SPECIAL JOINT EVENT

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Karlsruhe, Germany
14-15 September 2022

BeYOND-IX 2022
9th Industrial Forum on Beryllium Opportunities & New Developments
Karlsruhe, Germany
16 September 2022

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EUROfusion

Current design of the EU DEMO Helium Cooled Pebble Bed breeding blanket

Dr. Guangming Zhou (KIT)
Lead Engineer of HCPB Breeding Blanket

Karlsruhe Institute of Technology

Breeding Blanket Project in EUROfusion

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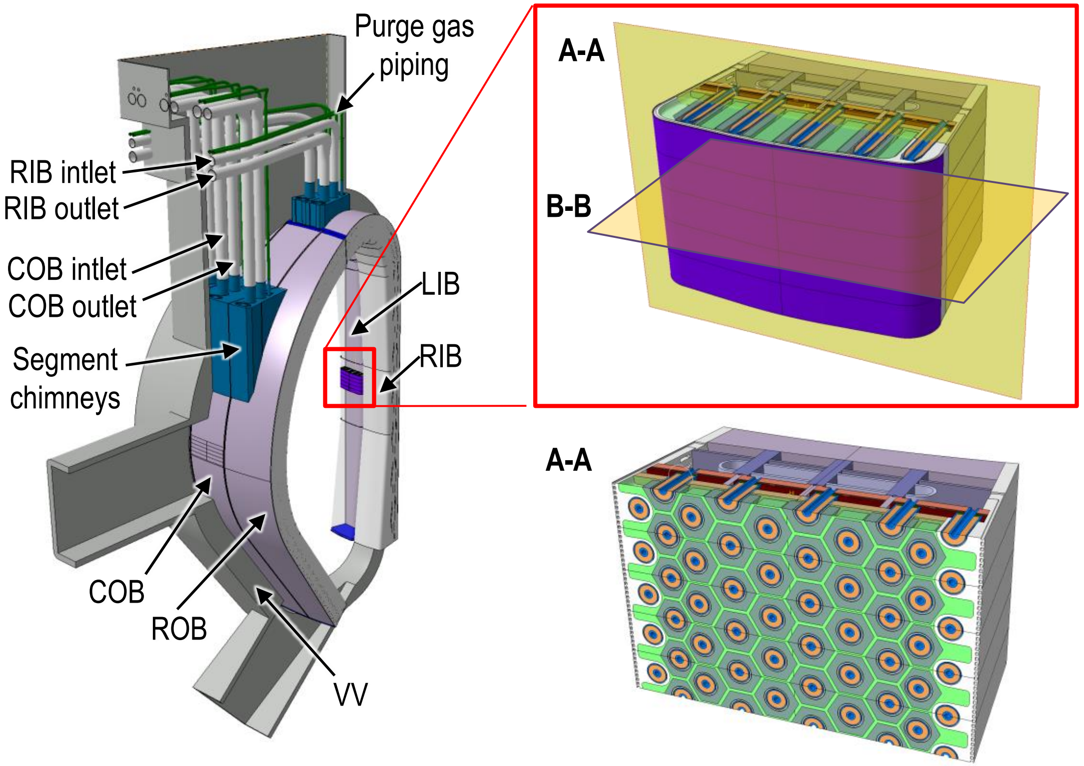
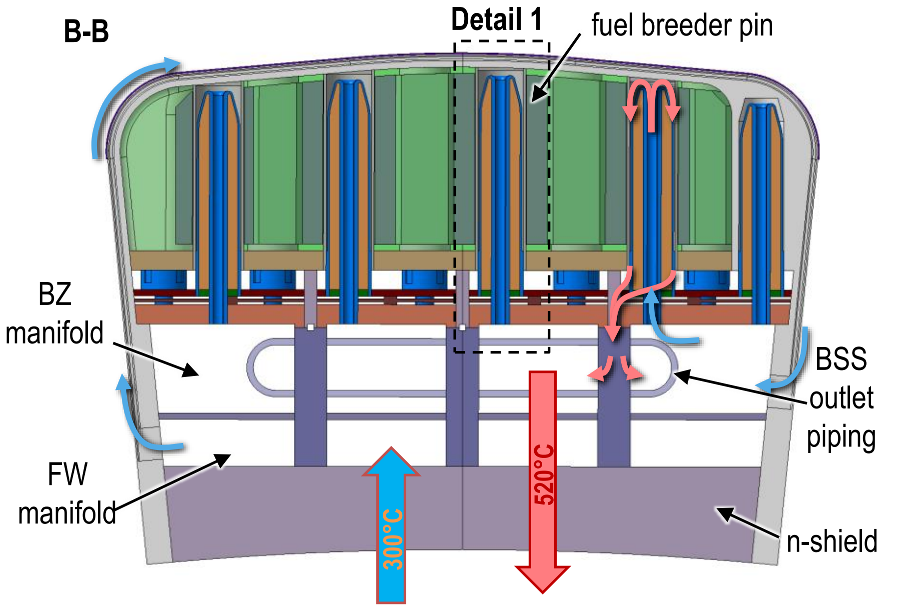
Outline of content

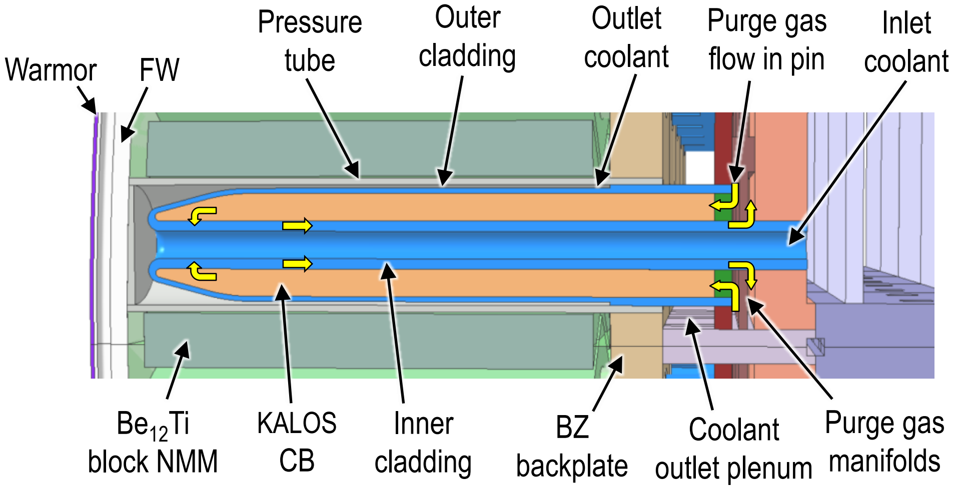
- Status at the end of Pre-Concept Design Phase (2014-2020)
- Identified risks
- Design activities to address the risks
- Outlook

Status at the end of Pre-Concept Design Phase (2014-2020)





