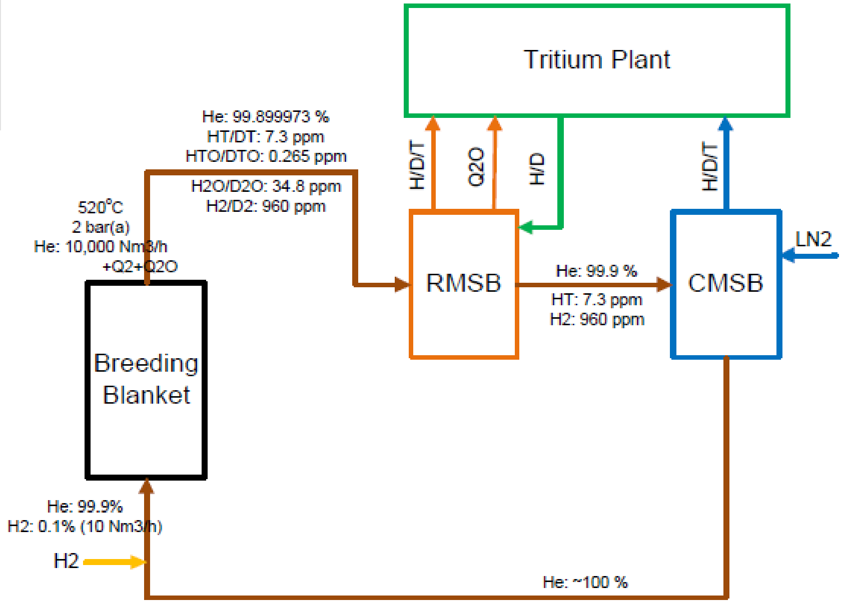
- Two stages in series, first the adsorption of Q2O on the Reactive Molecular Sieve Bed (RMSB), thereafter the adsorption of Q2 on the Cryogenic Molecular Sieve Bed (CMSB) at 77 K

Q = H, D, T

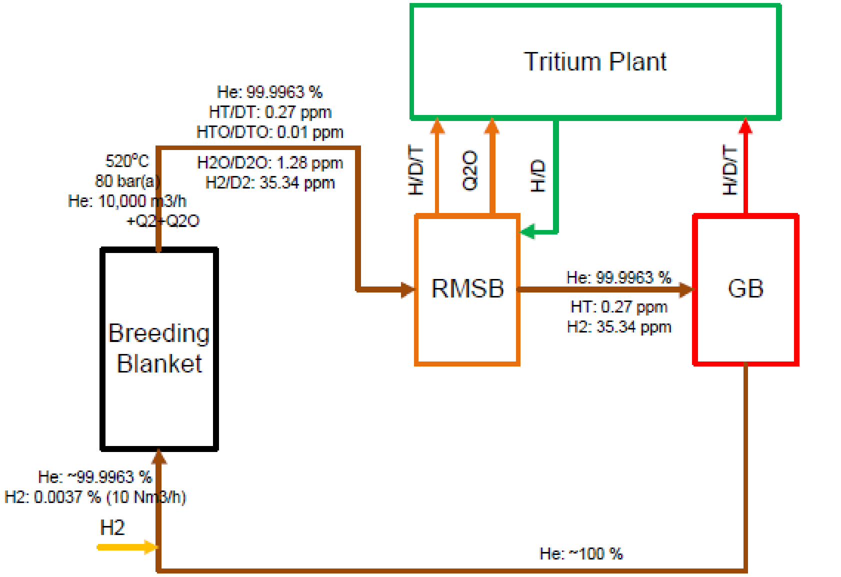
- Tritium recovered via catalytic isotope exchange on RMSB and by heating-up of the CMSB
- Extrapolated to DEMO scale is realizable, high Tech. Readiness Level

▪ Proposed design

- 80 bar purge gas, introduced to improve reliability of BB
- CMSB requires large amount of liquid N2, getter bed is explored as alternative
- Getter bed, in particular ZAO, shows to be a viable option to replace CMSB in TER configuration for Q2 recovery from the purge gas



