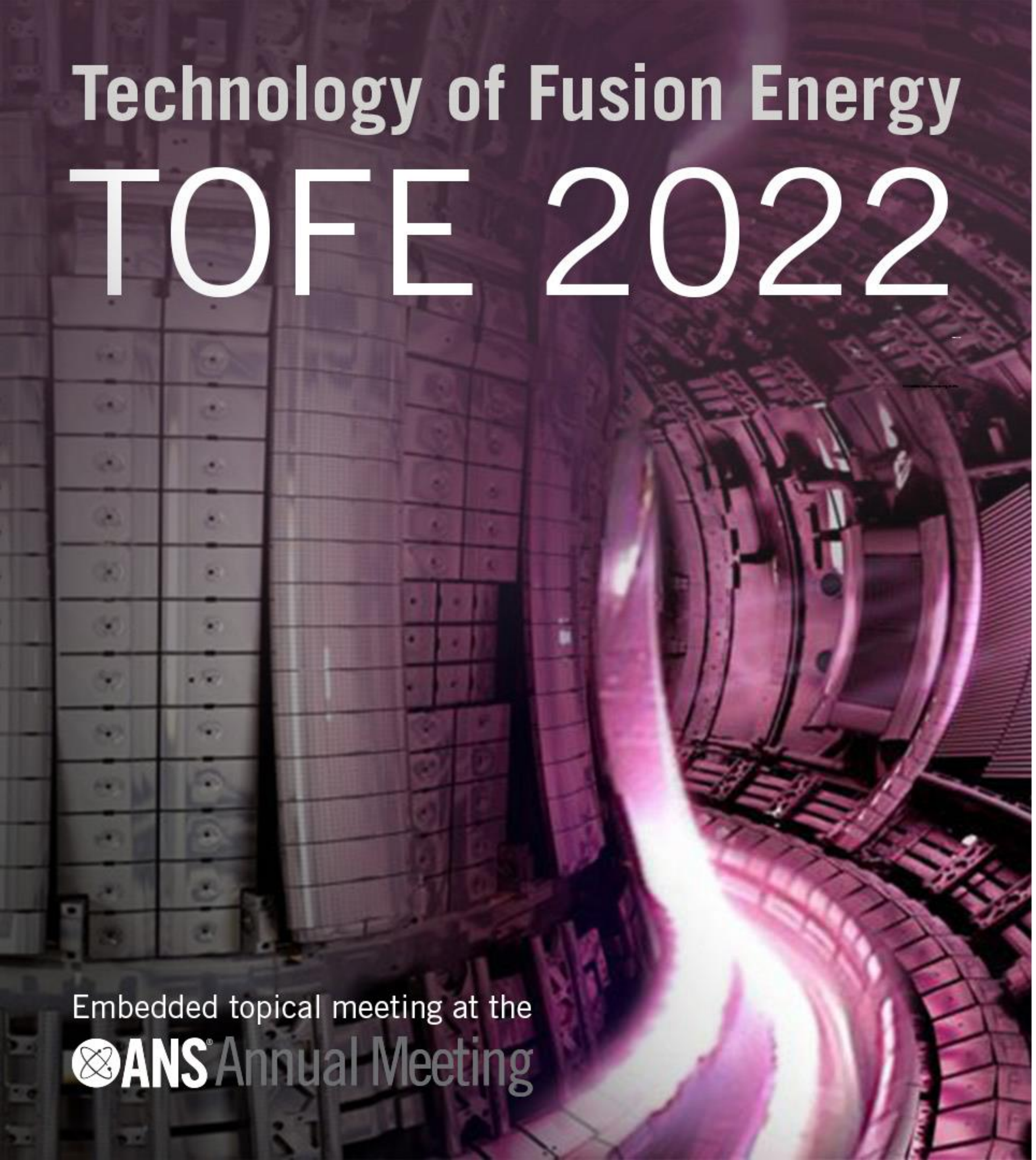


Status of design activities of the DEMO Helium Cooled Pebble Bed breeding blanket in Europe