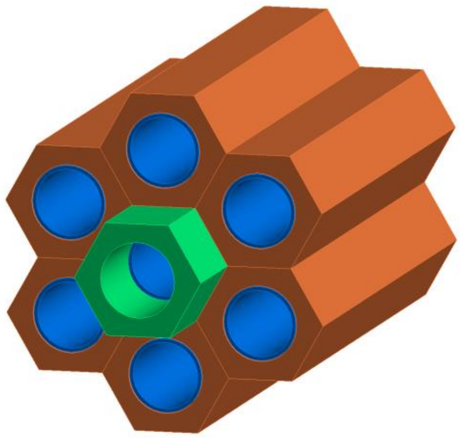
Detail 1: Fuel-breeder pin



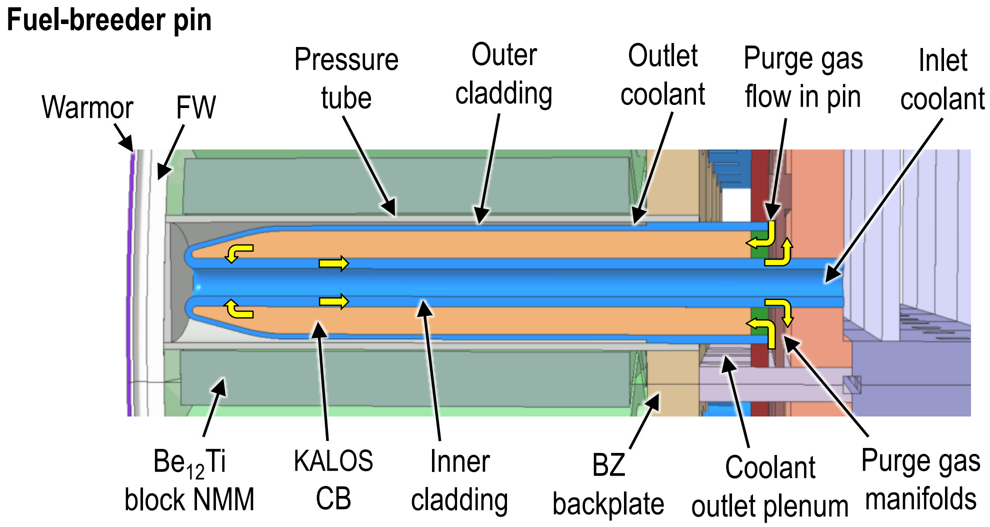
- Coolant: He @80 bar, 300-520°C
- Fuel-breeder pins containing advanced ceramic breeder (ACB) pebble bed
- Pins inserted into blocks of Be12Ti neutron multiplier
- Structural steel: Eurofer97
- Purge gas: He + 0.1vol% H_2 @2 bar
- Easier manufacturing, easier filling of pebbles
- NA, TH & TM; TBR = 1.20; Ppump per blower < 6 MW; satisfying shielding

Identified risks related to HCPB BB

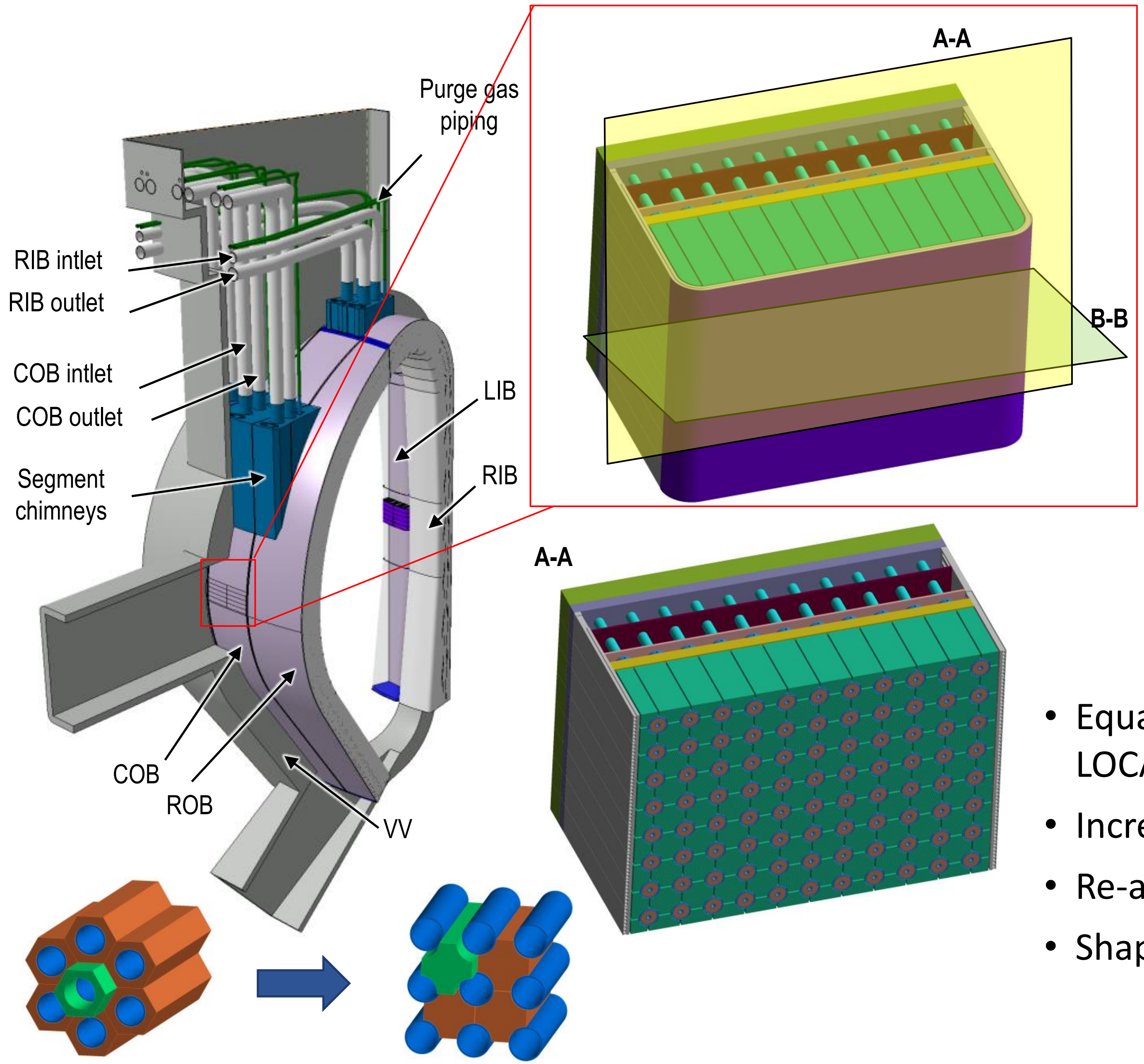
1. Low reliability of BB system under DEMO conditions [due to welds failure]
2. Loss of structural integrity of beryllide blocks → See Talk of S. Udartsev
3. High pressure drops in coolant loop contributing to total high pumping power
4. Large tritium permeation rates at the interface of breeder-coolant loop
5. Low BB shielding capability
6. Degradation of Eurofer at contact with pebbles in purge gas environment
7. Reduction of structural integrity of blanket during shutdown due to Eurofer irradiation embrittlement

