The 21st International Workshop on
Ceramic Breeder Blanket Interactions (CBBI-21)

19-20th October 2023
Granada, Spain

EUROfusion

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

Guangming Zhou[1], Jarir Aktaa[1], David Alonso[2], Lorenzo V. Boccaccini[1], Ion Cristescu[1], Christophe Garnier[3], Francisco A. Hernández[1,4], Mathias Jetter[1] Béla Kiss[5], Christina Koehly[1], Luis Maqueda[2], Carlos Moreno[6], Iole Palermo[7], Jin Hun Park[1], Volker Pasler[1], Anoop Retheesh[1], Álvaro Yáñez[2]

[1] Karlsruhe Institute of Technology, Germany
[2] ESTEYCO, Spain
[3] CEA, France
[4] EUROfusion PMU, Germany
[5] Budapest University of Technology and Economics, Hungary
[6] Heffen Technologies, Spain
[7] CIEMAT, Spain

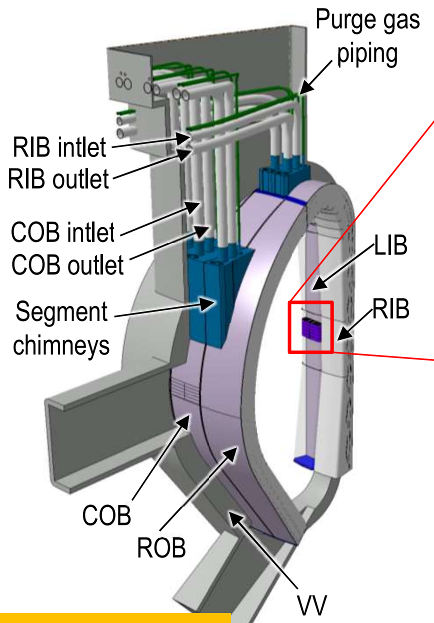
Breeding Blanket Project in EUROfusion

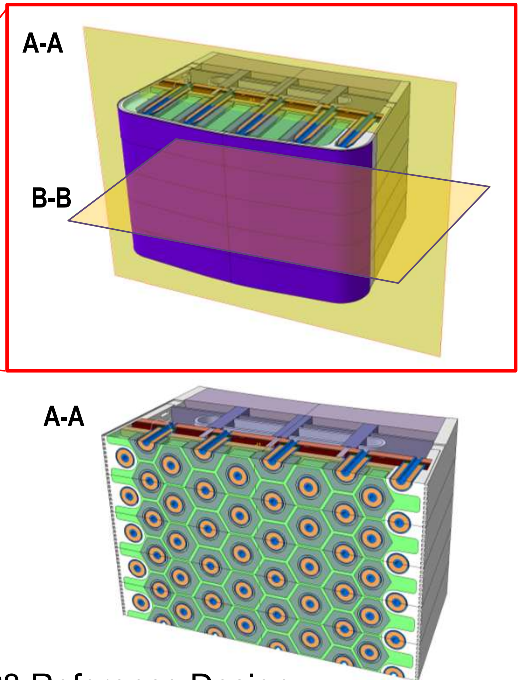
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission.

Outline

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

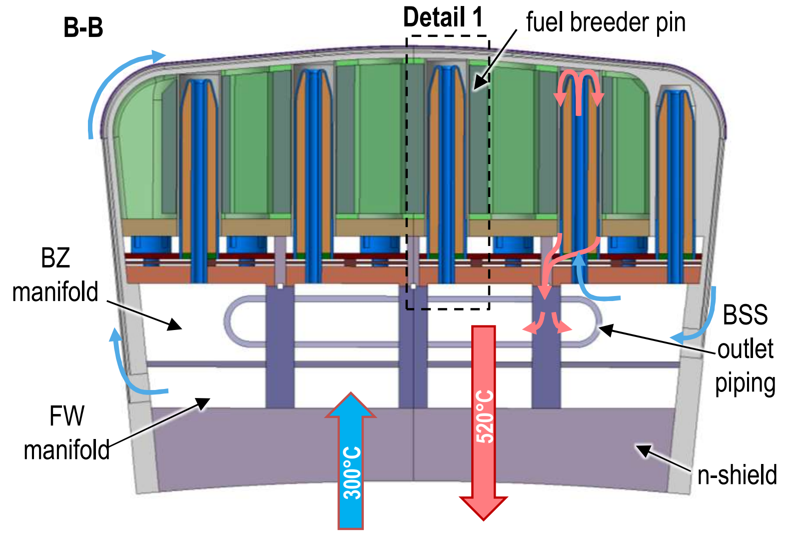
Status of HCPB at the conclusion of FP8 (2014-2020)

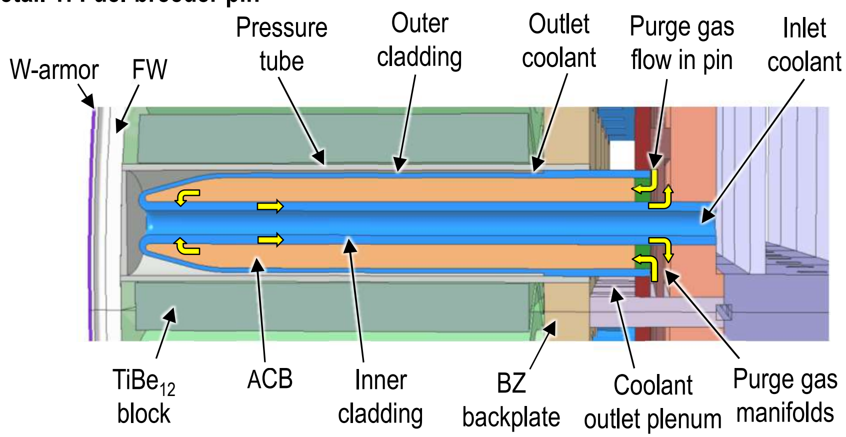




Hernández FA et al., 2020
Fusion Eng Des 157, 111614.

HCPB-FP8 Reference Design





- 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

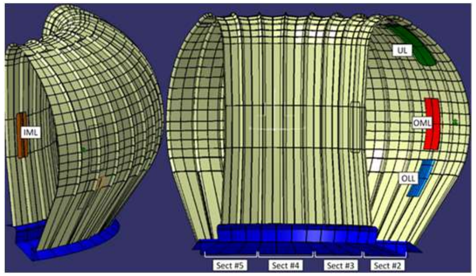
▪ Highlighted Challenges

1. Low reliability of BB system under DEMO conditions (Adressed by [1])

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

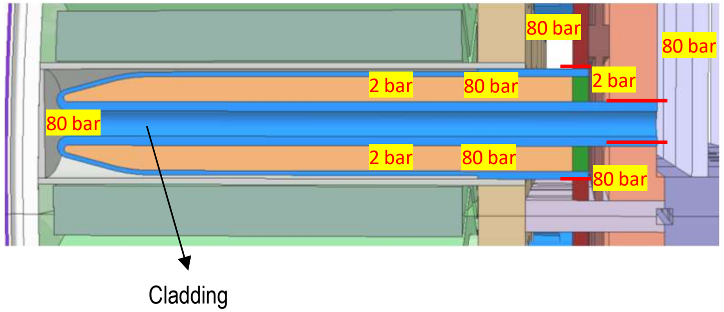
2. Cracking of beryllide blocks (Adressed by [2] + R&D)
3. Degradation of Eurofer at contact with pebbles in purge gas environment (Adressed by [1] + R&D)
4. Low BB shielding capability (Addressed by Efficient shield)
5. Limited heat flux removal capability of the He-cooled FW

