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LAS PALMAS DE GRAN CANARIA, SPAIN

EUROfusion

Overview of the design activities of the EU DEMO Helium Cooled Pebble Bed breeding blanket

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Breeding Blanket Project in EUROfusion

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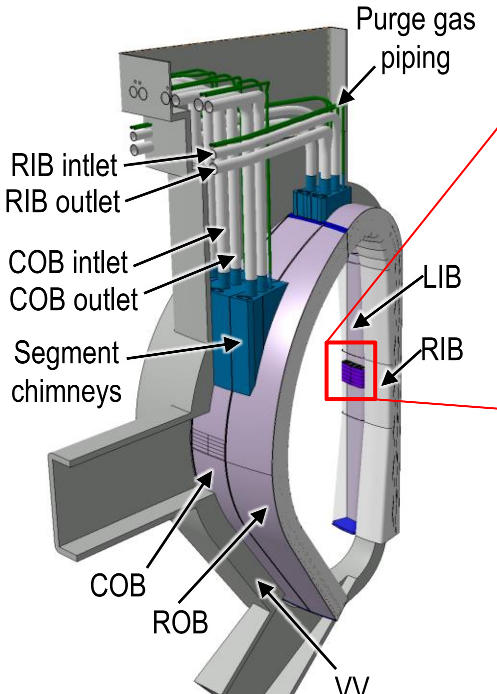
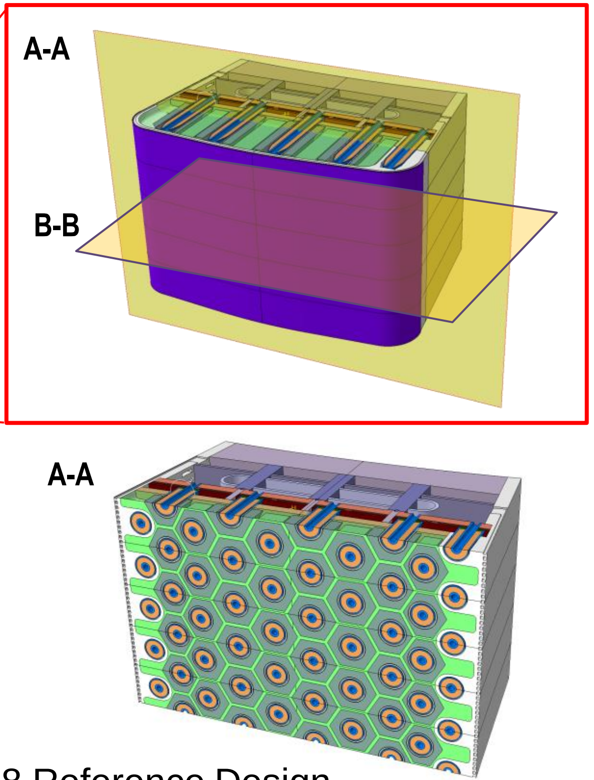
Outline

1. Status of HCPB at the conclusion of FP8 (2014-2020)
2. Challenges related to HCPB & solutions
3. Design activities
4. Conclusions

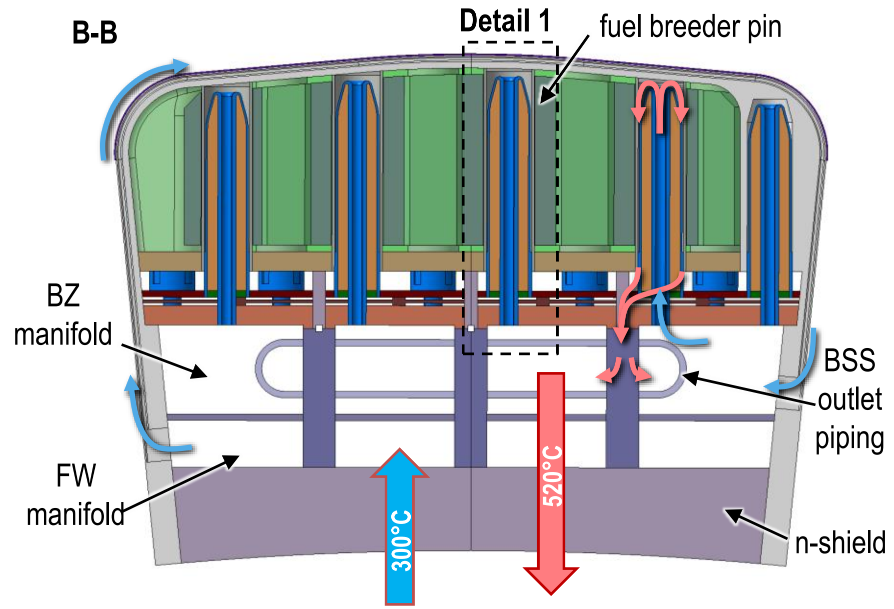
Status of HCPB at the conclusion of FP8 (2014-2020)



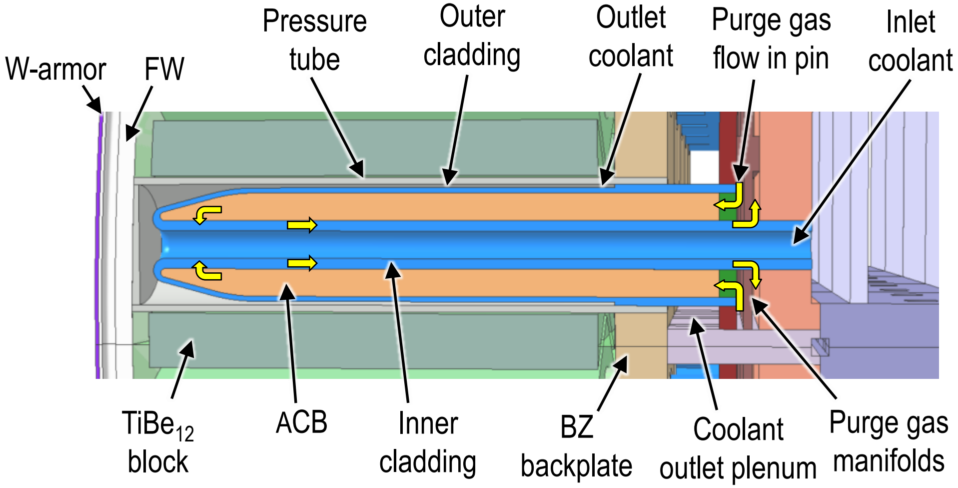
Hernández FA et al., 2020
Fusion Eng Des 157, 111614.