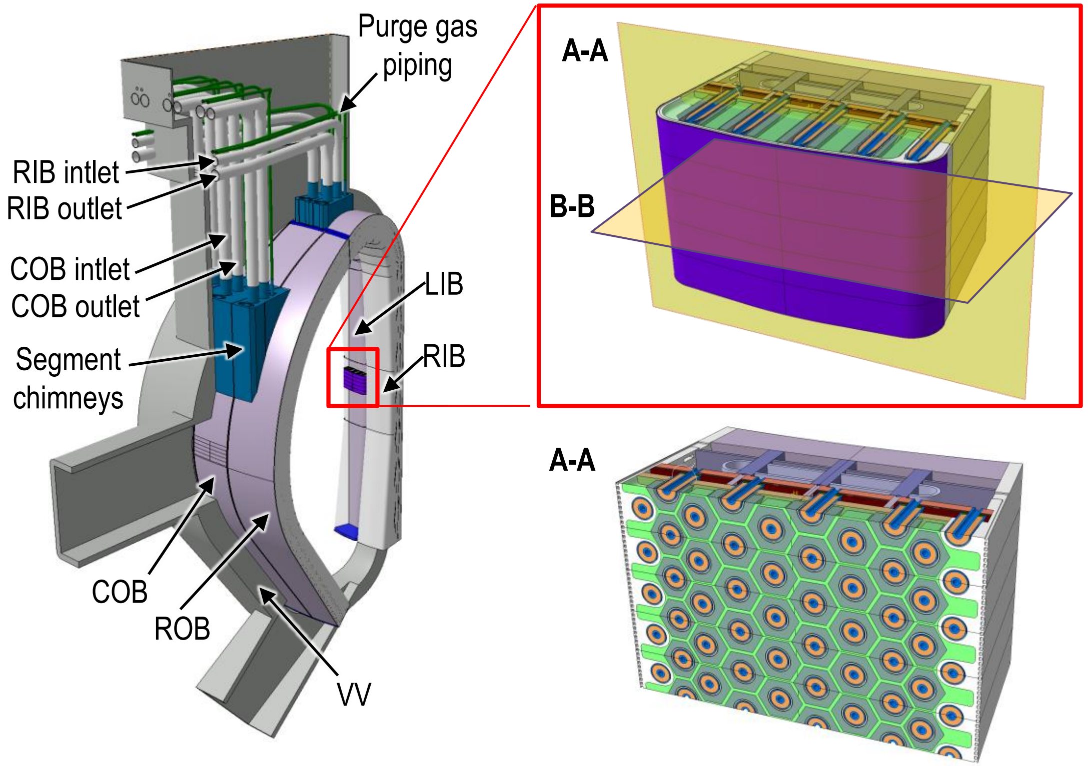
Dr. Guangming Zhou (KIT)
Lead of HCPB Breeding Blanket Sector