Limiters



▪ Solutions

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

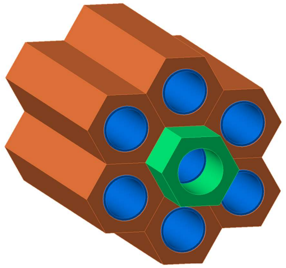


Large number of welds: 400e3

Max. failure rate of welds: 2.58e-08 (1/h)

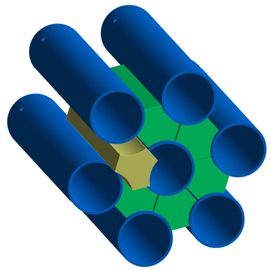
400e3 x 2.58e-08 = 0.01 (1/h)

[2] Change shape of TiBe12 blocks



HCPB-FP8

Hexagonal prism with a central hole

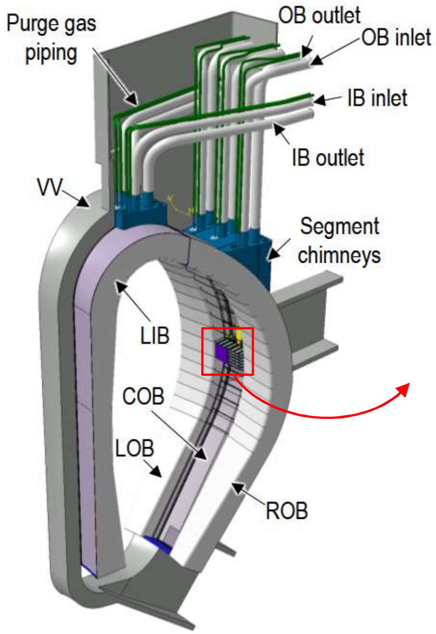


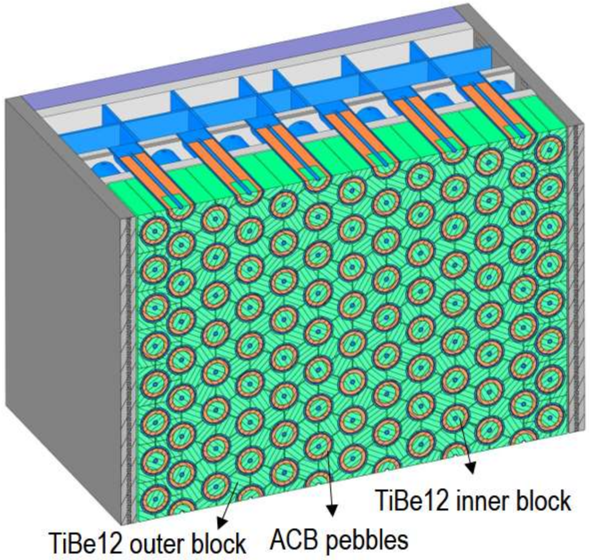
HCPB-BL2017-HP-v1

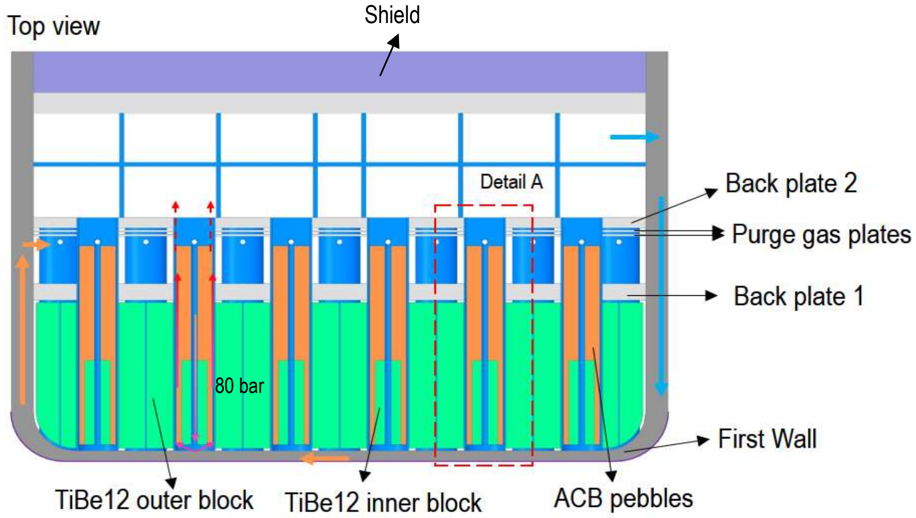
Triangular prism with lateral edges filleted

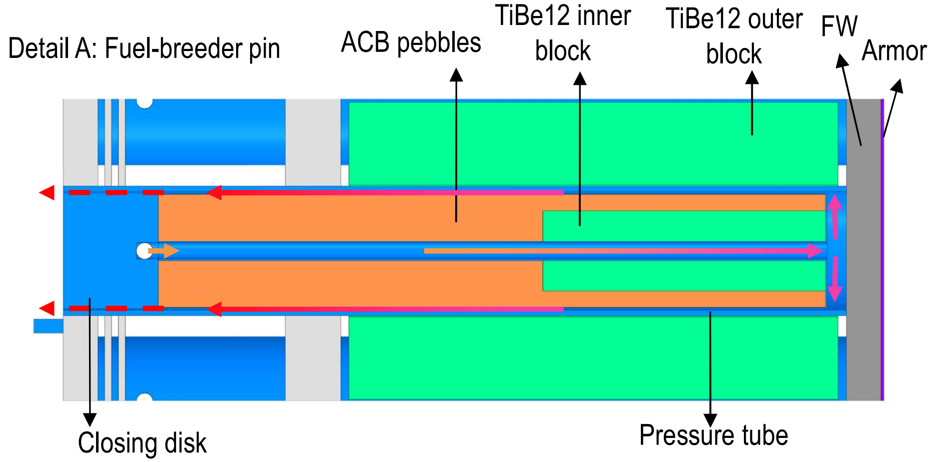
Solid block shape improves structural integrity and reduce fabrication time

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









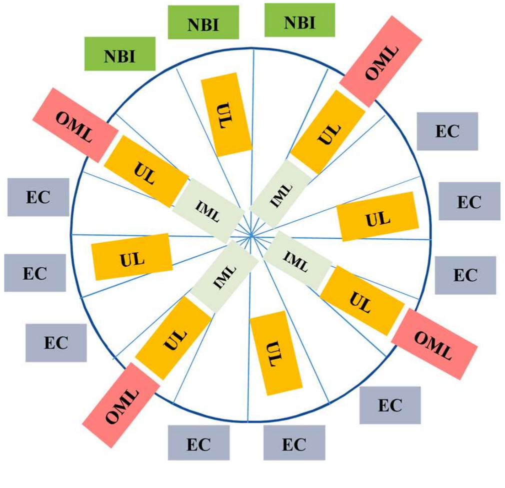
HCPB-BL2017-HP-v1

- 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

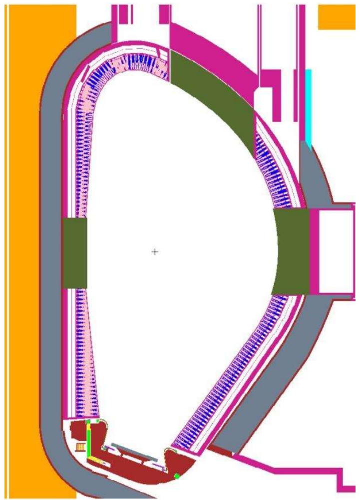
Tritium breeding assessment

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

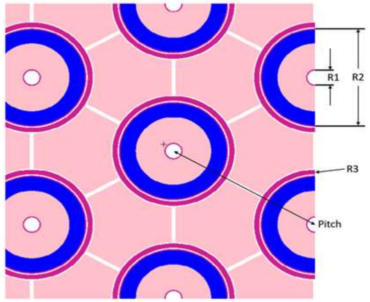
- **Considering cut-outs by Heating system & Limiters**
  - TBR reduction of 10.5% (TBR=1.04~1.07)