HCPB-FP8 Reference Design



Detail 1: Fuel-breeder pin



- Coolant: He @80 bar, 300-520°C
- Structural steel: Eurofer97
- Fuel-breeder pins contain advanced ceramic breeder (ACB) pebble
- Pins inserted into hexagonal beryllide blocks of neutron multiplier
- T-extraction: Purge gas of He + 0.1vol% H_2 @2 bar
- NA, TH & TM, TBR = 1.20

Challenges related to HCPB BB & solutions

Highlighted Challenges

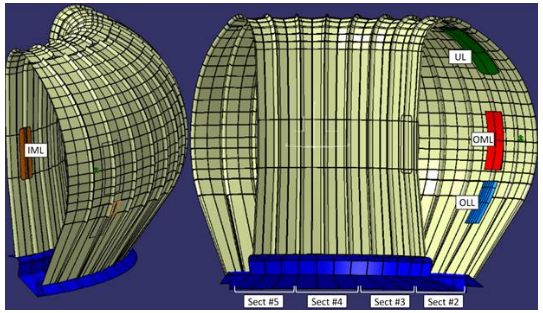
1. Low reliability of BB system under DEMO conditions (Adressed by [1])
2. Cracking of beryllide blocks (Adressed by [2] + R&D)
3. Degradation of Eurofer at contact with pebbles in purge gas (Adressed by [1] + R&D)
4. Low BB shielding capability (Addressed by [3] Efficient shield)
5. Limited heat flux removal capability of the He-cooled FW

Pinna T, Dongiovanni DN, 2020
Fusion Eng Des 161, 111937.

→ R. Krüssmann: PS2-36 Tue.

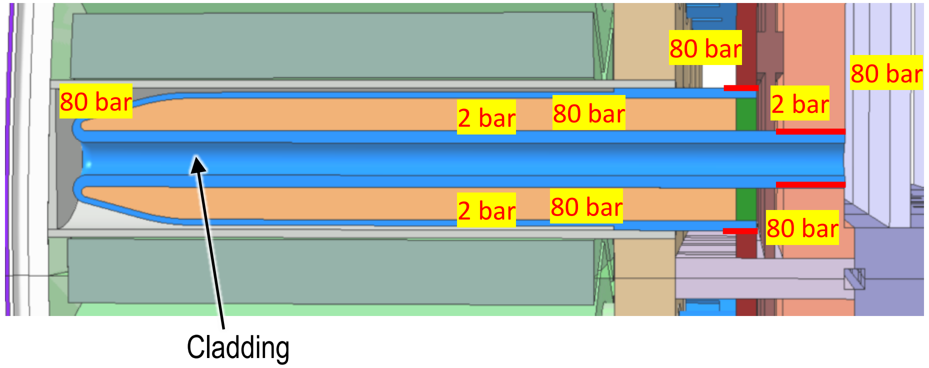
He-cooled FW → C. Klein: P3A4 Tue.

Limiters → M. L. Richiusa: P6A4 Thu.



Solutions

[1] Equalize purge gas and coolant pressure to establish a fault-tolerant blanket design, 80 bar pressure under normal condition

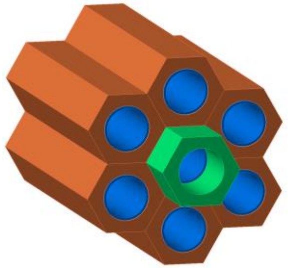


Large number of welds: 400e3

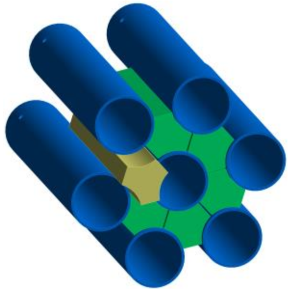
Failure rate of welds: 2.58e-08 (1/h)

400e3 x 2.58e-08 = 0.01 (1/h)

[2] Change shape of beryllide blocks → R. Gaisin: PS3-52 Thu.



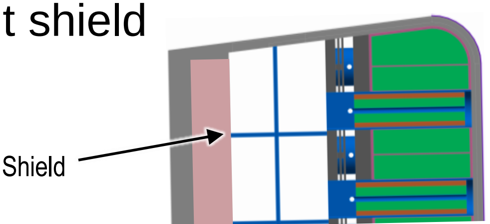
HCPB-FP8
Hexagonal prism with a central hole



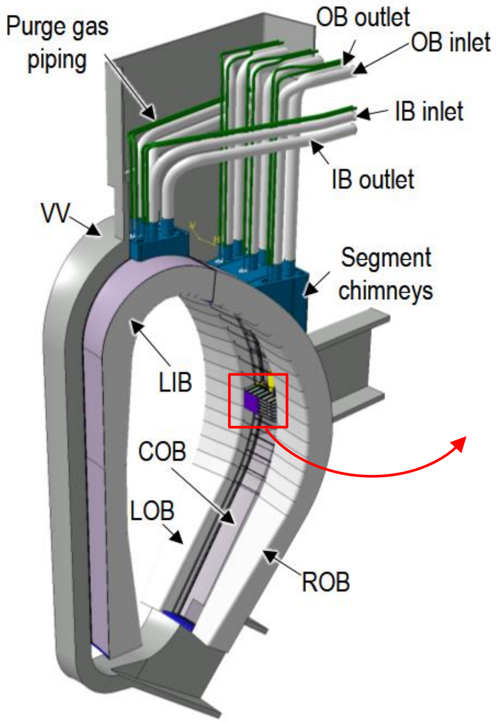
Triangular prism with lateral edges filleted