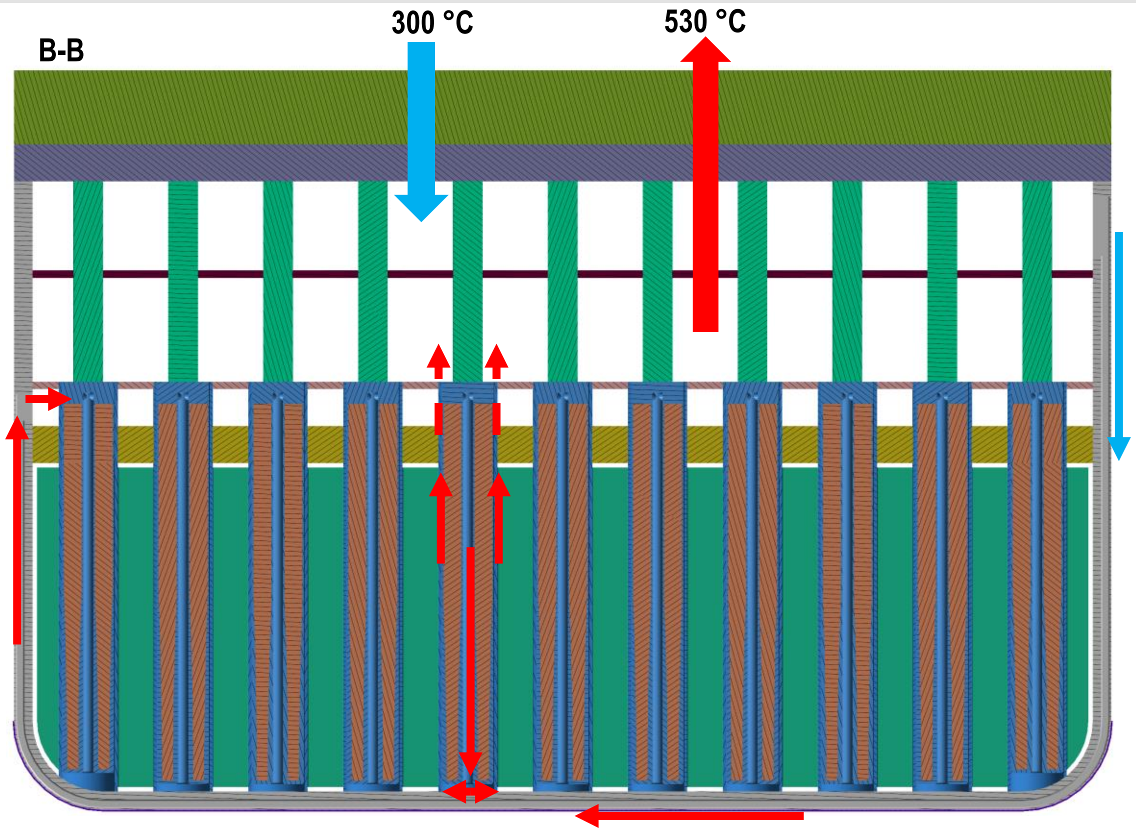


$Be_{12}Ti$ block NMM



Proposed design changes for improvements

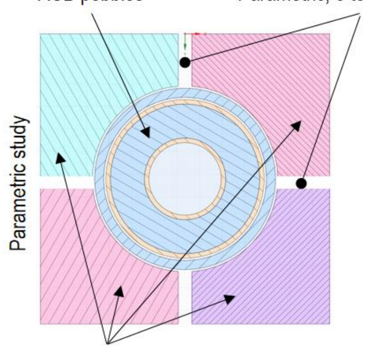


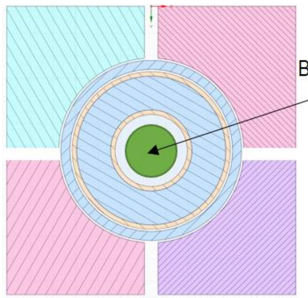


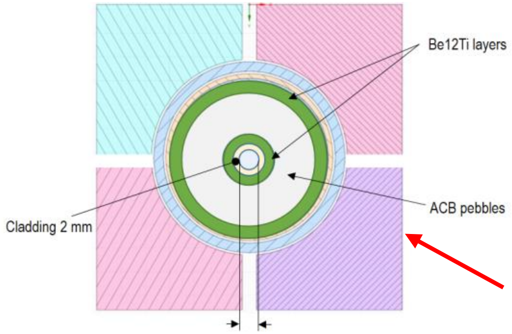
- Equalize purge gas and coolant pressure to eliminate in-box LOCA welds to improve reliability
- Increase ΔT (300°C-530°C) to further reduce pressure drop
- Re-arrange flow scheme to cool key structure with fresh coolant
- Shape of Be12Ti block to square

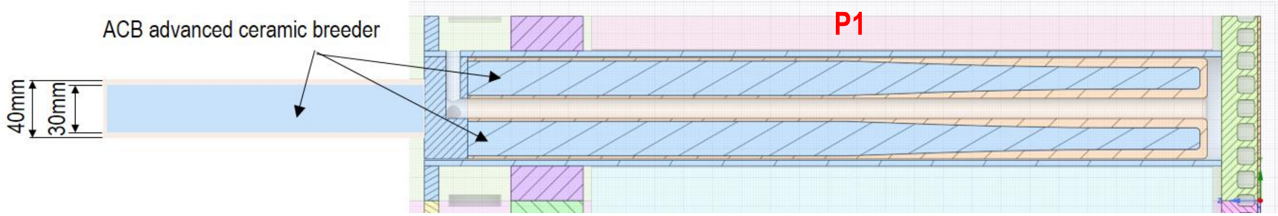
Tritium breeding ratio (TBR) optimization

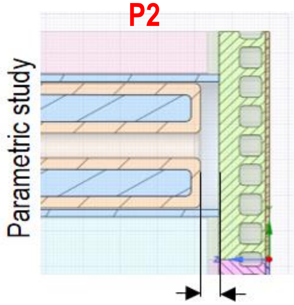
P1. Study influence of ACB in back side of the pin (whole length of back side of pin)
P2. Study reduction of the front pin cladding distance to FW
P3. Study influence of Be12Ti radial length
P4. Study influence of Be12Ti block gaps
P5. Introduction of a Be12Ti rod in the inner tube
P6. Introduce Be12Ti in ACB pebbles (on both sides)
P7. Like P6, Introduce Be12Ti in ACB pebbles (only on inner side)
P8. Combined the positive effects