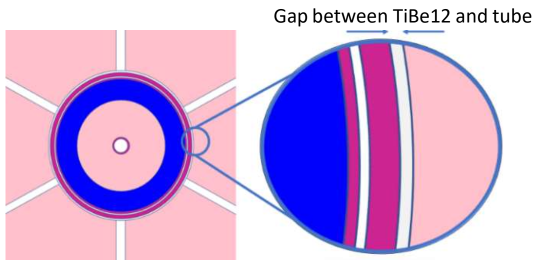
Scheme of the IVCs arrangement

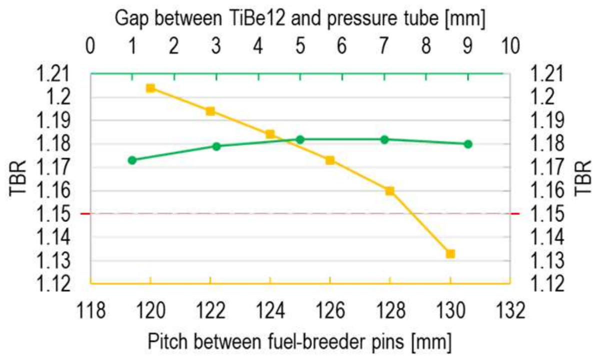


Cut-outs of BB

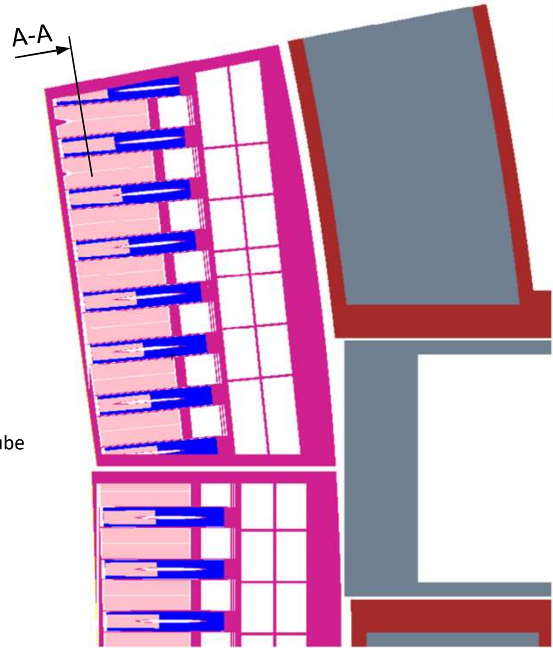


A-A: Poloidal-toroidal view

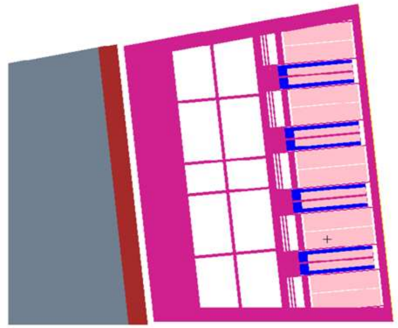




Scoping analysis

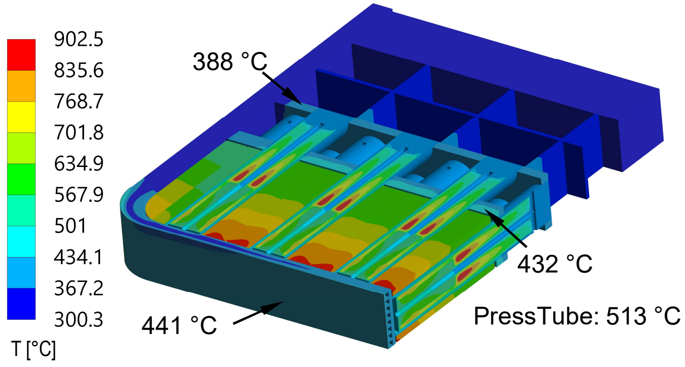


Radial-toroidal cut view - outboard

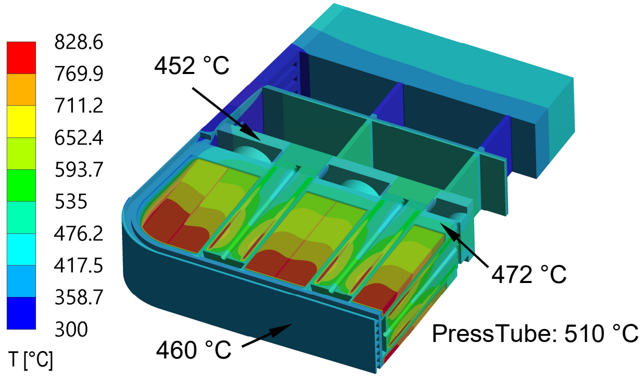


Radial-toroidal cut view - inboard

Thermal hydraulics: Temperature, flow distribution, pressure drop

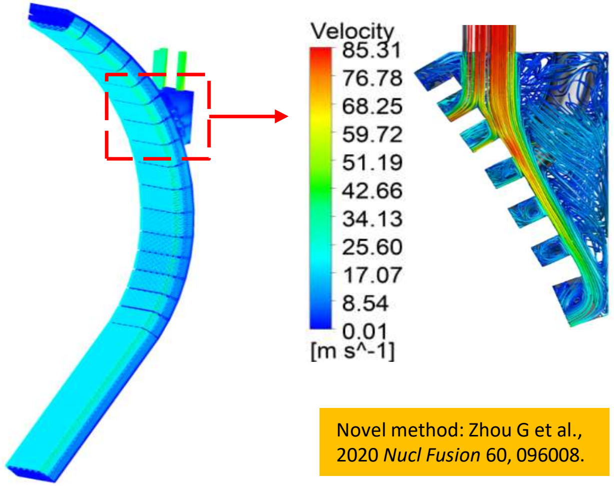


Temp. field of half unit-slice of COB

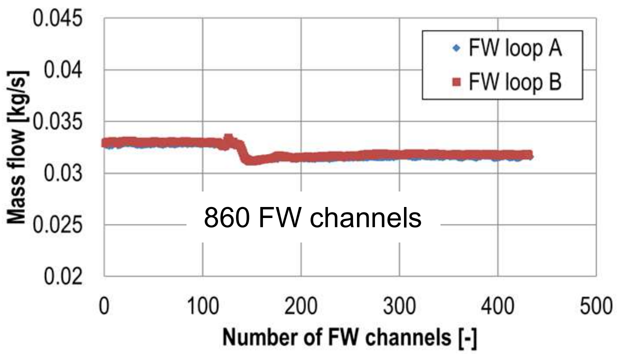


Temp. field of half unit-slice of LIB

- Temp. of ACB, TiBe12 and Eurofer within corresponding design limits