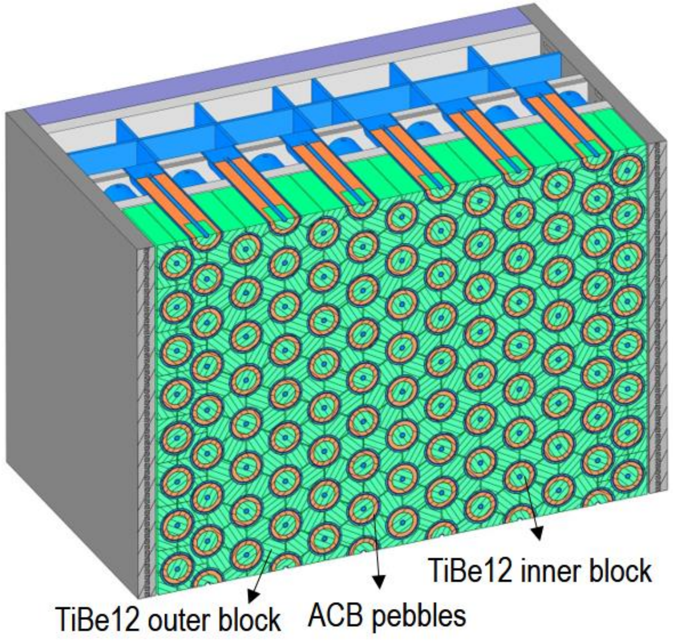
Small solid block
- less cracking
- reduces fabrication time

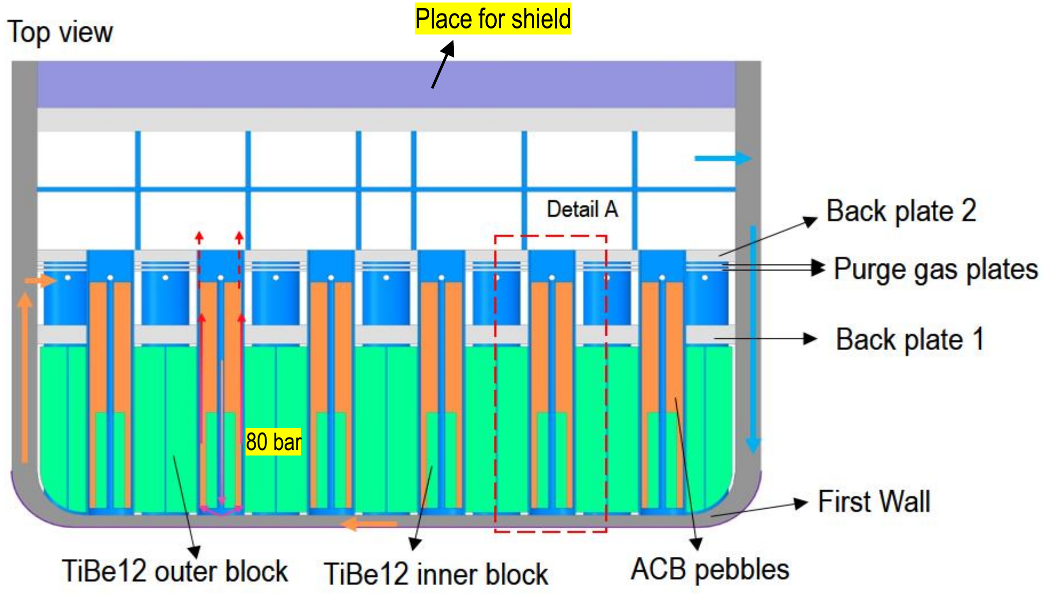
[3] Design efficient shield

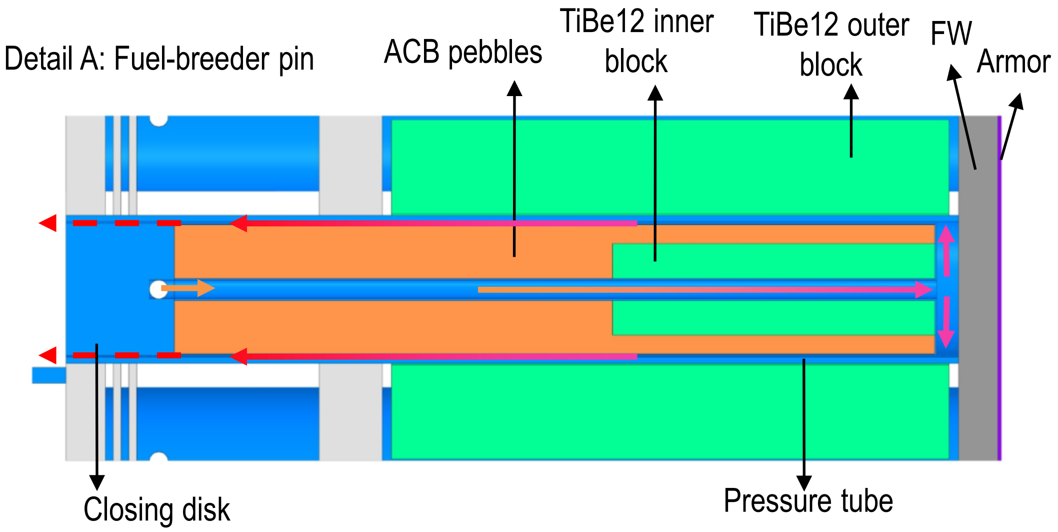


Design of high pressure purge gas HCPB (HCPB-BL2017-HP-v1)









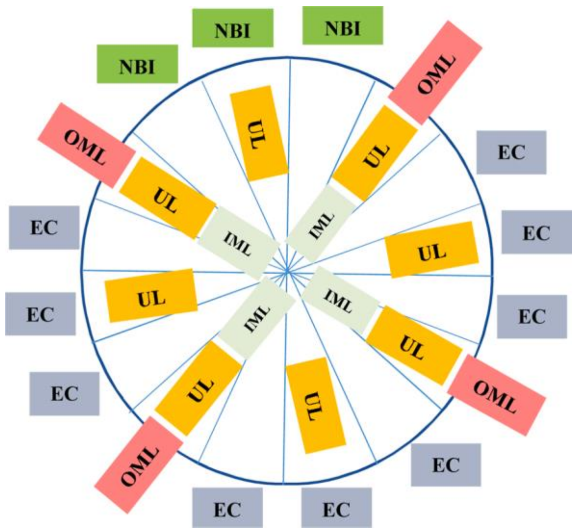
HCPB-BL2017-HP-v1

- Coolant: He @80 bar, 300-520°C
- Structural steel: Eurofer97
- Fuel-breeder pins contain advanced ceramic breeder (ACB) pebble
- Beryllide neutron multiplier of triangular prism with lateral edges filleted
- T-extraction: He + 200 Pa H_2 @80 bar; He + 200 Pa H_2O @80 bar (backup)
- FW and critical structure thicker + cooler by fresh coolant
- Inner beryllide block inside ACB pebble
- Nuclear, thermal hydr. & thermal-mech. analysis to confirm soundness