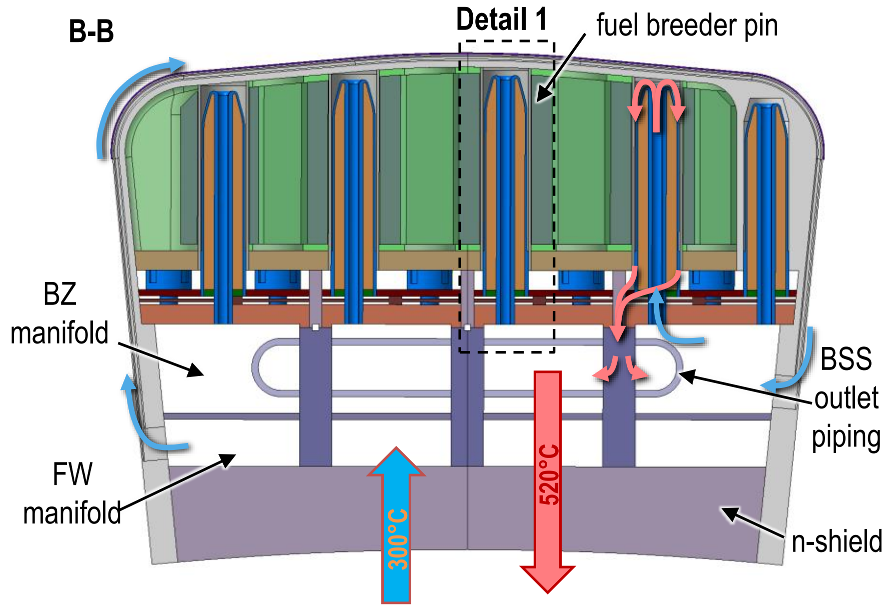
Breeding Blanket Project in EUROfusion

Outline of content

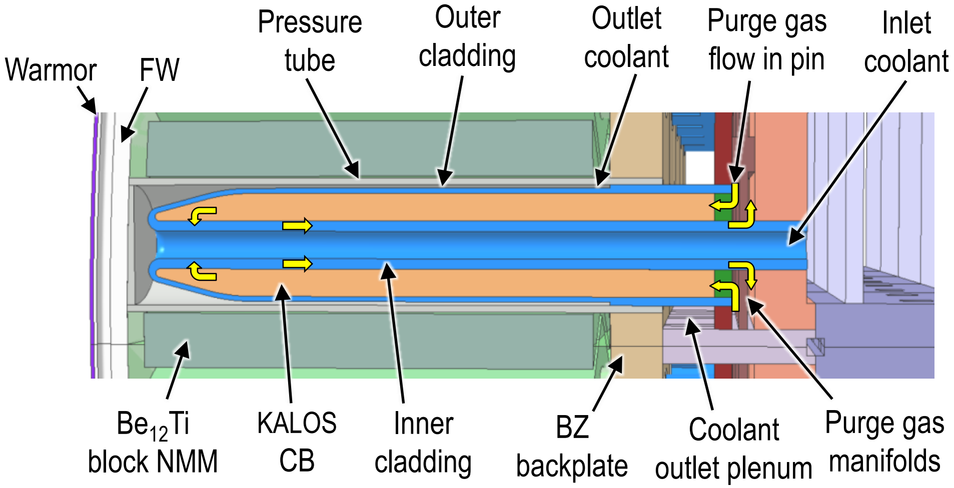
- Status at the end of Pre-Concept Design Phase
- Identified risks
- Design activities to address the risks
- Outlook