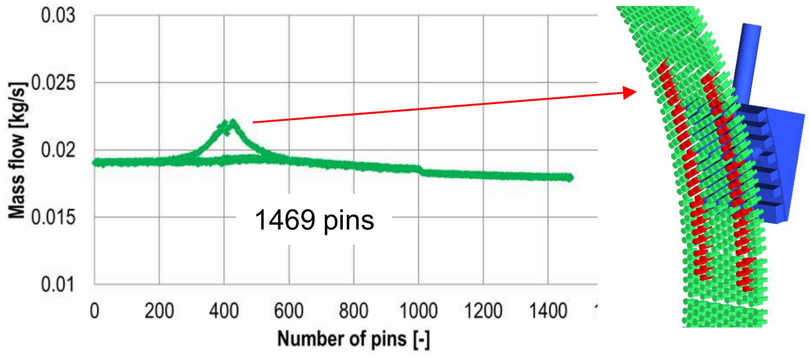


CFD analysis of blanket segment



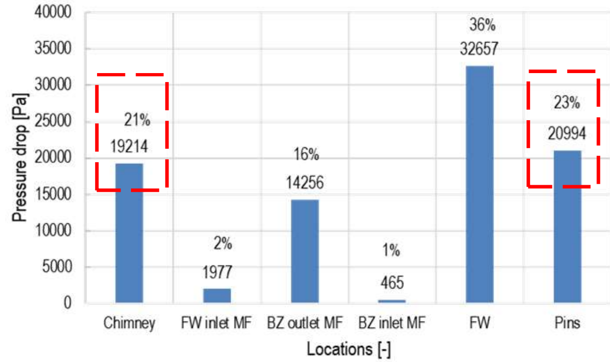
Mass flow rate distribution in FW

- Max deviation from target value: 4.4%



Mass flow rate distribution in pins

- Max deviation from target value: 17.3%

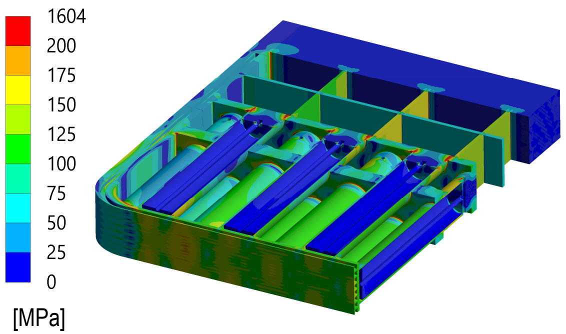


Pressure drop distribution

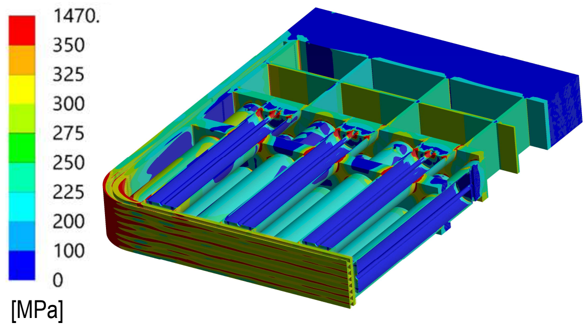
- Total pressure drop: 0.89 bar

Thermal mechanical assessment

- **Stress assessment using plane strain**

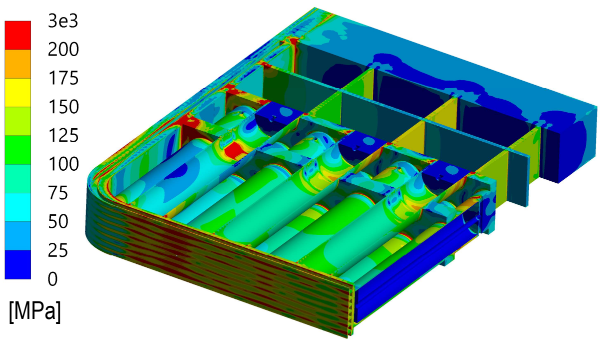


Primary stress of COB

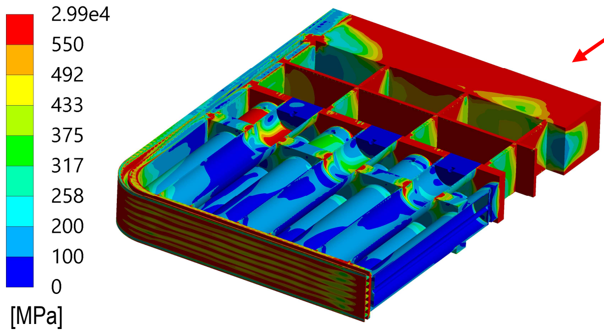


Primary+Secodary stress of COB

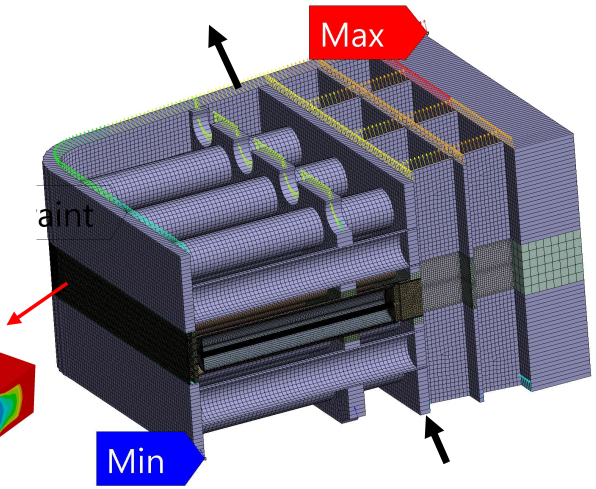
- **Stress assessment using submodelling technique**



