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

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In the Work Package Breeding Blanket (WPBB) of the European DEMO program, the Helium Cooled Pebble Bed (HCPB) breeding blanket is one of the two driver-blanket candidates for the European DEMO and to be tested as test blanket module (TBM) in ITER. In the Pre-Concept Design (PCD) phase (2014-2020), within the framework of the EUROfusion consortium in Europe, the design of the HCPB breeding blanket has been changed to address various challenges facing the HCPB blanket concept. One of the big challenges was the use of Beryllium pebbles as the neutron multiplier in the previous design. Irradiation campaign showed that the tritium retention in the Be pebbles could impose severe safety issues and exceed the tritium limit of EU DEMO. Beryllides, on the other hand, have better properties in terms of volumetric swelling, tritium retention, irradiation and melting temperature.

This talk will focus on the current design status of the European DEMO HCPB breeding blanket and conclude with future activities in the Concept Design phase (2021-2027).

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EUROfusion

BeWS-15 2022
15th International Workshop On Beryllium Technology
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14-15 September 2022

SPECIAL JOINT EVENT

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

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

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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

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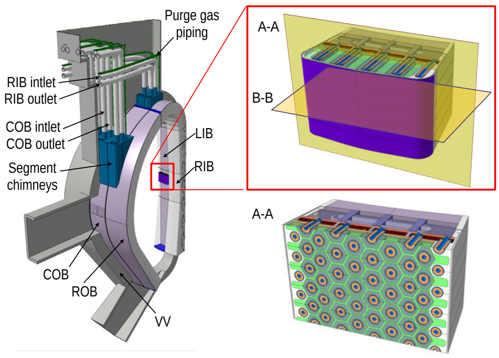
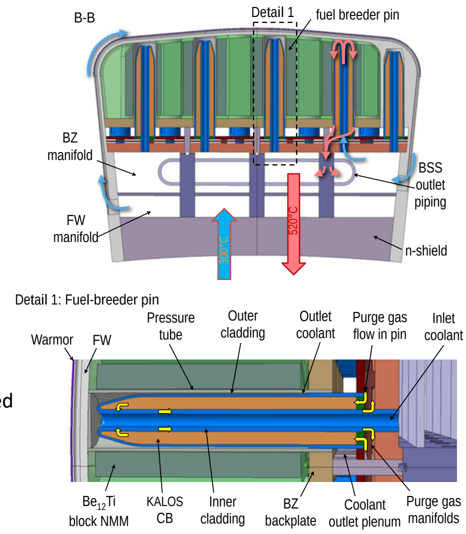
Status at the end of Pre-Concept Design Phase (2014-2020)





- 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

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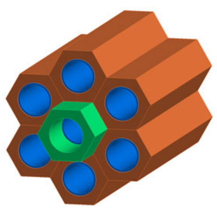
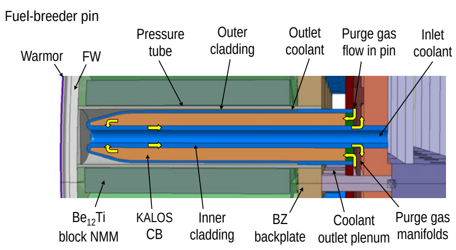
Identified risks related to HCPB BB

1. Low reliability of BB system under DEMO conditions [due to welds failure]
2. Loss of structural integrity of beryllide blocks
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
8. Low TRL of Codes & Standards for design of DEMO components