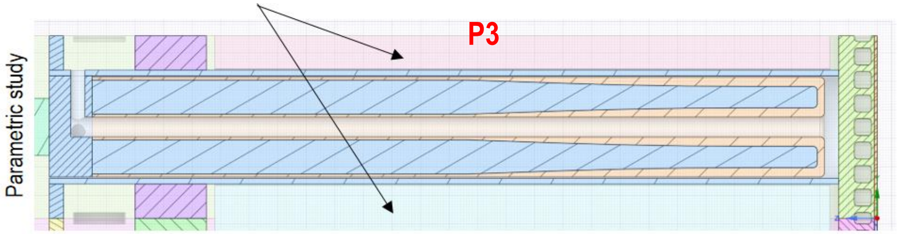


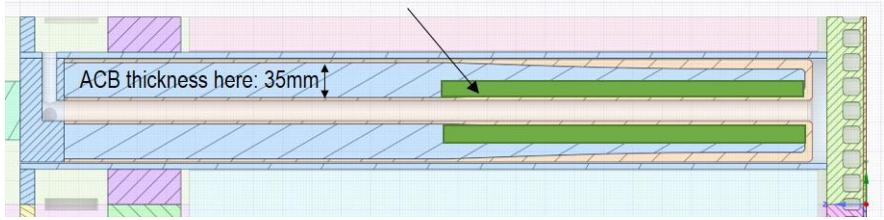


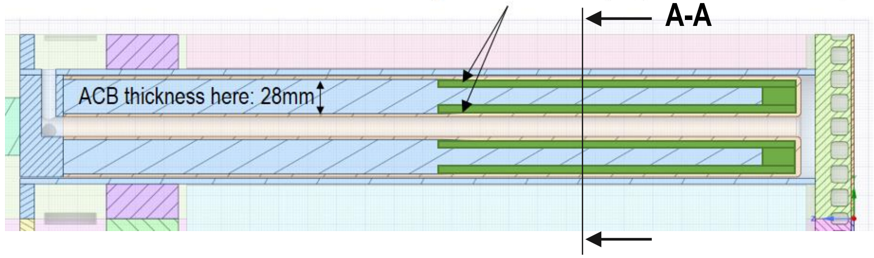






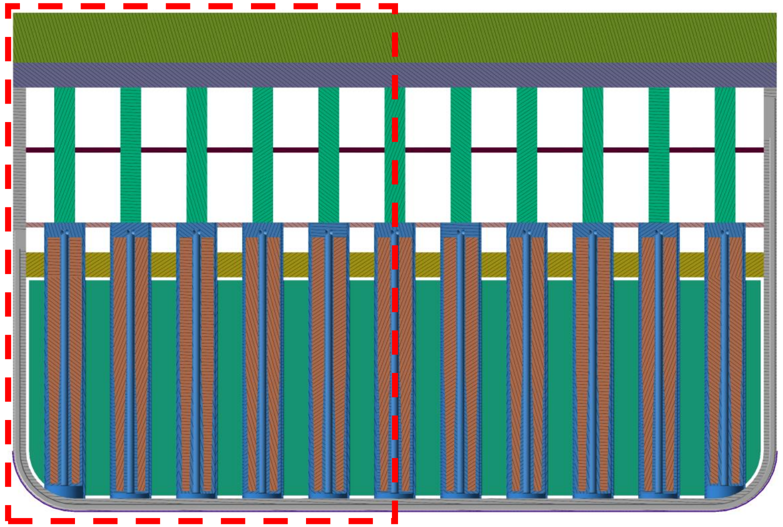




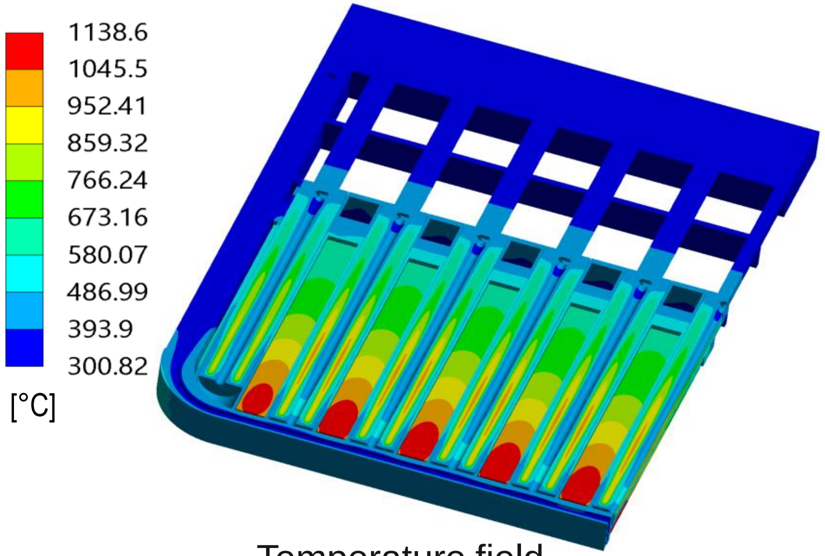


- Combined all positive effects, TBR = 1.17 > 1.15

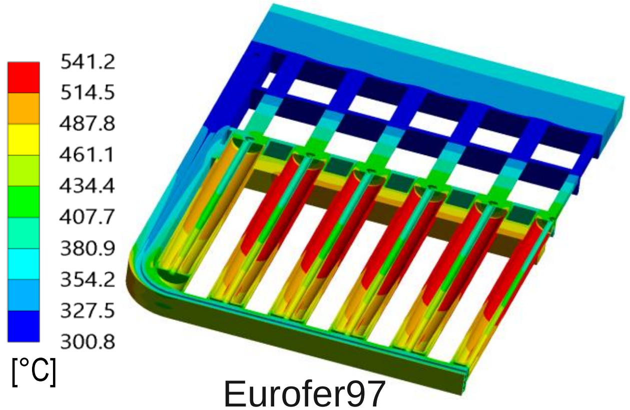
Thermal and structural analysis



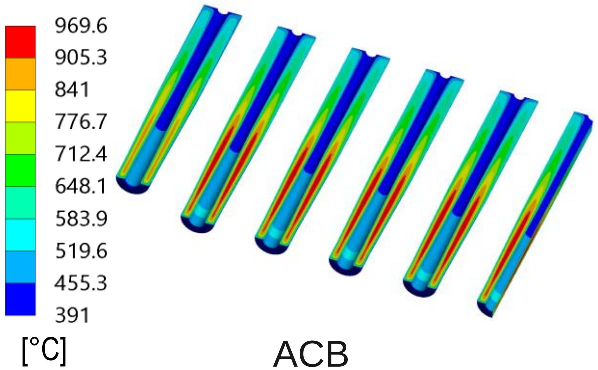
FEM model



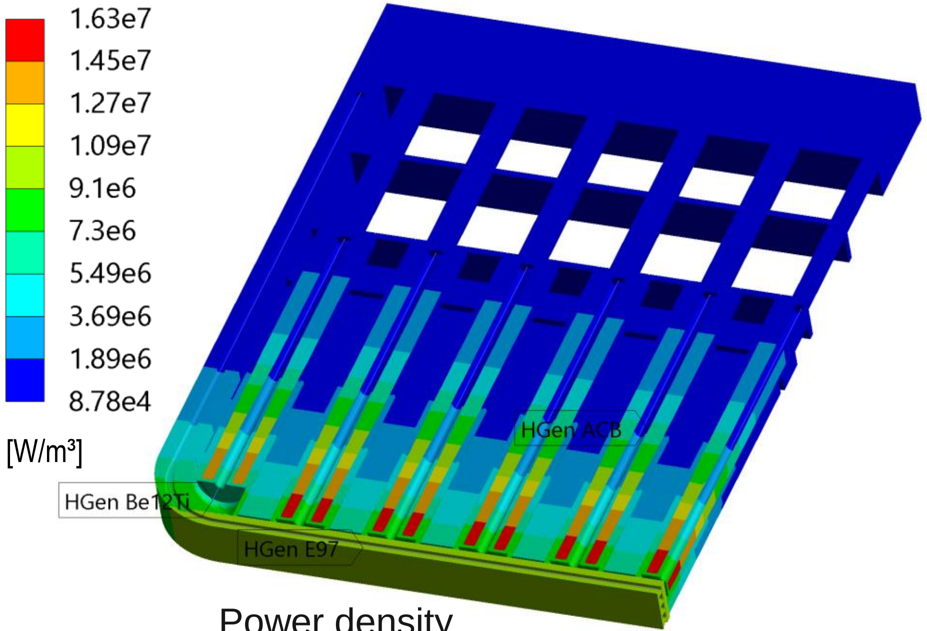
Temperature field



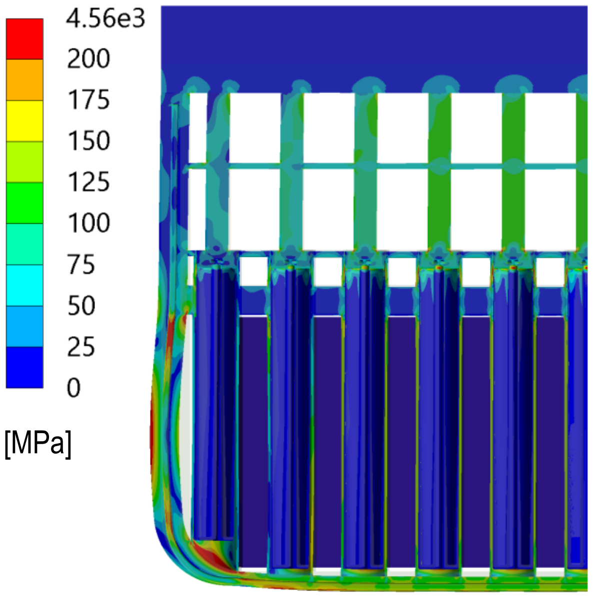
Eurofer97



ACB



Power density



Stress field (P)