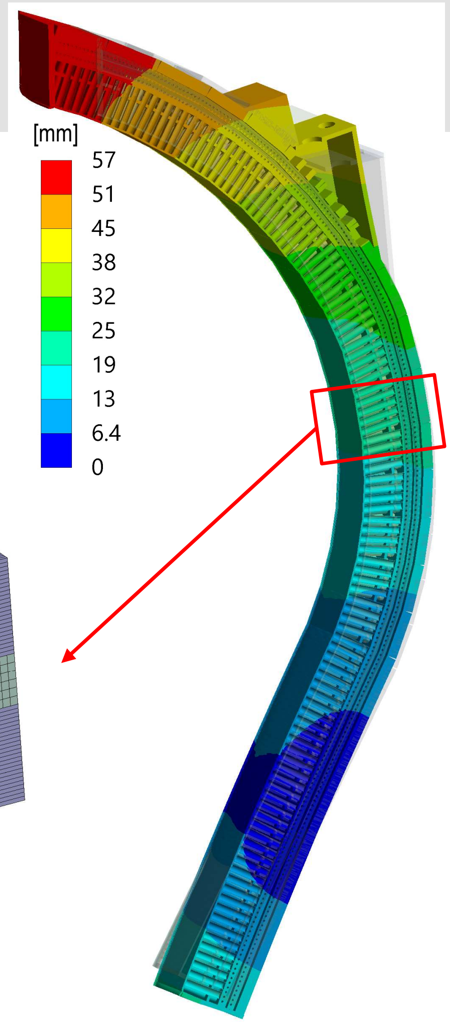
Primary stress of COB



Primary+Secodary stress of COB



Submodel



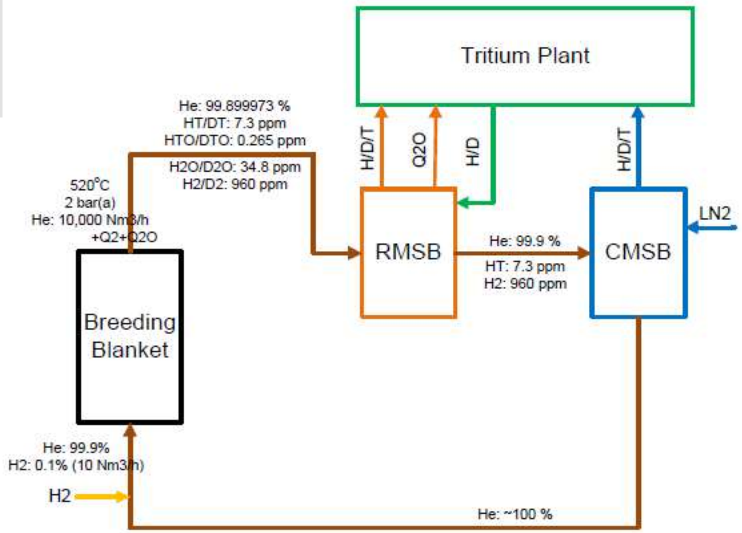
Displacement of global model

- 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

Tritium Extraction and Recovery (TER) system

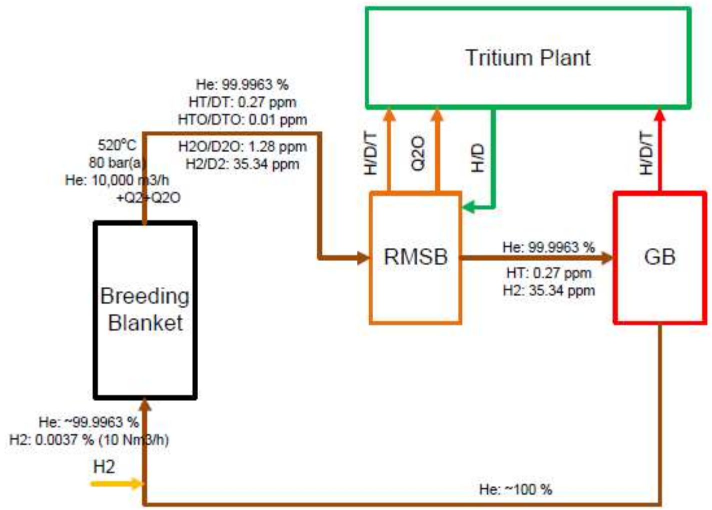
- Reference design
  - Two stages in series, first the adsorption of Q2O on the Reactive Molecular Sieve Bed (RMSB), thereafter the adsorption of Q2 on the Cryogenic Molecular Sieve Bed (CMSB) at 77 K

    Q = H, D, T
  - Tritium recovered via isotope exchange on RMSB and by heating-up of the CMSB
  - Extrapolated to DEMO scale is 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 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



80 bar purge gas

Shield design

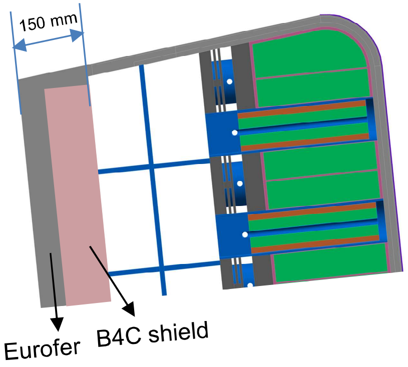
Palermo I et al., 2022 *Energies* 15, 5734.

- 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
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 B_4C

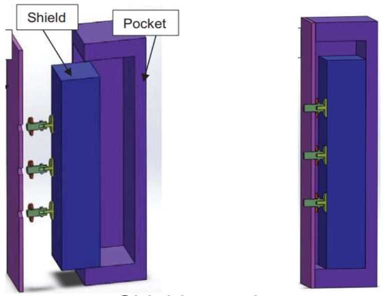
$$ {}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{3}_{1}T + 2\,{}^{4}_{2}He $$

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
- 90 mm B_4C is needed for meeting all the requirements
- Container of B_4C is designed to contain fragmentation
- ITER-like solution seems feasible

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



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 confirms 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

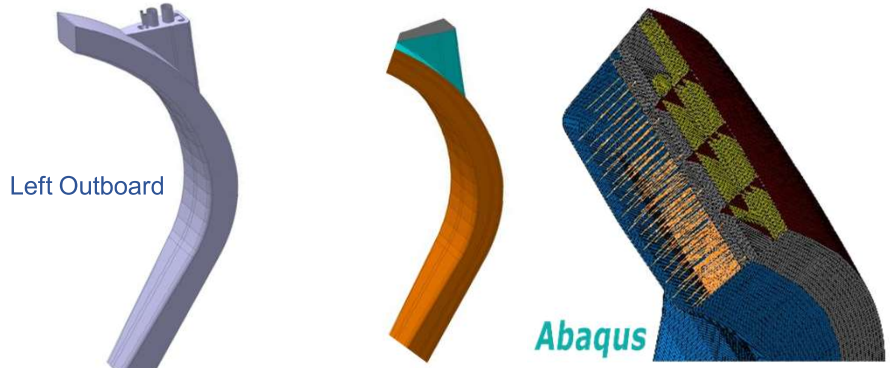
Contact: Guangming Zhou
Email: guangming.zhou@kit.edu

Backup slides

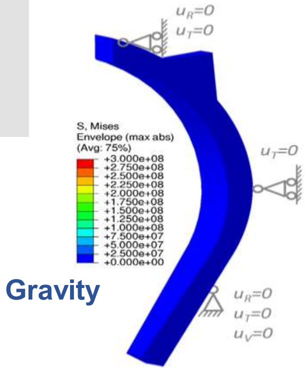
Optioneering of blanket attachment (1/2)

- Attachment: accomodate gravity, thermal, pressure and EM loads, conform remote handling

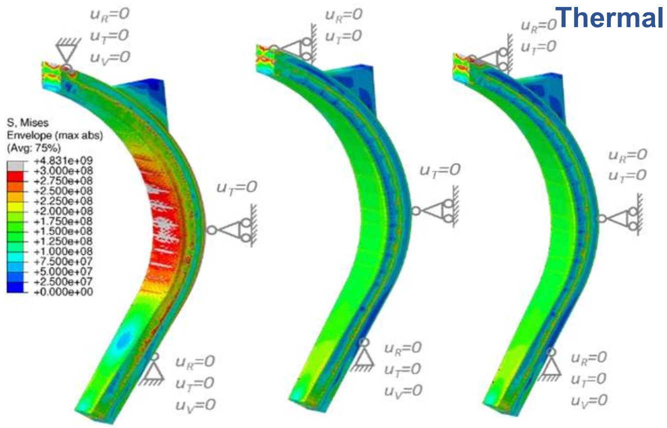
Equivalent shell and beam elements used to get quick feedback



Solid geometry | Surface bodies | Shell and beam elements



Gravity loads do not cause a large global stress, thus not critical. However, it is important that the segments are fully supported before any thermal expansion occurs.

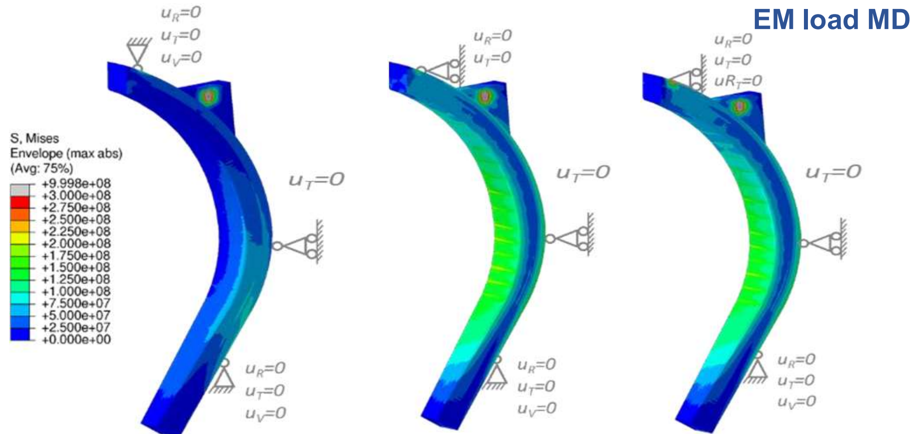


Constrained vertically | Free vertical expansion | Free vertical expansion

When fully constrained, causing a large global stress on the First Wall.