$Be_{12}Ti$ block NMM



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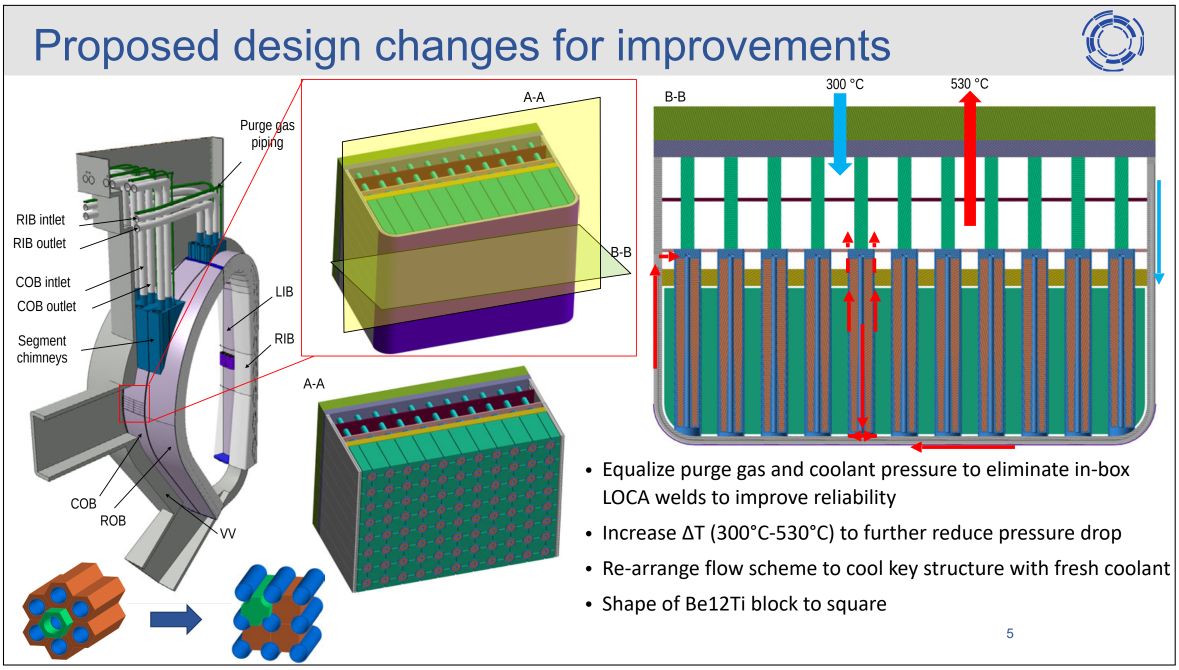
Proposed design changes for improvements
Purge gas piping
RIB intlet
RIB outlet
COB intlet
COB outlet
Segment chimneys
LIB
RIB
COB
ROB
VV
A-A
B-B
300 °C
530 °C
• Equalize purge gas and coolant pressure to eliminate in-box LOCA welds to improve reliability
• Increase ΔT (300°C-530°C) to further reduce pressure drop
• Re-arrange flow scheme to cool key structure with fresh coolant
• Shape of Be12Ti block to square
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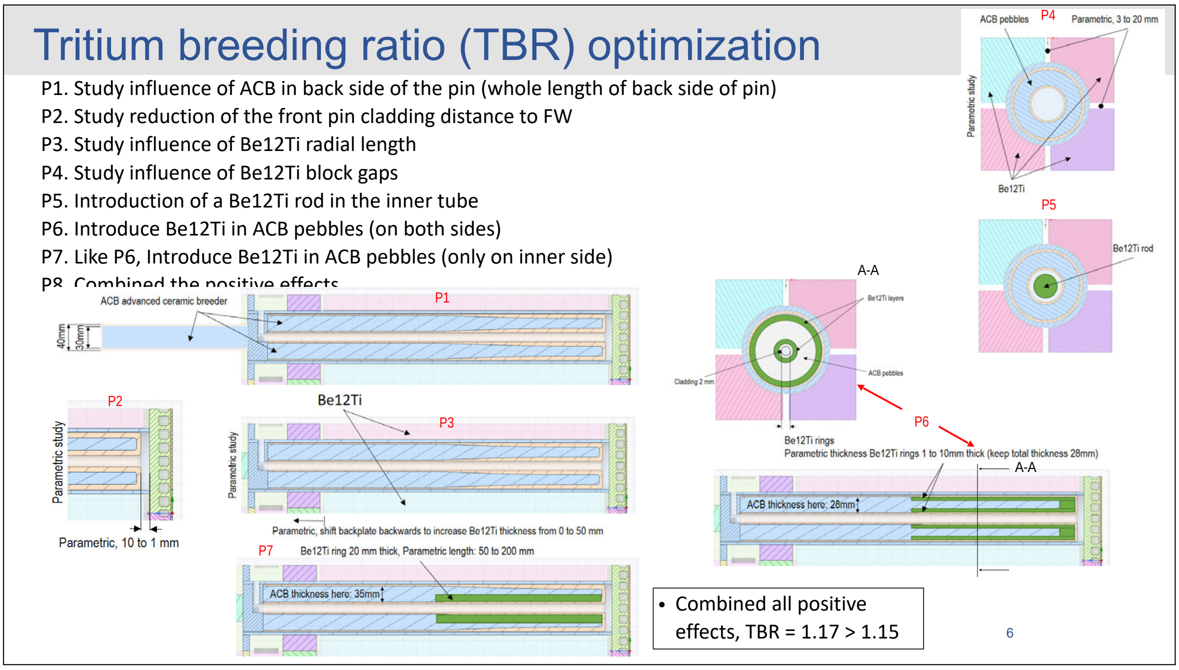
Tritium breeding ratio (TBR) optimization
P1. Study influence of ACB in back side of the pin (whole length of back side of pin)
P2. Study reduction of the front pin cladding distance to FW
P3. Study influence of Be12Ti radial length
P4. Study influence of Be12Ti block gaps