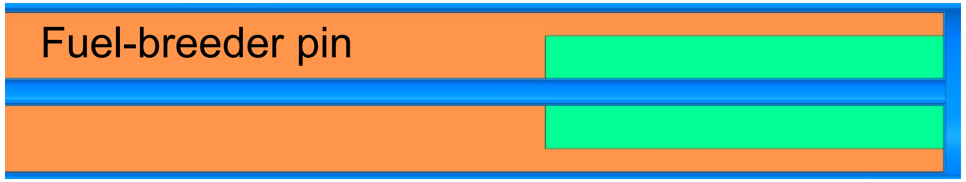
2 bar purge gas



80 bar purge gas

Tritium permeation analysis

- 3D component level solver
  - Developed based on the OpenFOAM and benchmarked with TMAP 7

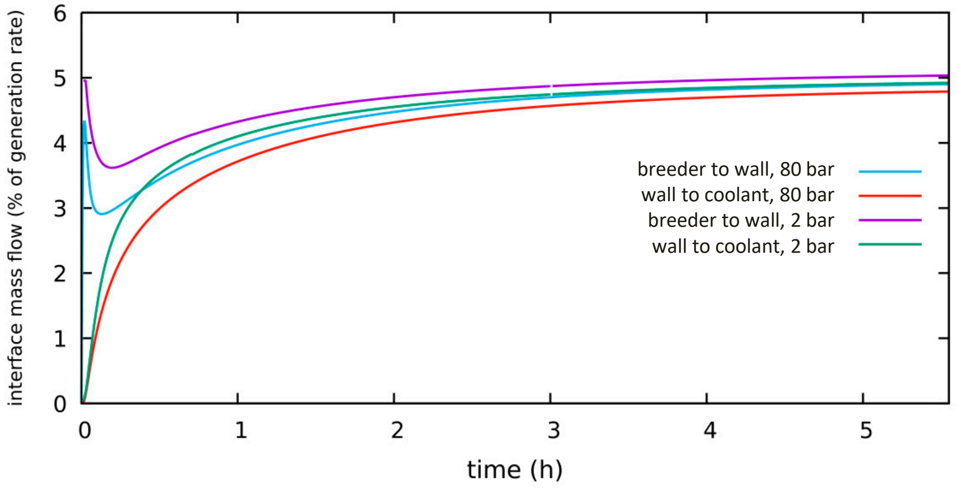


OpenFOAM

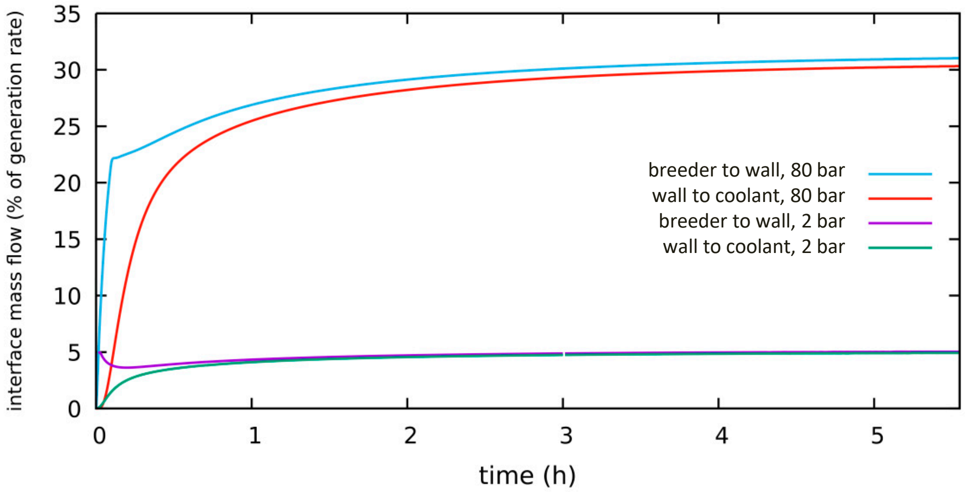
The Open Source CFD Toolbox

- Tritium permeation analysis
  - Tritium permeation analysis under 2 bar pressure purge gas vs 80 bar pressure purge gas, with same H_2 partial pressure
  - Wet purge gas vs dry purge gas