When free to expand vertically, the stress level at the FW is almost negligible.

A slightly larger stress level is reached at the FW when a radial support is included.



Constrained vertically | Free vert. expan. | Constrained tor. rotation

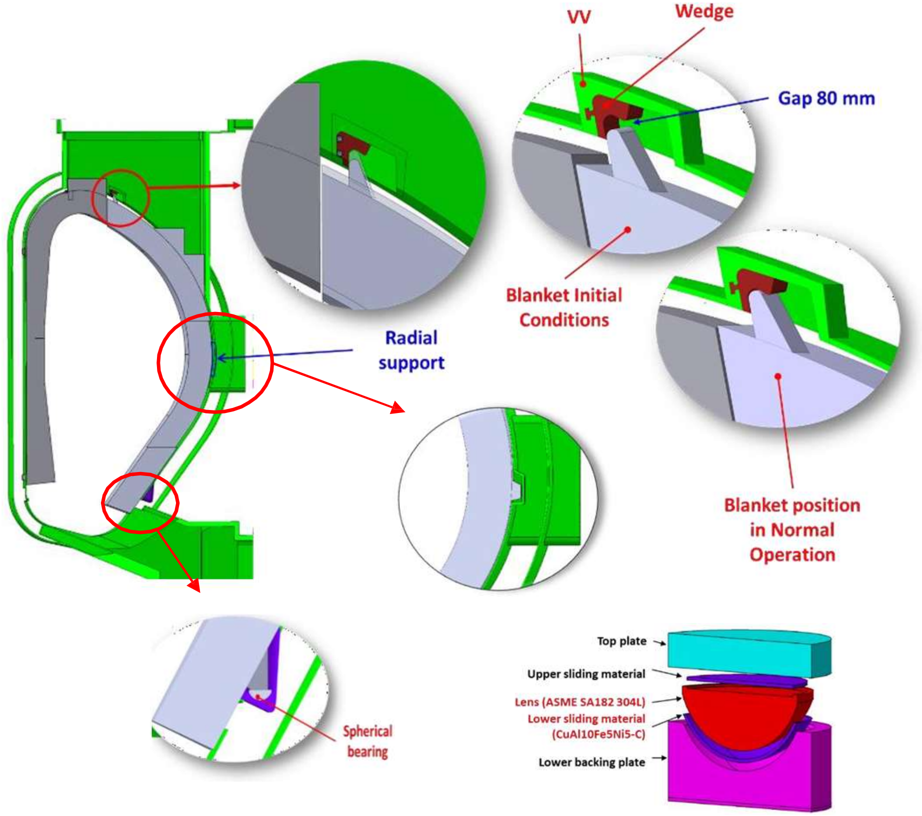
When fully constrained, the stress on FW is negligible, but stresses become large if the segment is free to expand vertically.

An important requirement derived: sufficient supporting conditions to withstand EM and seismic loads during operation

Optioneering of blanket attachment (2/2)

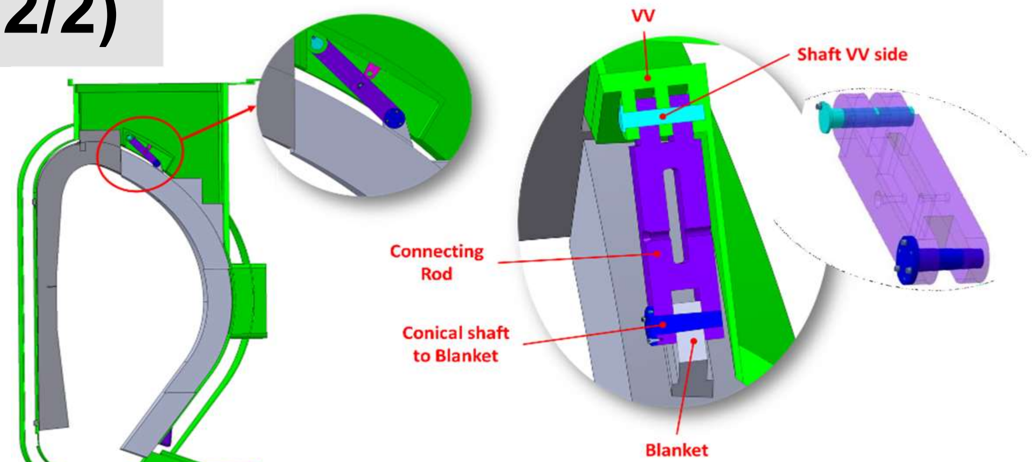
- Proposed concepts of BB-to-VV attachment

Bottom, middle and top supporting structures



ITER Cryostat Support Bearings to take 1100 tonnes

Proposal 1

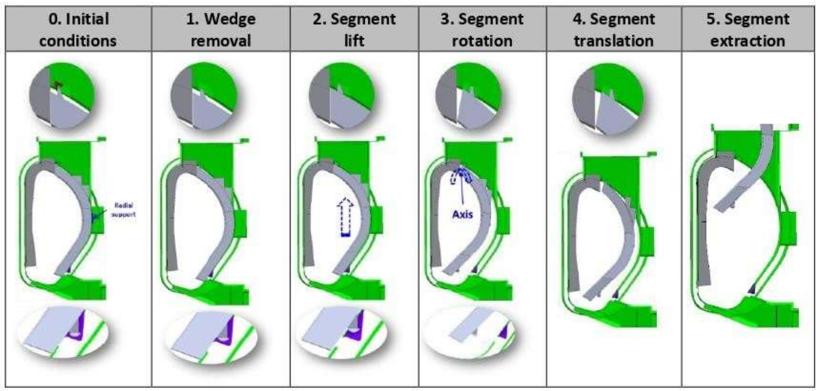


Proposal 2

At bottom, spherical bearing similar to ITER Cryostat Support Bearings

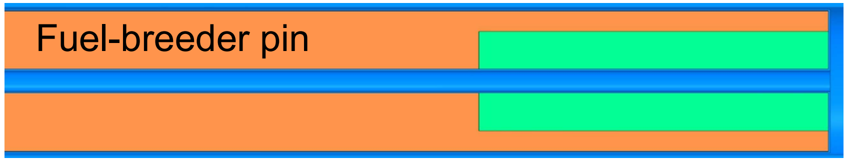
At midplane, toroidal key is proposed. The toroidal key has a toroidal gap to facilitate assembly by RH tools. The pocket at the VV allows sufficient vertical displacement (124 mm) of the segment for the assembly process.

At top, two proposals are being considered. Wedge (Proposal 1) and Conical shaft (Proposal 2).