P5. Introduction of a Be12Ti 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
ACB pebbles
P4
Parametric, 3 to 20 mm
Parametric study
Be12Ti
P5
Be12Ti rod
ACB advanced ceramic breeder
P1
40mm
30mm
A-A
Be12Ti layers
ACB pebbles
Cladding 2 mm
P2
Parametric study
Parametric, 10 to 1 mm
Be12Ti
P3
Parametric study
Parametric, shift backplate backwards to increase Be12Ti thickness from 0 to 50 mm
P6
Be12Ti rings
Parametric thickness Be12Ti rings 1 to 10mm thick (keep total thickness 28mm)
A-A
ACB thickness here: 28mm
P7
Be12Ti ring 20 mm thick, Parametric length: 50 to 200 mm
ACB thickness here: 35mm
• Combined all positive effects, TBR = 1.17 > 1.15
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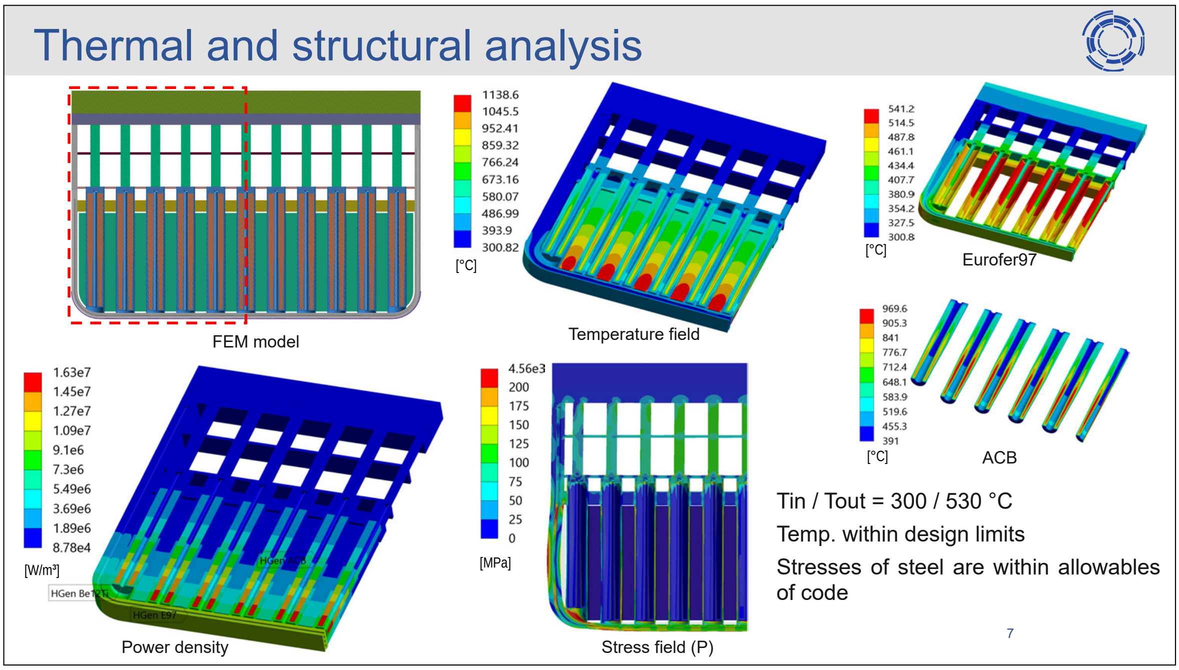
Thermal and structural analysis
FEM model
1138.6
1045.5
952.41
859.32
766.24
673.16
580.07
486.99
393.9
300.82
[°C]
Temperature field
541.2
514.5
487.8
461.1
434.4
407.7
380.9
354.2
327.5
300.8
[°C]
Eurofer97
969.6
905.3
841