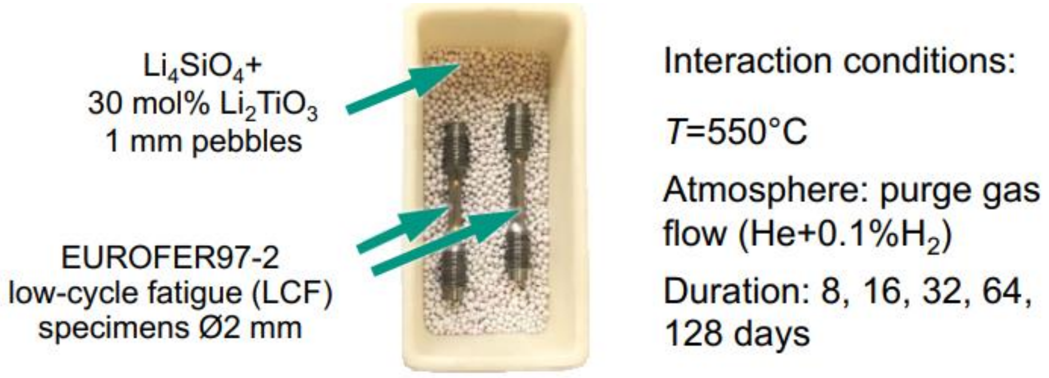
Tin / Tout = 300 / 530 °C

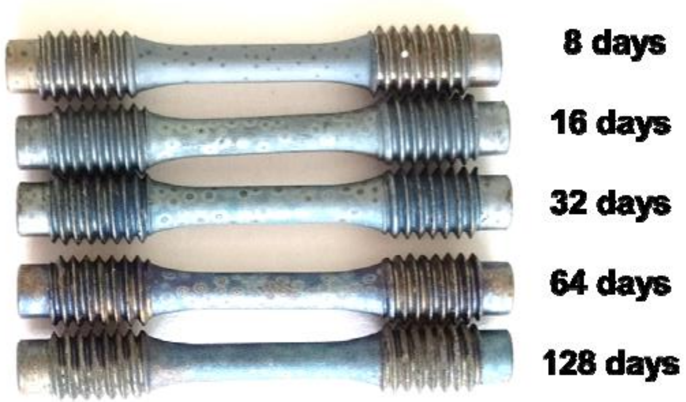
Temp. within design limits

Stresses of steel are within allowables of code

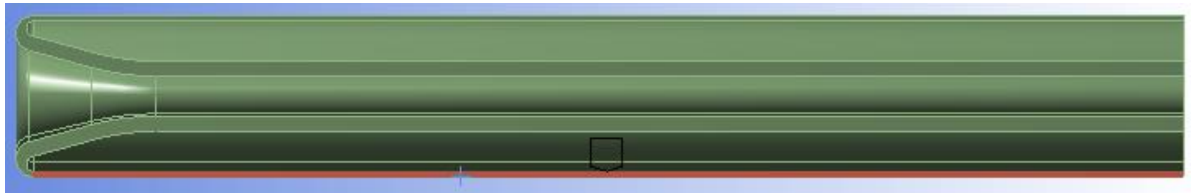
Assessment of pebble-Eurofer interaction

- Acc. to [1], the fatigue lifetime reduced due to interaction between pebbles and Eurofer97



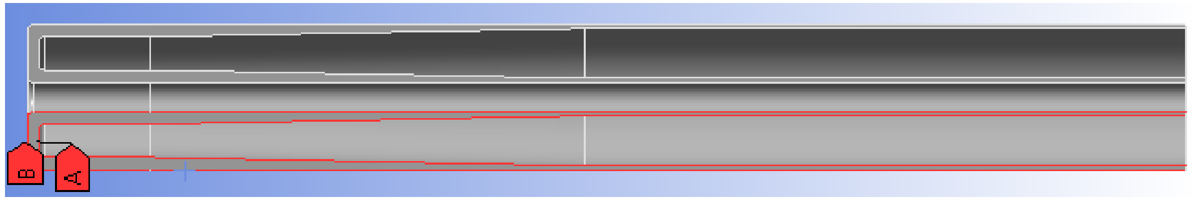


- Creep-Fatigue-Assessment tool [2] used to assess different design options (2 bar vs 80 bar purge gas)



2 bar purge gas

- Along the indicated paths, most regions failed to withstand the required 7787 cycles



80 bar purge gas

- Along the indicated paths, most regions succeeded to withstand the required 7787 cycles

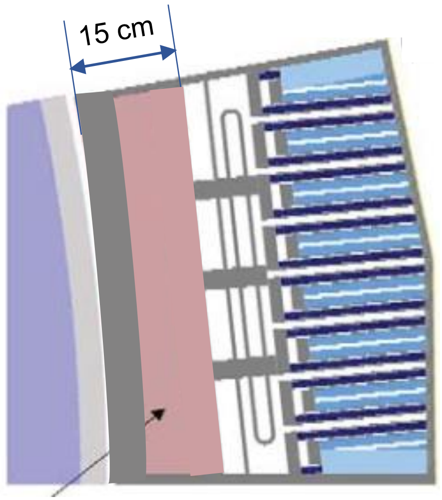
- New design able to improve lifetime.

[1] J. Aktaa et al., Fusion Eng. Des. 157 (2020) 111732.
[2] M. Mahler, J. Aktaa. Nucl. Mat. Energ. 15 (2018) 85-91.

Shielding design (1/2)

- Parametric neutronics analysis [3]

  3D MCNP model by SuperMC
  - *Baseline*: 15 cm Eurofer
  - *v1*: 1 cm B_4C, 14 cm Eurofer
  - *v2*: 2 cm B_4C, 13 cm Eurofer
  - …
  - *v5*: 5 cm B_4C, 10 cm Eurofer
  - …
  - *v10*: 10 cm B_4C, 5 cm Eurofer



Part of MCNP6 model

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 production at 1st cm of VV (limit: 0.16)
	W/cm³	n/cm²/s			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

- Tritium and helium production in B4C

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

Negligible, 120 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 mole (5.52 g) T per FPY, 500 mole (2 kg) He per FPY in EU-DEMO

Due to fragmentation of B4C, container of B4C is needed.

Nuclear heating in B4C and Eurofer used as input for structural design of the shield.

[3] I. Palermo et al., ICRS 14/RPSD 2022. September 25-29, 2022. Seattle, WA.