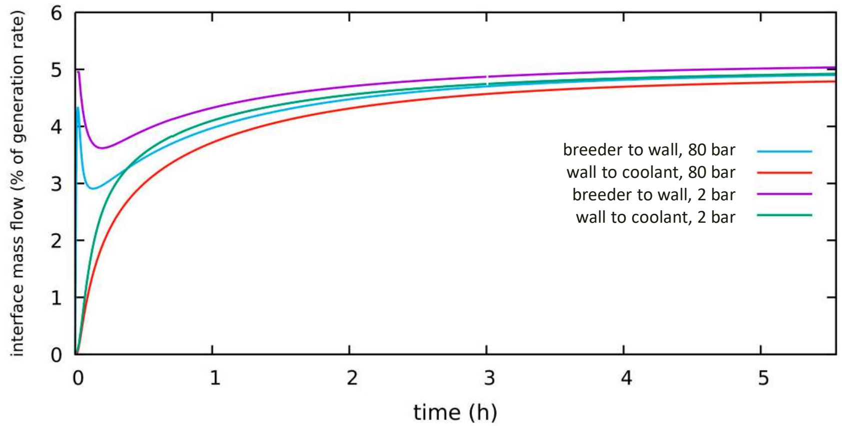


Tritium permeation analysis

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



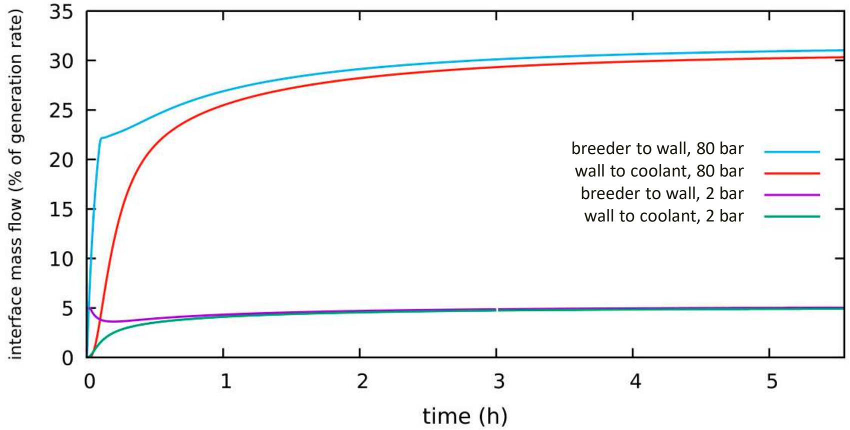
OpenFOAM
The Open Source CFD Toolbox



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
  - 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 mass flow

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

Assessment of lifetime due to pebble-Eurofer interaction

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

Li_4SiO_4+
30 mol% Li_2TiO_3
1 mm pebbles

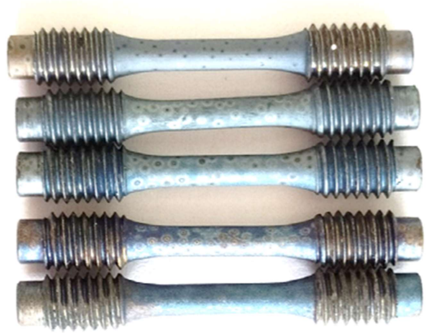
EUROFER97-2
low-cycle fatigue (LCF)
specimens Ø2 mm

Interaction conditions:

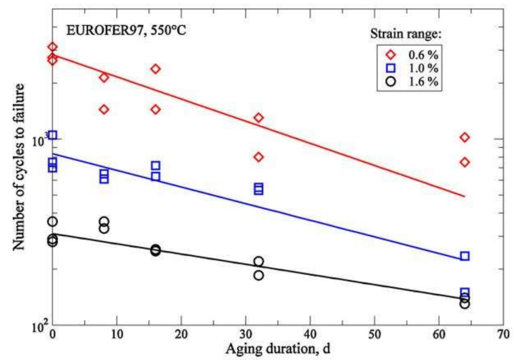
T=550°C

Atmosphere: purge gas flow (He+0.1%H_2)

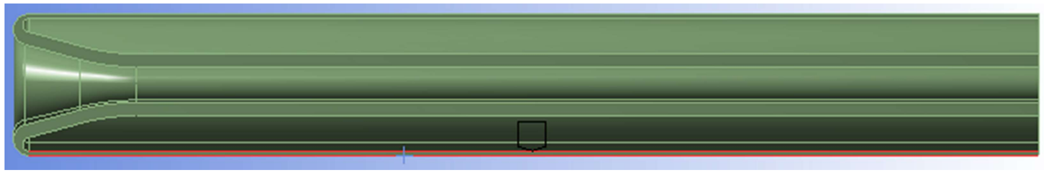
Duration: 8, 16, 32, 64, 128 days



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

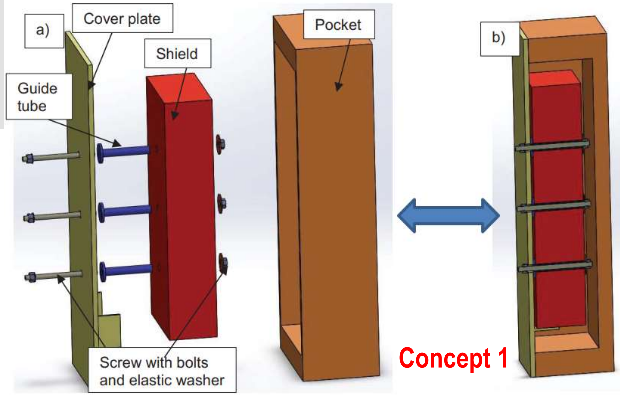
- New design able to improve lifetime

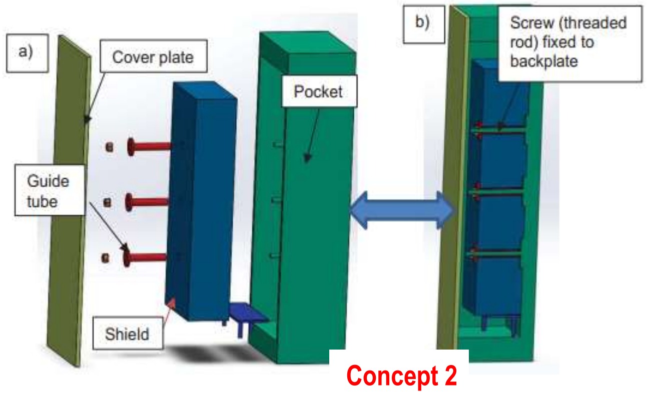
[1] Aktaa J et al., 2020 *Fusion Eng Des* 157, 111732.
[2] Mahler M, Aktaa J, 2018 *Nucl Mat Energ* 15, 85-91.

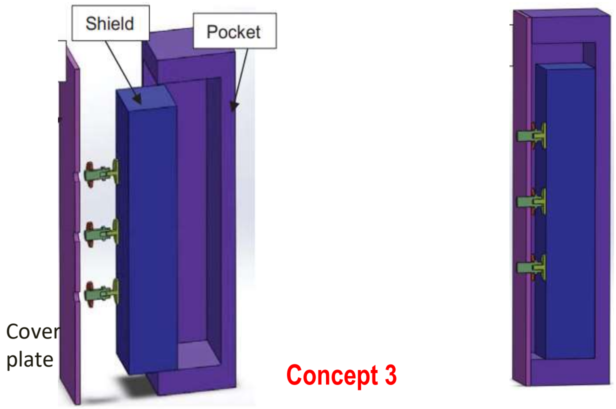
Shield design: Structural design and analysis

To confine the fragmentation, B_4C shield 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