Purge gas	Permeation to coolant	Wall T inventory
200Pa H_2, no H_2O	0.077% of T generation	65 ng
200Pa H_2 + 200Pa H_2O	0.022% of T generation 3.5 times less	19.2 ng



Permeation under equal volumetric flow



Permeation under equal mass flow

Conclusions and outlook

- Nuclear, thermal hydraulics and thermal mechanics assessments confirms the soundness of high pressure purge gas HCPB concept
- RAMI analysis confirms the improvement of availability of HCPB
- Tritium Extraction and Recovery system can cope with high pressure purge gas

Future work:

- Looking for simple, scalable and modular design with cost-effective neutron multiplier (Pb)

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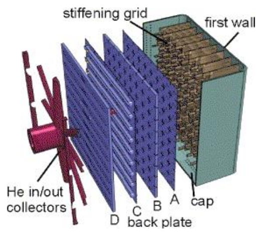
Backup slides

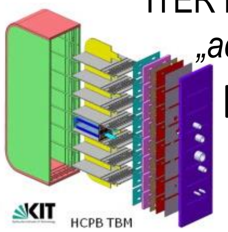
Solid breeding blanket in Europe: HCPB Design evolution

- HCPB and WCLL are two reference blanket concepts for EU DEMO

Pre-Concept Design Phase (FP8)

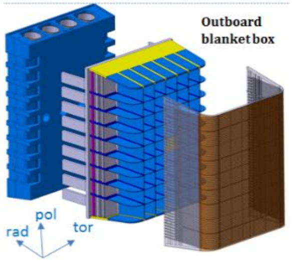


ITER HCPB TBM „act-alike“



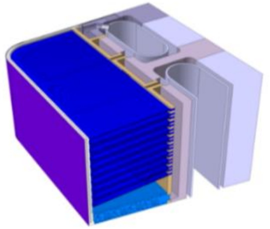
PPCS Model B (HCPB)

2014 — "Beer-box" DEMO baseline 2014



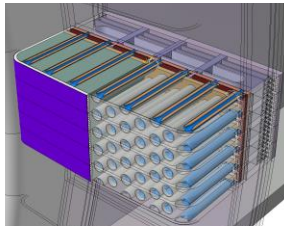
+ ↑↑ Robustness (in-box LOCA)
– ↓↓ TBR (1.06)
– ↑↑ Fabrication & assembly complexity
– ↑↑ Δp (P_{pump}≈250MW, low TRL BoP)

2015, 2016 — DEMO baseline 2015 "Sandwich"



+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.15)
– ↑ Fabrication & assembly complexity
– ↑ Δp (P_{pump}≈150MW, low TRL BoP)

2017, 2018, 2019, 2020 — DEMO baseline 2017 "Fuel-breeder pin"

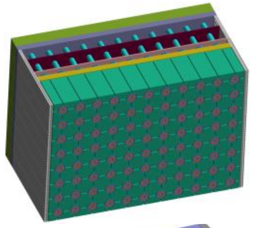


+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.20)
+ ↓ Fabrication & assembly complexity
+ ↓ Δp (P_{pump}≈ 90MW, high TRL BoP)
– RAMI

- Coolant: He @80 bar, 300-520°C
- Structural steel: Eurofer97
- T-breeder: Li-ceramics
- n-multiplier: Beryllide
- T-extraction: purge gas

Concept Design Phase (FP9)

2021
2022
2023
2024



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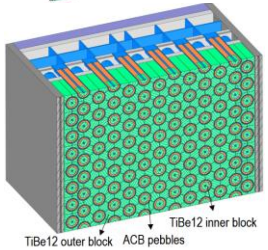

G. Zhou et al. 2023. ISFNT-15

+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.20)
+ ↓ Fabrication & assembly complexity
+ ↓ Δp (P_{pump}≈ 90MW, high TRL BoP)
+ ↑ High reliability