Shielding design (2/2)

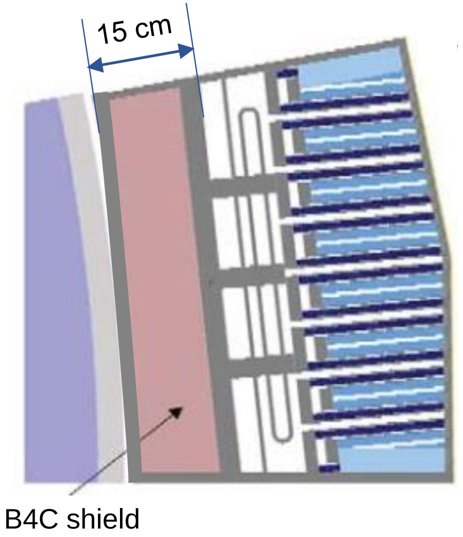
- Structural design

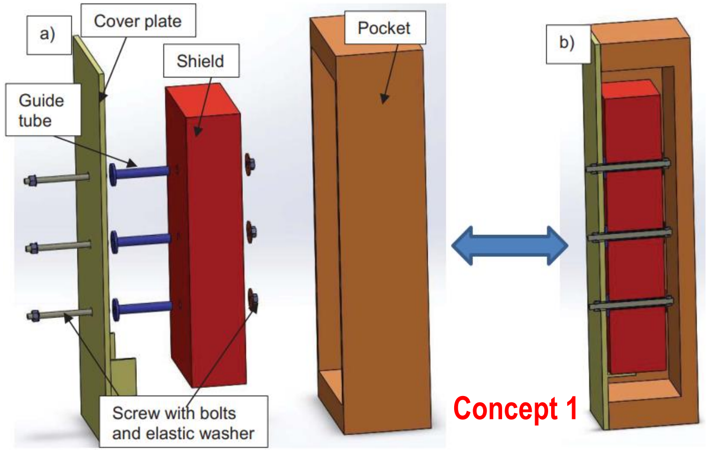
To confine the fragmentation, B4C is designed to be contained.

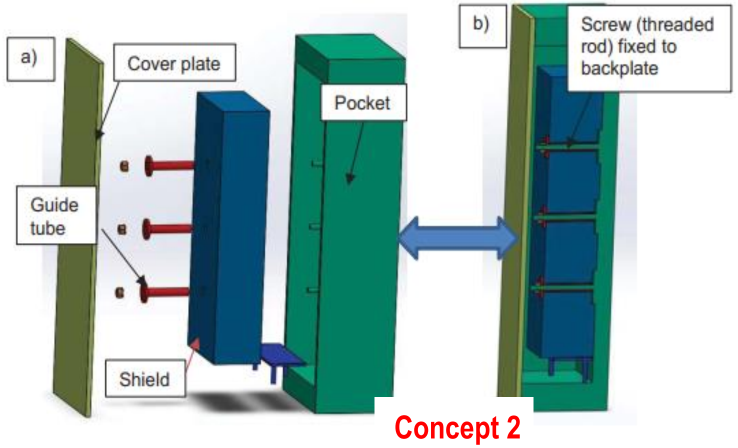
Concept 1: Radiation, shield fixed to cover plate

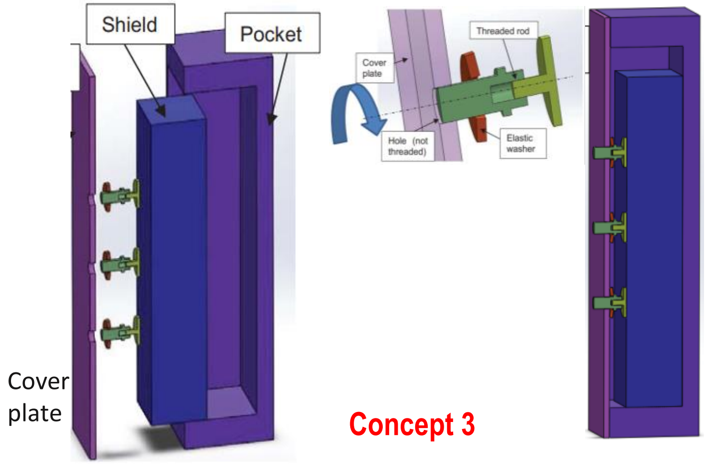
Concept 2: Contact, shield fixed to BSS backplate

Concept 3: Contact, shield fixed to BSS backplate with external clamping

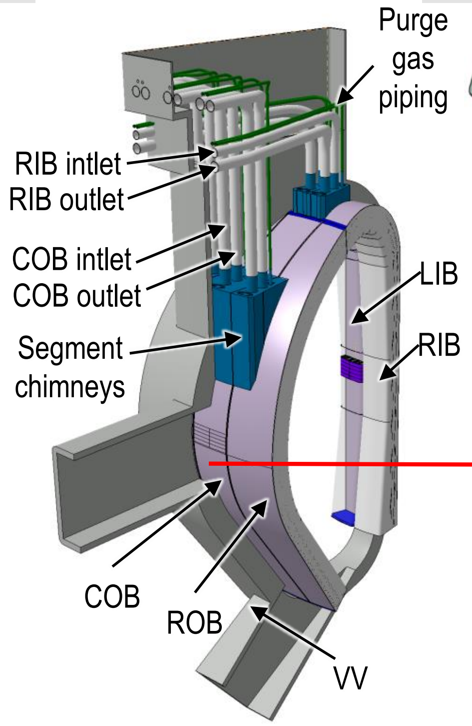


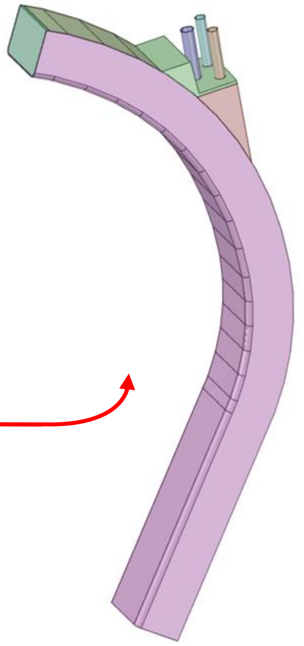




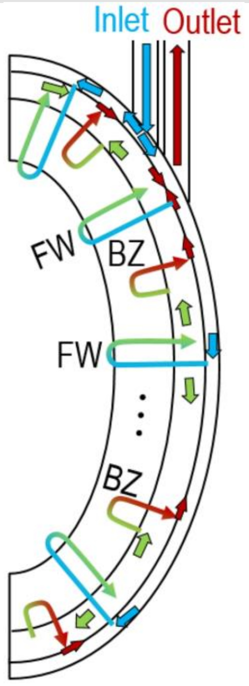


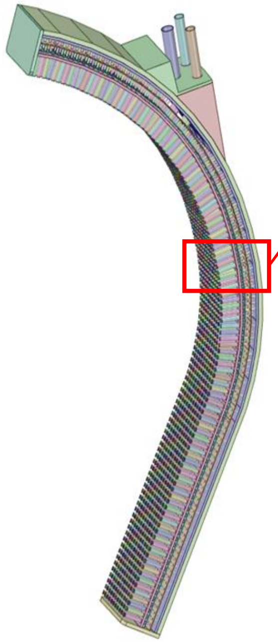
Global segment hydraulics



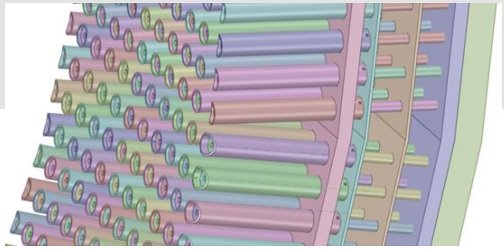


COB segment





COB segment w/o FW



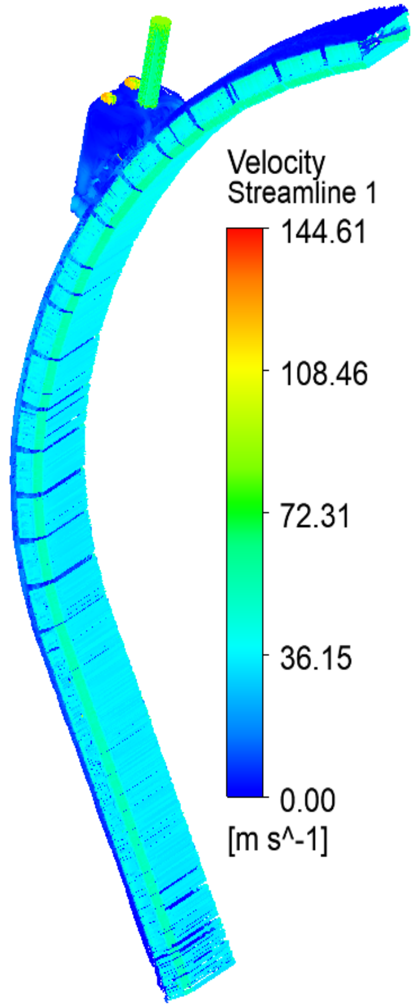
Porous media approach [4]