776.7
712.4
648.1
583.9
519.6
455.3
391
[°C]
ACB
1.63e7
1.45e7
1.27e7
1.09e7
9.1e6
7.3e6
5.49e6
3.69e6
1.89e6
8.78e4
[W/m³]
Power density
4.56e3
200
175
150
125
100
75
50
25
0
[MPa]
Stress field (P)
Tin / Tout = 300 / 530 °C
Temp. within design limits
Stresses of steel are within allowables of code
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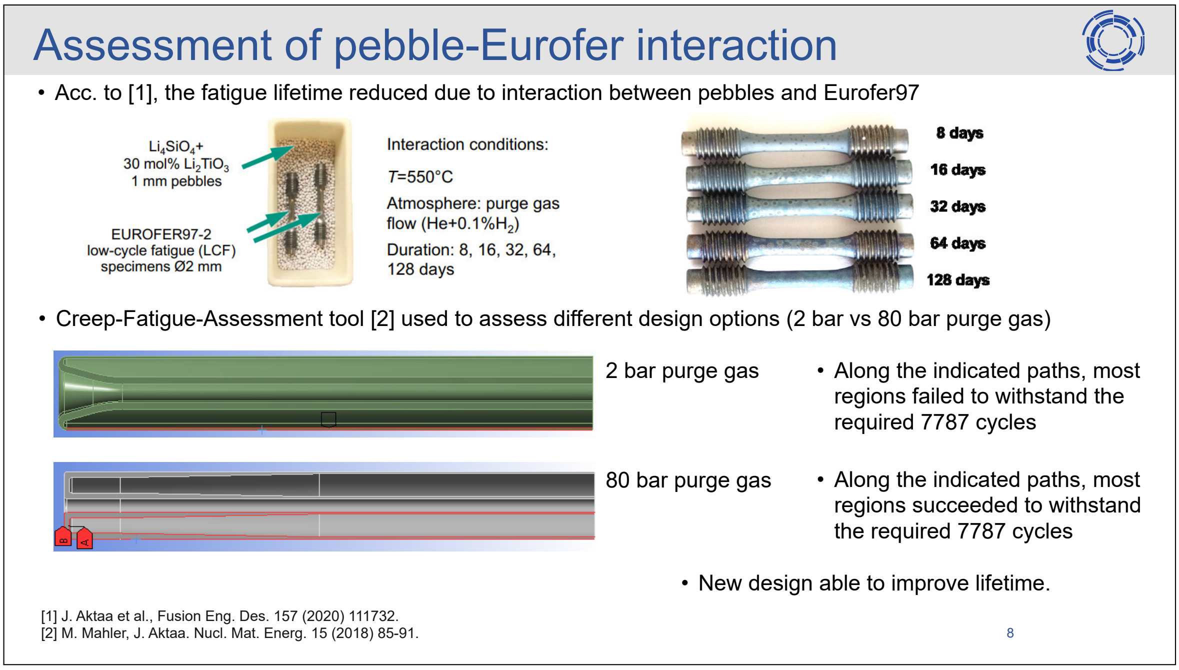
Assessment of pebble-Eurofer interaction
• Acc. to [1], the fatigue lifetime reduced due to interaction between pebbles and Eurofer97
Li4SiO4+ 30 mol% Li2TiO3 1 mm pebbles
EUROFER97-2 low-cycle fatigue (LCF) specimens Ø2 mm
Interaction conditions:
T=550°C
Atmosphere: purge gas flow (He+0.1%H2)
Duration: 8, 16, 32, 64, 128 days
8 days
16 days
32 days
64 days
128 days
• 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.
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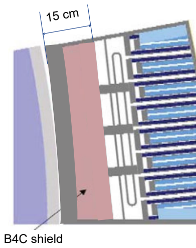
Shielding design (1/2)