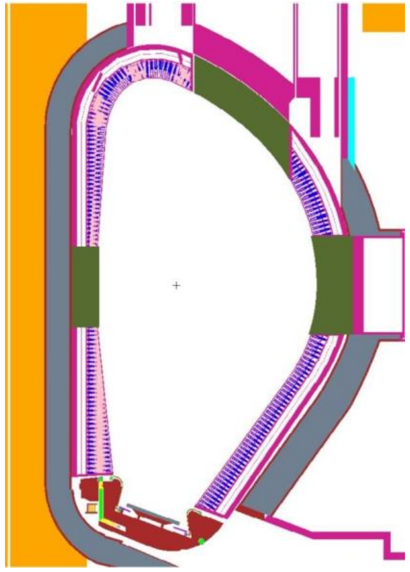
Tritium breeding assessment

- **Without considering cut-outs**
  - 3D heterogenous model calculated using MCNP6.2 and JEFF-3.3
  - 11.25°: half sector
  - Larger gap facilitates neutron streaming, saturates at 5 mm
  - The smaller the pitch, the higher the TBR (TBR=1.16~1.20 ±0.01%)

- **Considering cut-outs by Heating system & Limiters**
  - TBR reduction of 10.5% (TBR=1.04~1.07)



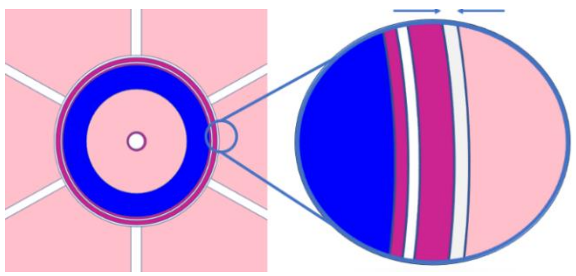
Top view of the IVCs arrangement

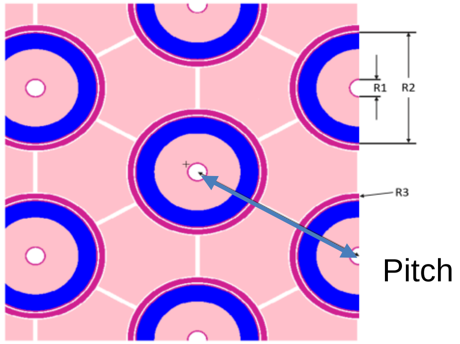


Cut-outs of BB

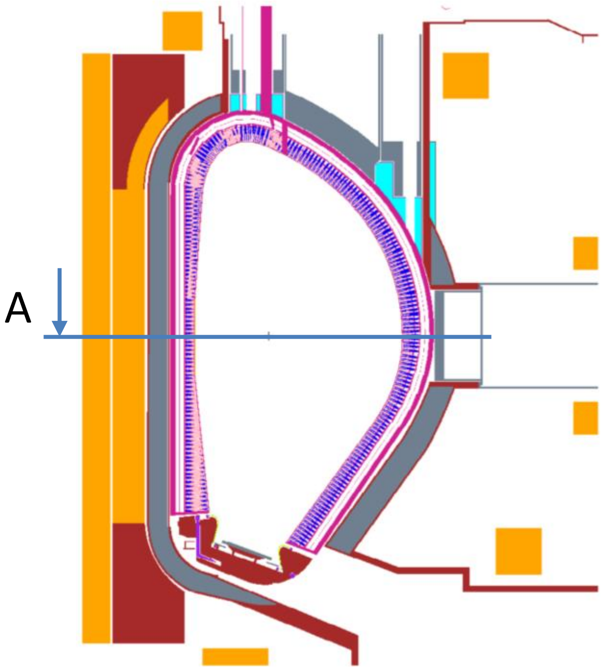
J. Park: PS3-27 Thu.