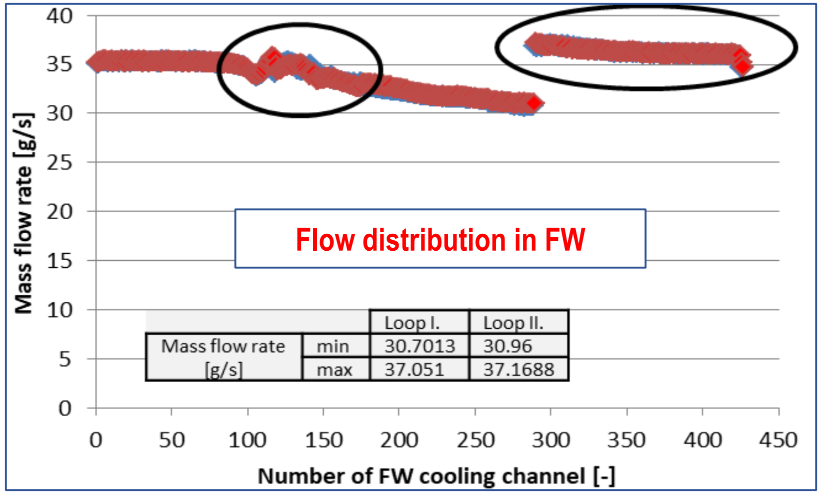
Totally in COB

- 1232 pins
- 860 FW channels

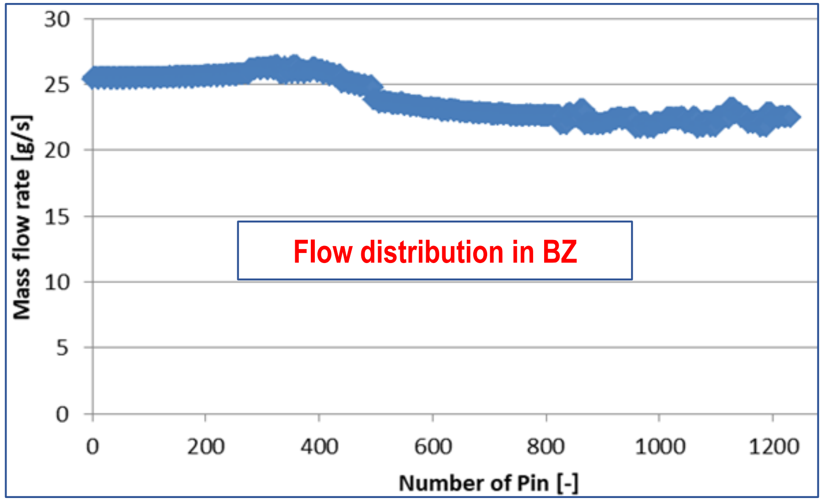
Pressure drop: 0.96 bar

Flow distribution relative OK





		Loop I.	Loop II.
Mass flow rate [g/s]	min	30.7013	30.96
	max	37.051	37.1688



[4] G. Zhou et al. Nucl. Fusion 60 (2020) 096008.

Tritium Extraction and Removal (TER) system

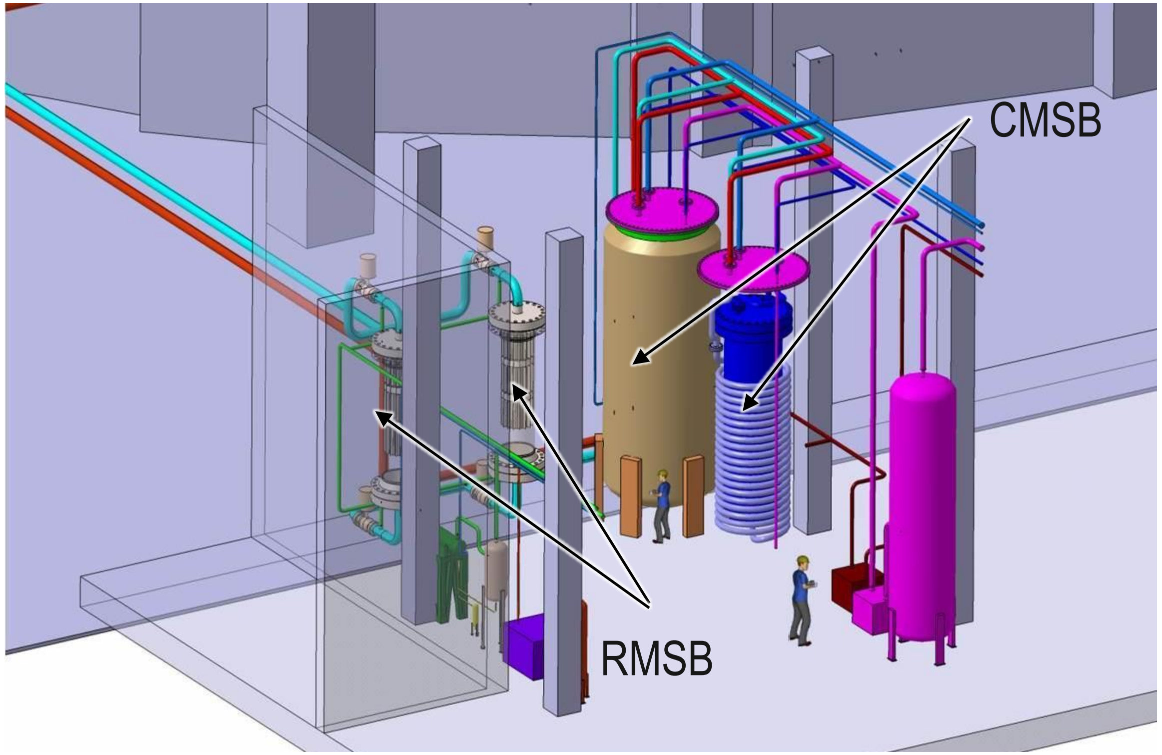
- Reference design

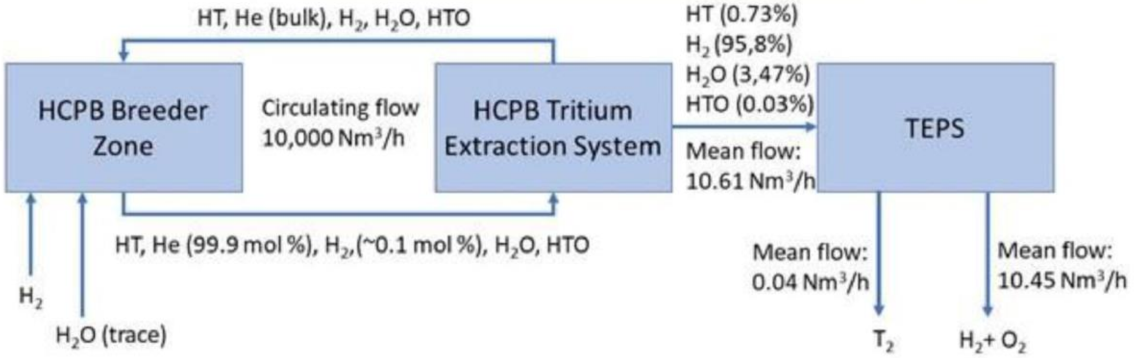
➢ Two stages in series
First the adsorption of Q2O on the Reactive Molecular Sieve Bed (RMSB), thereafter the adsorption of Q2 on the Cryogenic Molecular Sieve Bed (CMSB) at 77 K.