Status at the end of Pre-Concept Design Phase





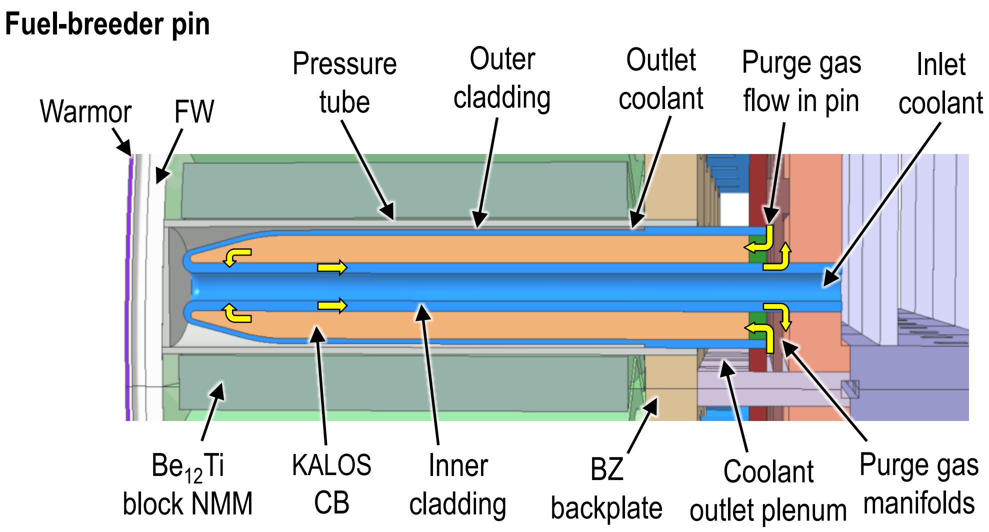
Detail 1: Fuel-breeder pin



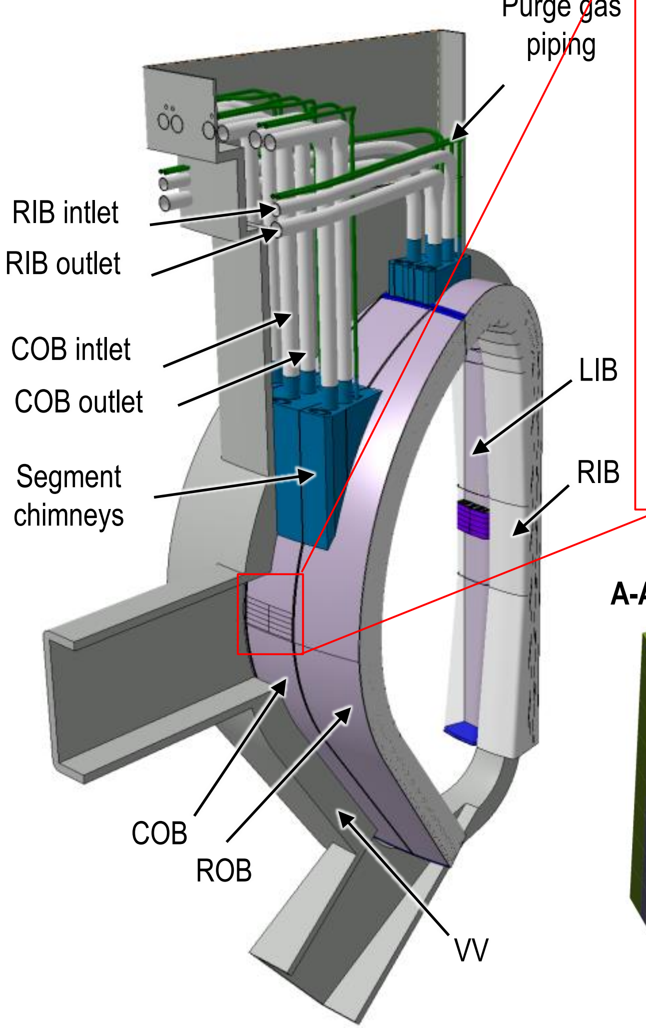
- Structural steel: Eurofer97
- Fuel-breeder pins containing advanced ceramic breeder (ACB)
- Pins inserted into blocks of Be12Ti neutron multiplier
- Coolant: He @80bar, 300-520°C
- Purge gas: He + 0.1vol% H_2 @2 bar
- Easier manufacturing, easier filling of pebbles
- NA, TH & TM; TBR = 1.20; Ppump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

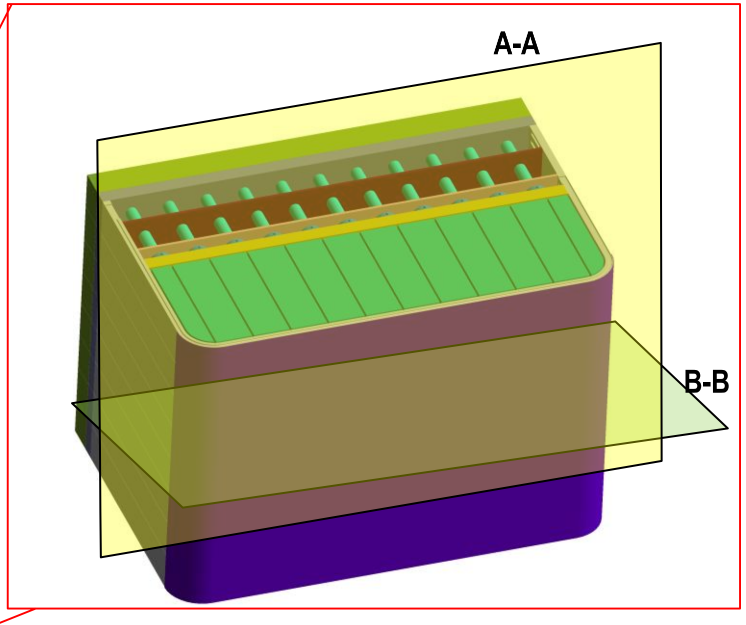
Identified risks related to HCPB BB & Measures