Gap between TiBe12 and tube

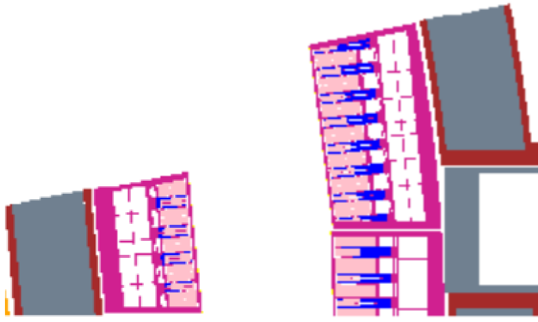




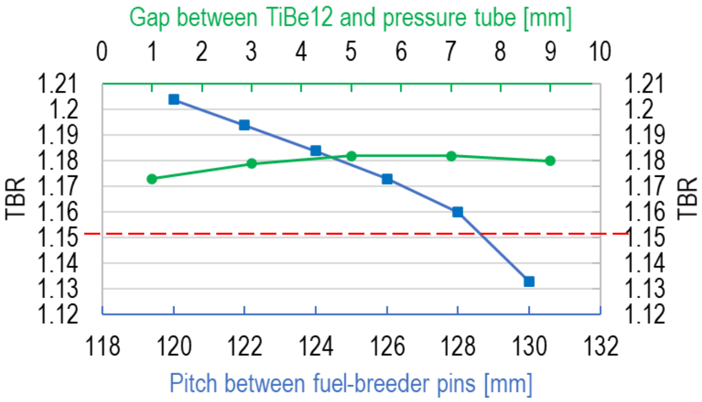
Pitch between pins



MCNP model of HCPB

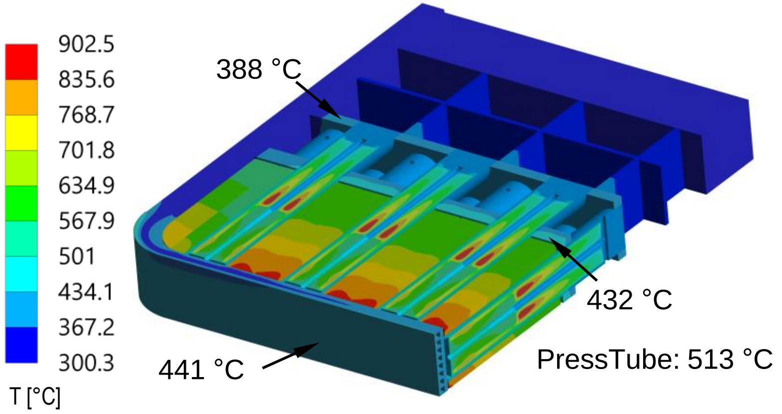


A-A: Radial-toroidal cut view

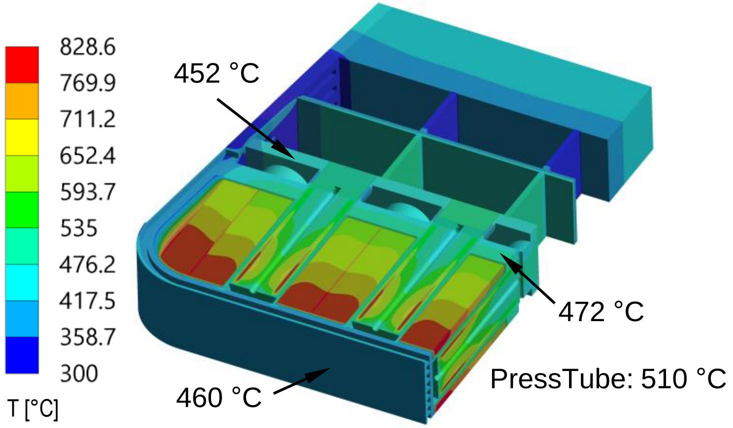


Scoping analysis

Thermal hydraulics: Temperature, flow distribution, pressure drop

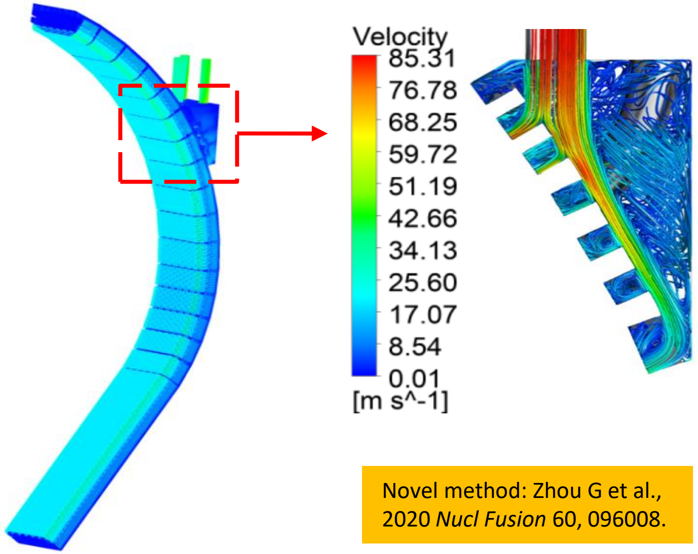


Temp. field of half unit-slice of COB



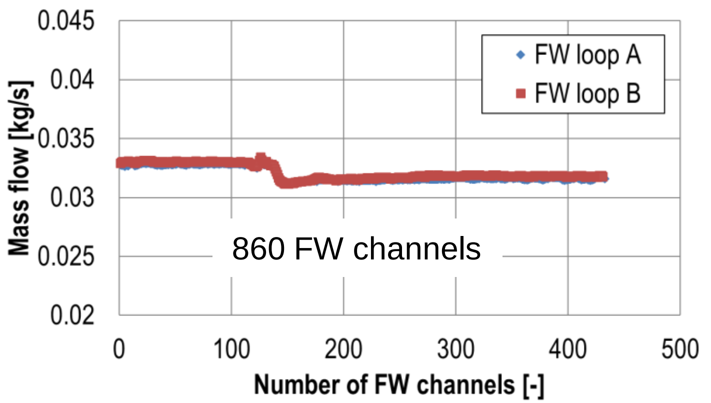
Temp. field of half unit-slice of LIB

- Temp. of ACB, Beryllide and Eurofer within corresponding design limits



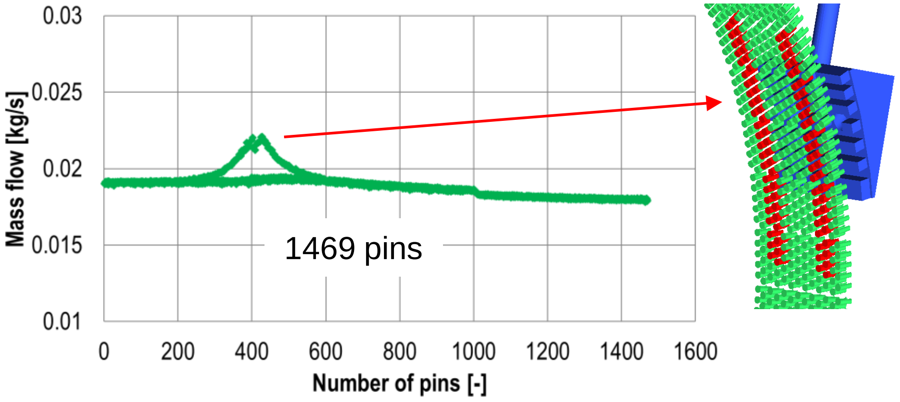
Novel method: Zhou G et al., 2020 *Nucl Fusion* 60, 096008.