Q = H, D, T

➢ Tritium recovered via isotope exchange on RMSB and by heating-up of the CMSB.

➢ Extrapolated to DEMO scale is realized with industry.





- Outlook

➢ 80 bar purge gas, introduced to improve reliability of BB, results show that TER operating at 80 bar not a issue.

➢ CMSB requires large amount of liquid N2, getter bed is explored as alternative.

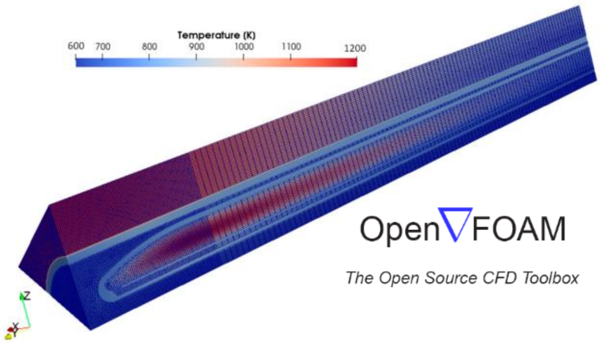
➢ Wetted purge gas to have a higher isotopic exchange rate compared to H2 and oxidized Q2, reducing permeation.

[5] I. Cristescu et al., Fusion Eng. Des. 158 (2020) 111558.

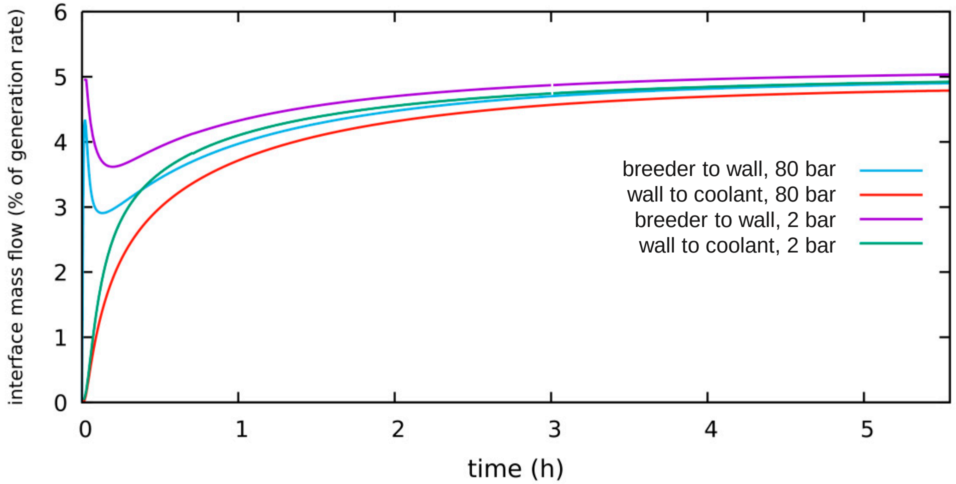
Tritium permeation analysis

- 3D component level solver [6]
  - Developed based on the OpenFOAM and benchmarked with TMAP 7
  - T release model

    Grain surface release model based on irradiation T release experiment [7]



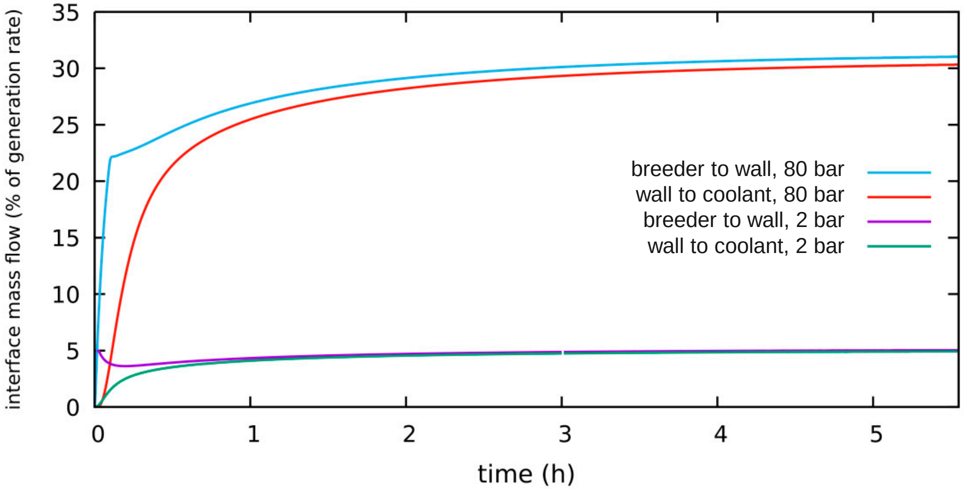
Temp. field of 1/6 fuel-breeder pin



Permeation under equal volumetric flow

- T permeation analysis
  - T permeation analysis under 2 bar pressure purge gas vs 80 bar pressure purge gas, with same H2 partial pressure
  - Wetted 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 290 mg/d	65 ng
200Pa H_2 + 200Pa H_2O	0.022% of T generation 83 mg/d	19.2 ng



Permeation under equal mass flow

[6] V. Pasler et al., Applied Sciences 11 (2021) 3481.
[7] T. Kinjyo et al. Fusion Engineering and Design 81 (2006) 573-577.

Outlook

- At end of 2022, the milestone of preliminary conceptual design of the HCPB blanket shall be reached.
- At second half of 2024, the milestone of reference conceptual design for the HCPB blanket shall be reached, together with R&D programme.
- At the end of 2024, the driver blanket for EU-DEMO will be selected from the HCPB and WCLL concepts.
- From 2025 to 2027, the selected blanket will be further consolidated and qualified via design and R&D activities.

Contributors & Acknowledgements

Guangming Zhou[1*], Francisco A. Hernández[1, 2], Jarir Aktaa[1], David Alonso[3], Frederik Arbeiter[1], Lorenzo V. Boccaccini[1], Ion Cristescu[1], Antonio Froio[4], Christophe Garnier[5], Mathias Jetter[1], Xue Zhou Jin[1], Marc Kamlah[1], Béla Kiss[6], Christine Klein[1], Christina Koehly[1], Ivan Maione[1], Luis Maqueda[3], Carlos Moreno[7], Ivo Moscato[2,8], Iole Palermo[7], Jin Hun Park[1], Volker Pasler[1], Dario Passafiume[1], Pavel Pereslavtsev[1], Anoop Retheesh[1], Álvaro Yáñez[3]

*Guangming.Zhou@kit.edu

[1]*Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany*

[2]*EUROfusion Programme Management Unit, Garching, Germany*

[3]*ESTEYCO, Madrid, Spain*

[4]*Dipartimento Energia, Politecnico di Torino, Turin, Italy*

[5]*French Alternative Energies and Atomic Energy Commission (CEA), Cadarache, France*

[6]*Budapest University of Technology and Economics (BME), Budapest, Hungary*

[7]*CIEMAT, Fusion Technology Division, Madrid, Spain*

[8]*University of Palermo, Palermo, Italy*

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Thank you for your attention!