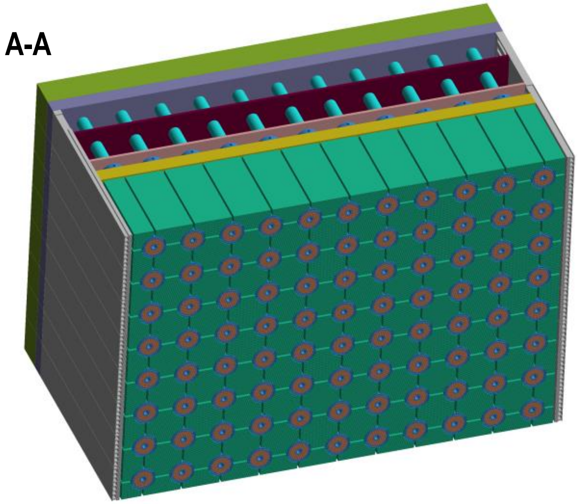
S 1.	Low reliability of BB system under DEMO conditions [due to welds failure]	1. Equalize purge gas and coolant to eliminate in-box LOCA welds, to improve reliability
S 2.	Loss of structural integrity of beryllide blocks	2. New shaping of block to reduce breakage
S 3.	High pressure drops in coolant loop contributing to total high pumping power	3. Increase ΔT, reduce flow velocity & reduce pressure drop
S 4.	Large tritium permeation rates at the interface of breeder-coolant loop	4. Different purge gas schemes (steam, counter-permeation, P_H2) to reduce permeation + R&D
S 5.	Low BB shielding capability	5. Explore more efficient shielding material (B4C)
S 6.	Degradation of Eurofer at contact with pebbles in purge gas environment	6. Lifetime assessment due to interaction + R&D
S 7.	Reduction of structural integrity of blanket during shutdown due to Eurofer ΔDBTT under irradiation	7. Not critical, acc. to J. Aktaa by fast fracture assessment
S 8.	Low TRL of Codes & Standards for design of DEMO components	8. Addressed in WPMAT, strong involvement in DEMO Design Criteria activities required