CFD analysis of blanket segment



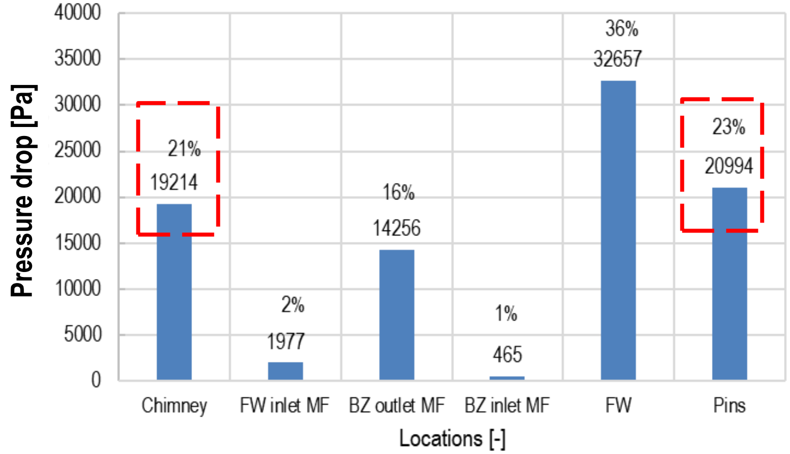
Mass flow rate distribution in FW

- Max deviation from target value: 4.4%



Mass flow rate distribution in pins

- Max deviation from target value: 17.3%

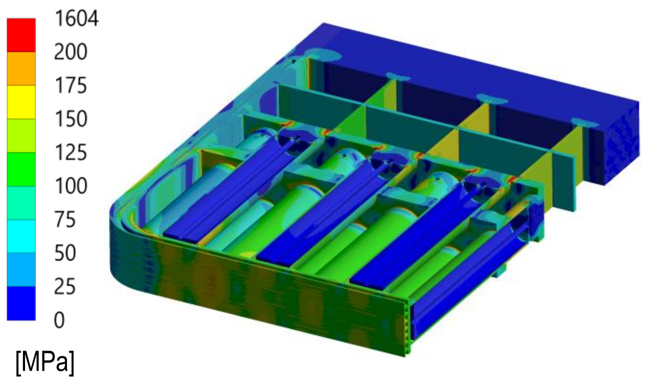


Pressure drop distribution

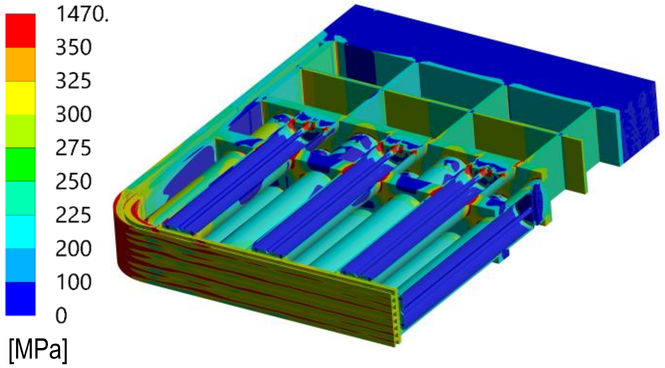
- Total pressure drop: about 0.9 bar

Thermal mechanical assessment

- **Stress assessment using plane strain**



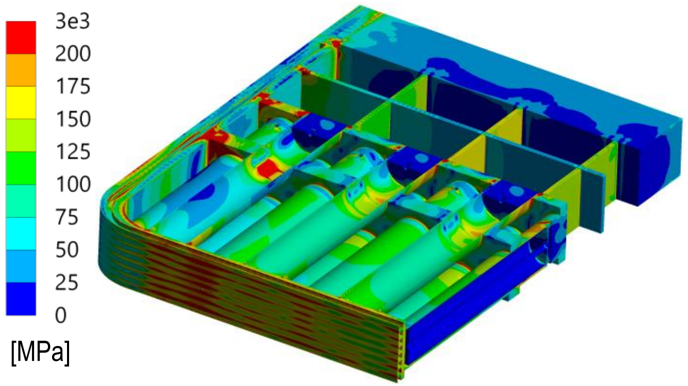
Primary stress of COB



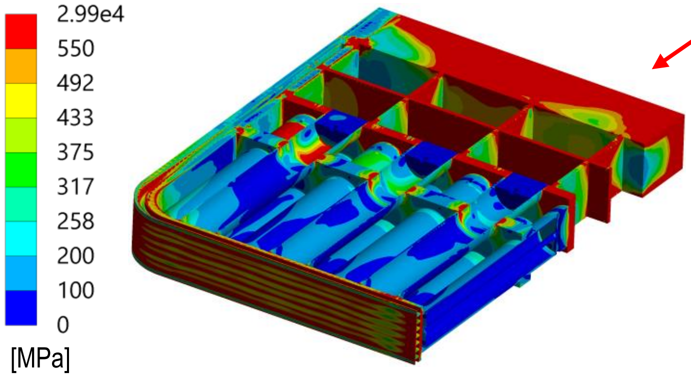
Primary+Secodary stress of COB

A. Retheesh: P1A4 this session

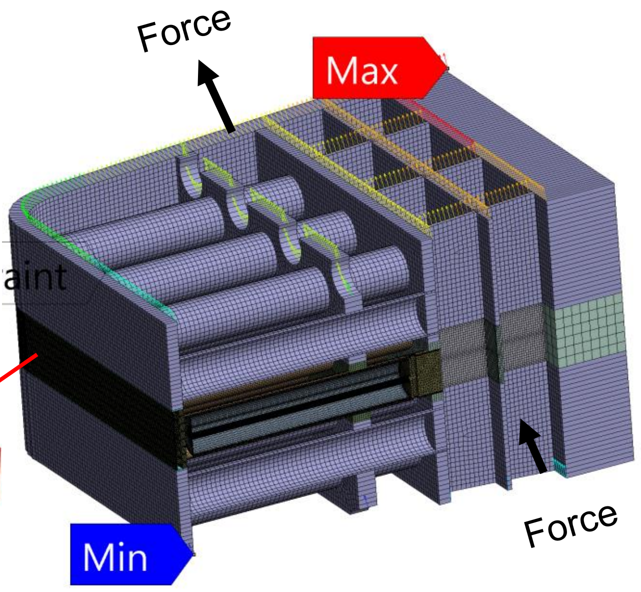
- **Stress assessment using submodelling technique**