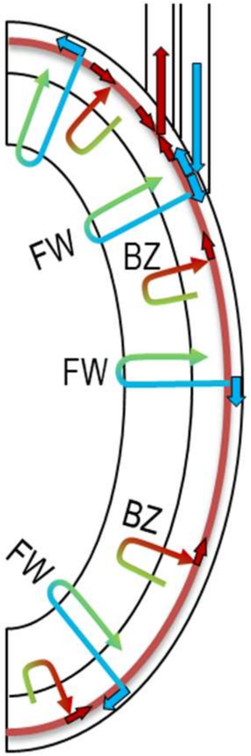
			Cover plate	Shield	BSS
Concept 1	Tmax	°C	795 > 450°C → **significant creep**	950°C	364 < 375°C → negligible creep
	Tmoy ΔT	°C	791 5	935 54	343 48
	Max($\bar{\sigma}$)	MPa	9	124	89
	$\overline{Q_m + Q_b} = \overline{\Delta Q}$	MPa	8 → low value	-	109
	Applied design criteria		Simplified analysis with negligible creep: Ratcheting $\overline{P_m + P_b} + \overline{\Delta Q} < 3\,Sm$	Max($\bar{\sigma}$)<155 MPa (B_4C Yield strength at 980°C)	Ratcheting, negligible creep $\overline{\Delta Q} < 1.5\,Sm$=275 MPa (350°C)
	Validation		**No analysis (low stress), should be validated**	**Validated**	**Validated**

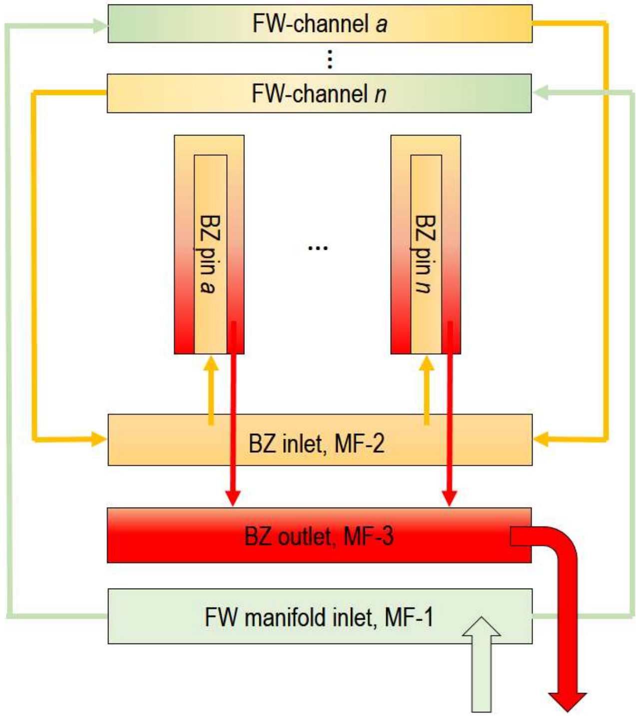
			Cover plate	Shield	BSS
Concepts 2 & 3	Tmax	°C	426 < 450°C → negligible creep	467	382 > 375°C → **significant creep**
	Tmoy ΔT	°C	425 1	443 85	353 62
	Max($\bar{\sigma}$)	MPa	2	156	113
	$\overline{Q_m + Q_b} = \overline{\Delta Q}$	MPa	2 → low value	-	132
	Applied design criteria		Ratcheting: $\overline{P_m + P_b} + \overline{\Delta Q} < 3\,Sm$	Max($\bar{\sigma}$)<155 MPa (B_4C Yield strength at 980°C)	Simplified analysis with negligible creep: Ratcheting $\overline{\Delta Q} < 1.5\,Sm$=275 MPa (350°C)
	Criteria		**No analysis, should be validated**	**Validated**	**Validated**

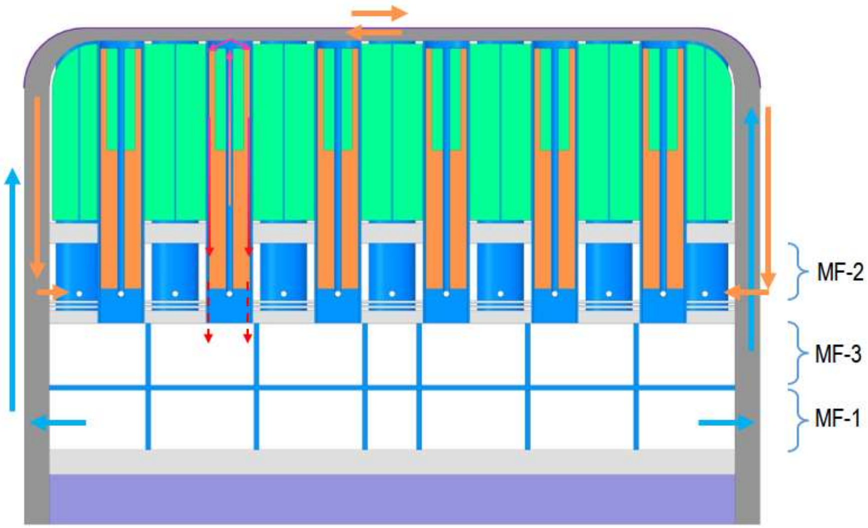
Shield of ITER diagnostic port-plug

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

Flow scheme


FW
BZ
FW
BZ
FW

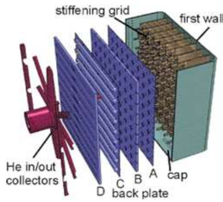

FW-channel *a*
FW-channel *n*
BZ pin *a*
...
BZ pin *n*
BZ inlet, MF-2
BZ outlet, MF-3
FW manifold inlet, MF-1


MF-2
MF-3
MF-1

Solid breeding blanket in Europe: HCPB Design evolution

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

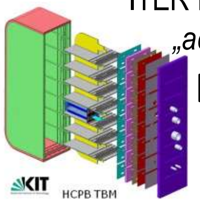
Pre-Concept Design Phase (FP8)



PPCS Model B (HCPB)

ITER HCPB TBM

„act-alike“

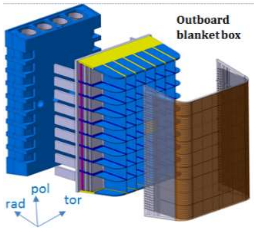


- Coolant: He @80 bar, 300-520°C
- Structural steel: Eurofer97
- T-breeder: Li-ceramics
- n-multiplier: Beryllide
- T-extraction: purge gas

2014

"Beer-box"

DEMO baseline 2014



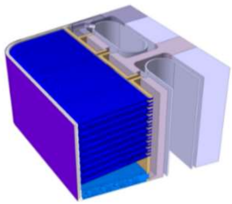
+ ↑↑ Robustness (in-box LOCA)
– ↓↓ TBR (1.06)
– ↑↑ Fabrication & assembly complexity
– ↑↑ Δp (P_{pump}≈250MW, low TRL BoP)

2015

2016

DEMO baseline 2015

"Sandwich"



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

2017

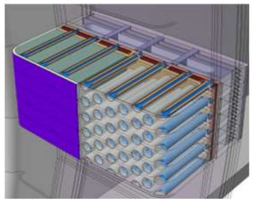
2018

2019

2020

DEMO baseline 2017

"Fuel-breeder pin"



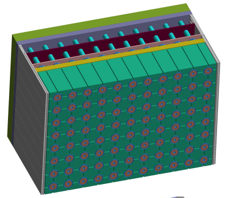
+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.20)
+ ↓ Fabrication & assembly complexity
+ ↓ Δp (P_{pump}≈ 90MW, high TRL BoP)
– RAMI

Concept Design Phase (FP9)

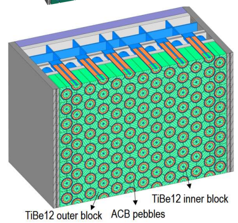
2021

2022

2023



G. Zhou et al. 2022. TOFE 2022



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