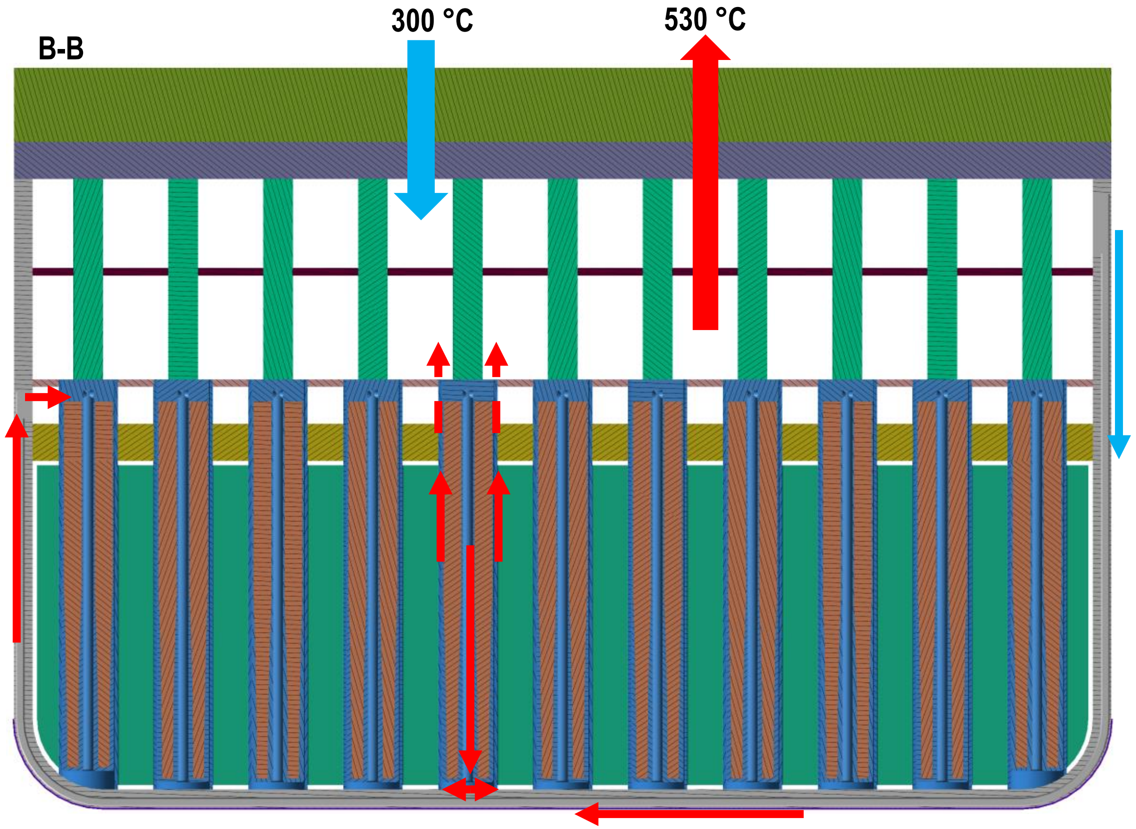


Proposed design changes for improvements









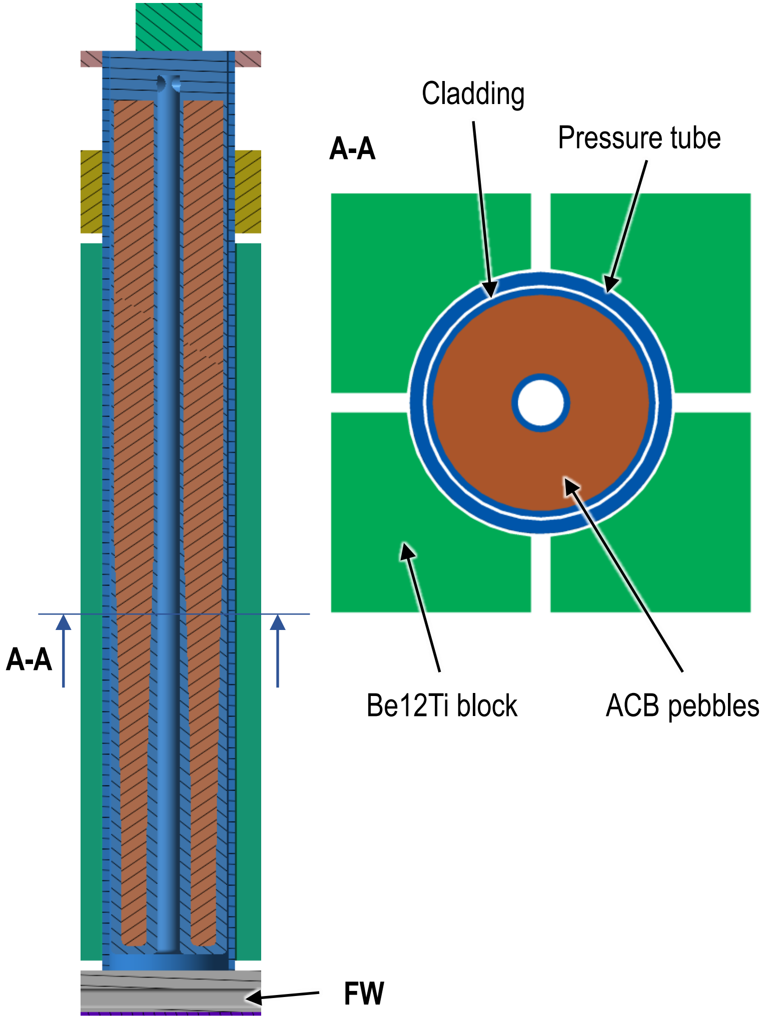
- Equalize purge gas and coolant pressure to eliminate in-box LOCA welds to improve reliability
- Increase ΔT (300°C-530°C) to further reduce pressure drop
- Re-arrange flow scheme to cool key structure with fresh coolant
- Shape of Be12Ti block to square