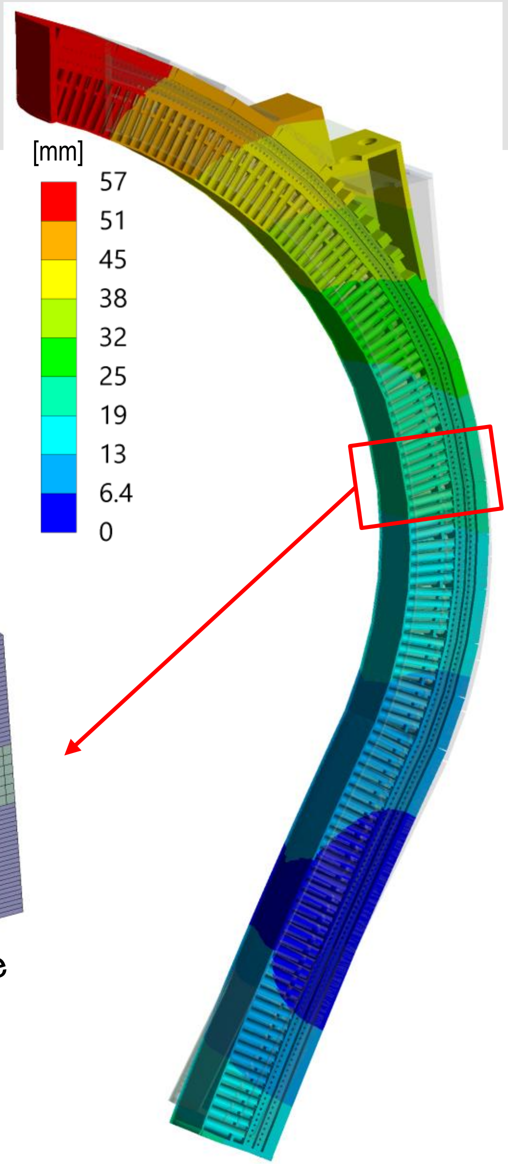
Primary stress of COB



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

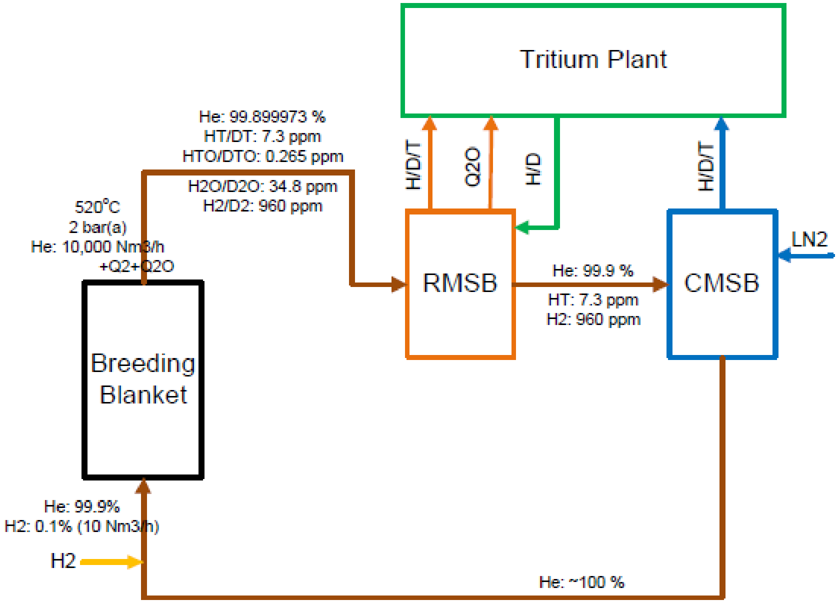
Tritium Extraction and Recovery (TER) system

▪ Reference design

- Two stages in series, first the adsorption of Q_2O on the Reactive Molecular Sieve Bed (RMSB), thereafter the adsorption of Q_2 on the Cryogenic Molecular Sieve Bed (CMSB) at 77 K

Q = H, D, T

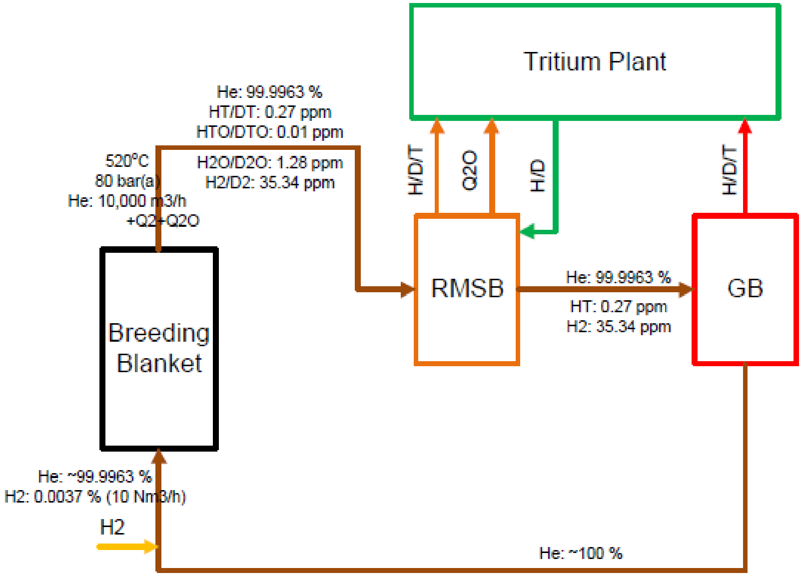
- Tritium recovered via isotope exchange on RMSB and by heating-up of the CMSB
- Extrapolated to DEMO scale is realizable, high Tech. Readiness Level



2 bar purge gas

▪ Proposed design

- 80 bar purge gas, introduced to improve reliability of BB
- CMSB requires large amount of liquid N_2, getter bed is explored as alternative
- Getter bed, in particular ZAO, shows to be a viable option to replace CMSB in TER configuration for Q_2 recovery from the purge gas ➡ G. Ana: PS4-48 Fri.



80 bar purge gas

Shield design

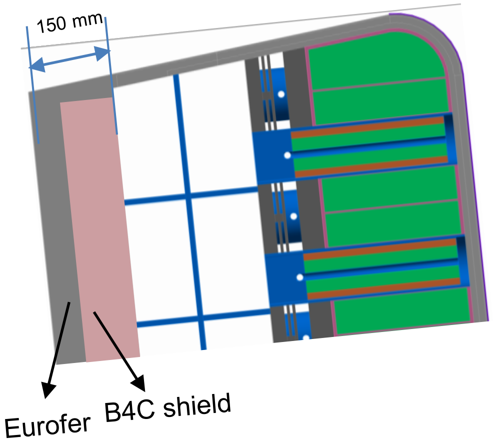
Palermo I et al., 2022 *Energies* 15, 5734.