- 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

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

At least 9 cm B4C is needed for meeting all the requirements.
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.

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Shielding design (2/2)

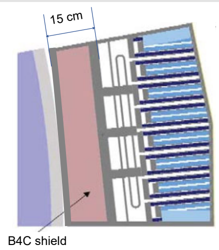
- Structural design

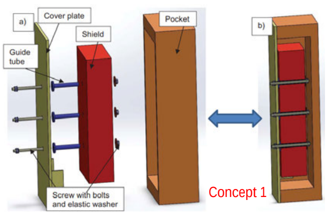
To confine the fragmentation, B4C is designed to be contained.

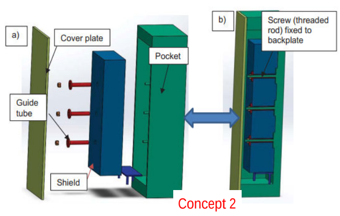
Concept 1: Radiation, shield fixed to cover plate

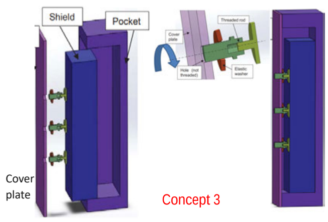
Concept 2: Contact, shield fixed to BSS backplate

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









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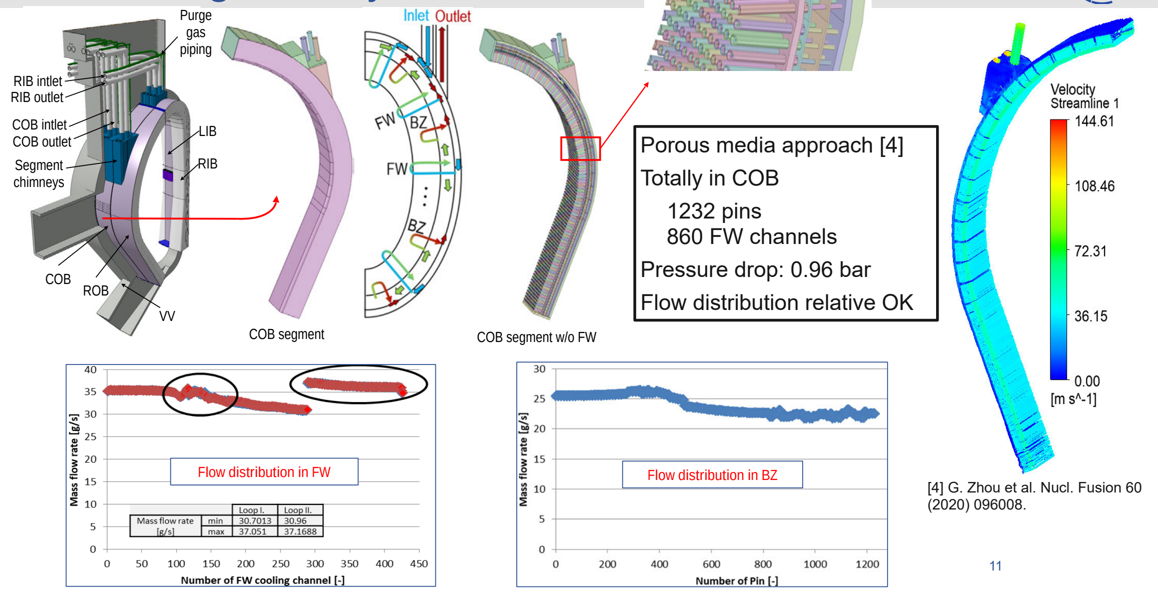
Global segment hydraulics



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

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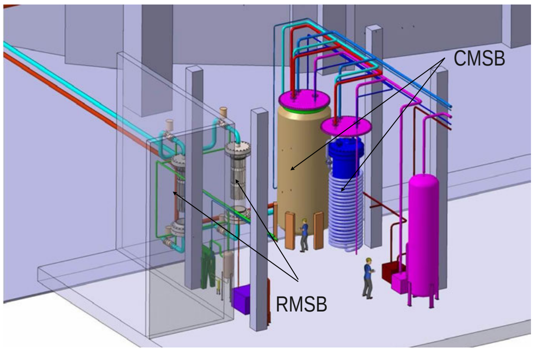
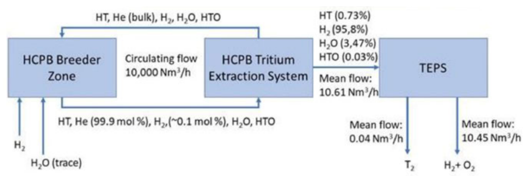
Tritium Extraction and Removal (TER) system

- 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.

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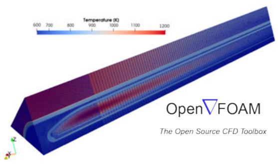
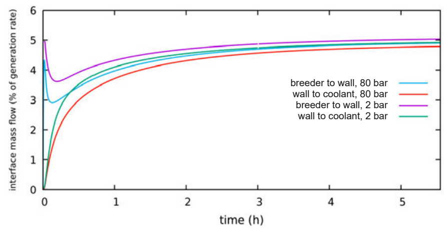
Tritium permeation analysis

- 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]



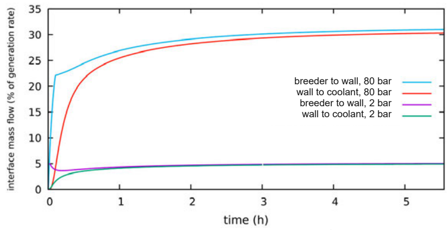
Temp. field of 1/6 fuel-breeder pin



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 H2, no H2O	0.077% of T generation 290 mg/d	65 ng
200Pa H2 + 200Pa H2O	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.

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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.

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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]

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