- Parametric neutronics analysis

Shield materials: B4C, WC, WB and hydrides

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

- **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



HCPB inboard blanket

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/cm³	n/cm²/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

- Tritium and helium production in B_4C

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

Negligible, 117 kg T/fpy in EU-DEMO

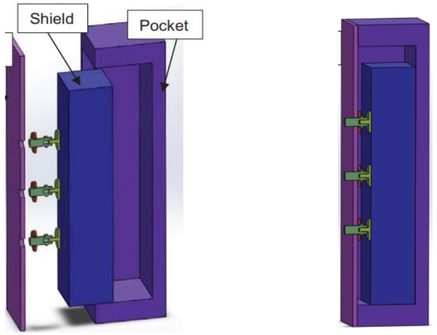
1e-28 [Pa·m³/(s·m²)] << Outgassing limit 1e-11

- 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

- Shield with 90 mm B_4C meeting all the requirements
- Container of B_4C is designed to contain fragmentation
- ITER-like solution is feasible

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


Shield of ITER diagnostic port



Shield container

Conclusions

Summary

- Solutions proposed to resolve the challenges of HCPB concept
- Key solution: high pressure purge gas, to establish a high-reliability HCPB concept
- Nuclear, thermal hydraulics and thermal mechanics assessments confirm the soundness of high pressure purge gas HCPB concept
- Tritium Extraction and Recovery system can cope with high pressure purge gas

Outlook

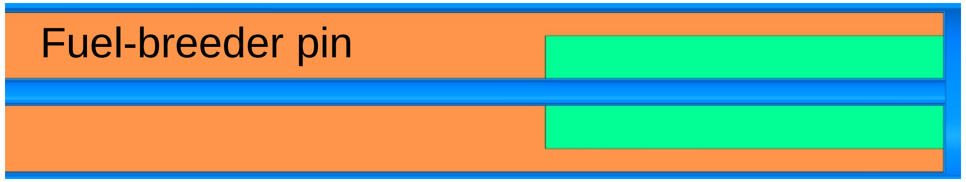
- Start RAMI analysis to check the reliability
- Complete the on-going safety analysis to confirm there is no show-stopper
- Introduce this design as baseline of HCPB breeding blanket for EU DEMO

Contact: Guangming Zhou
Email: guangming.zhou@kit.edu

Backup slides

Tritium permeation analysis

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

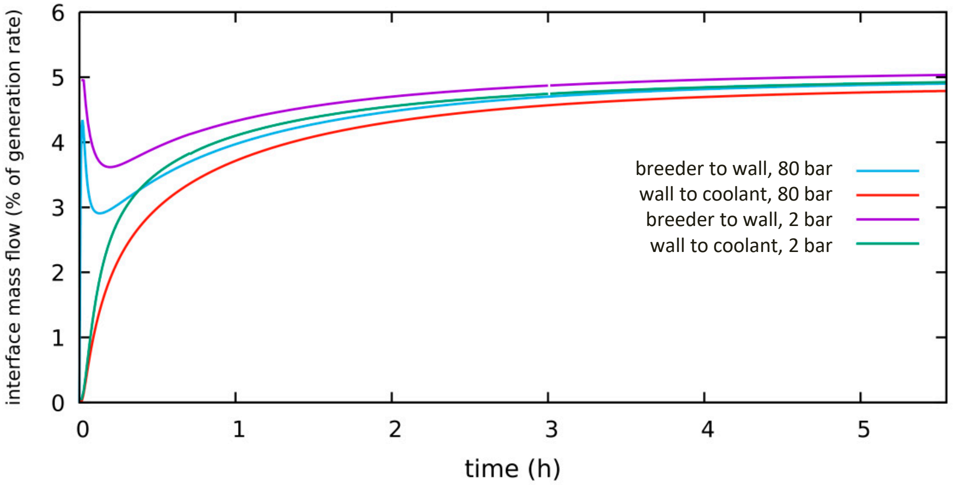


OpenFOAM

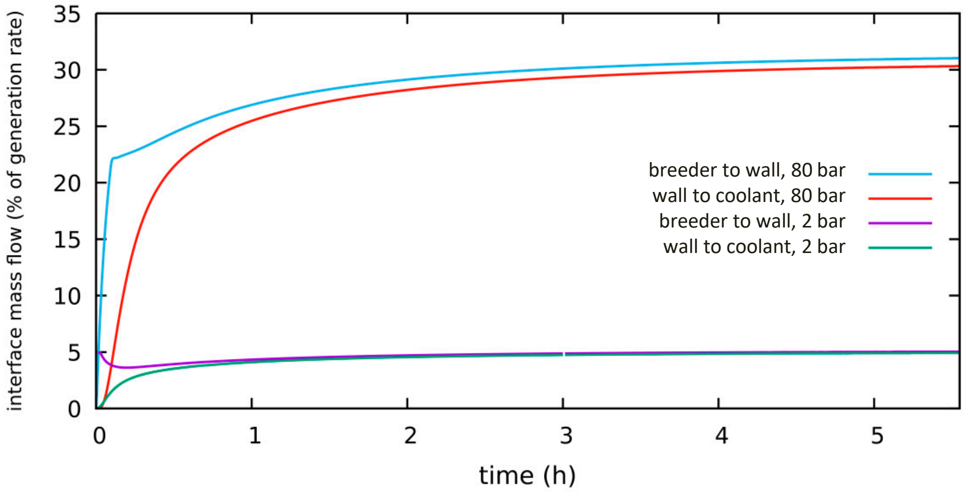
The Open Source CFD Toolbox

- T permeation analysis
  - T permeation analysis under 2 bar pressure purge gas vs 80 bar pressure purge gas, with same H2 partial pressure
  - Wet purge gas vs dry purge gas

Purge gas	Permeation to coolant	Wall T inventory
200Pa H2, no H2O	0.077% of T generation	65 ng
200Pa H2 + 200Pa H2O	0.022% of T generation 3.5 times less	19.2 ng



Permeation under equal volumetric flow



Permeation under equal mass flow

[3] Pasler V et al., 2021 *Applied Sciences* 11, 3481.