Tritium breeding ratio (TBR) optimization (1/2)

EUROfusion

- 3D heterogenous model by SuperMC, calculated using MCNP6 and JEFF 3.3

Original						
60% Li-6	0.975					
70% Li-6	0.994					
Option 1: Original + ACB thick reduced to 15mm + clad 2mm + front clad 5mm						
60% Li-6	1.051					
70% Li-6	1.071					
Option 2: Original + pin bellmouth at the front side						
60% Li-6	1.044					
70% Li-6	1.065					
Option 3: Option 1 + Study on Pitch (mm)	**128**	**126**	**124**	**122**	**120**	
60% Li-6	1.051	1.062	1.072	1.082	1.090	
70% Li-6	1.071	1.081	1.091	1.100	1.107	
Option 4: Option 2 + Study on Pitch (mm)	**128**	**126**	**124**	**122**	**120**	
60% Li-6	1.044	1.055	1.066	1.075	1.084	
70% Li-6	1.065	1.074	1.085	1.094	1.101	
Option 5: Option 1 + Study on ACB thickness (mm)	**15**	**17**	**19**	**21**	**23**	**25**
60% Li-6	1.051	1.061	1.069	1.076	1.080	1.085
70% Li-6	1.071	1.081	1.088	1.094	1.099	1.102
Option 6: Original + Cladding 2mm and front side ACB thickness 15 mm						
60% Li-6	1.053					
70% Li-6	1.072					
Option 7: Option 1 + Study on gas gap pressure tube – Be12Ti block (mm)	**1**	**3**	**5**	**7**	**9**	
60% Li-6	1.051	1.057	1.060	1.060	1.058	
70% Li-6	1.071	1.077	1.080	1.081	1.079	

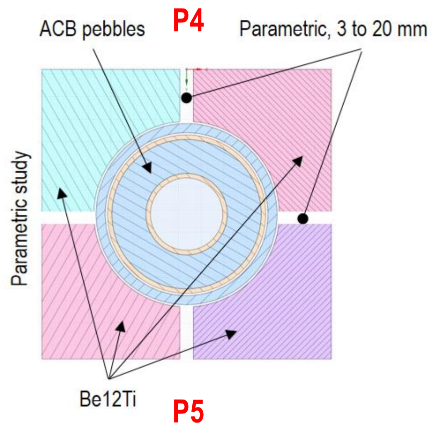


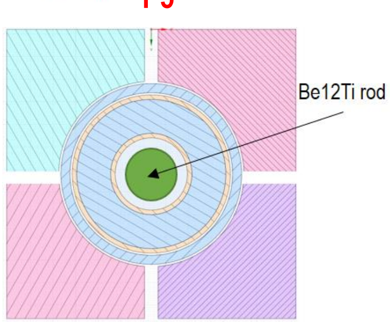
- Equalize the pressure between purge gas and coolant, leading to higher steel amount, TBR reduced, further optimization needed.

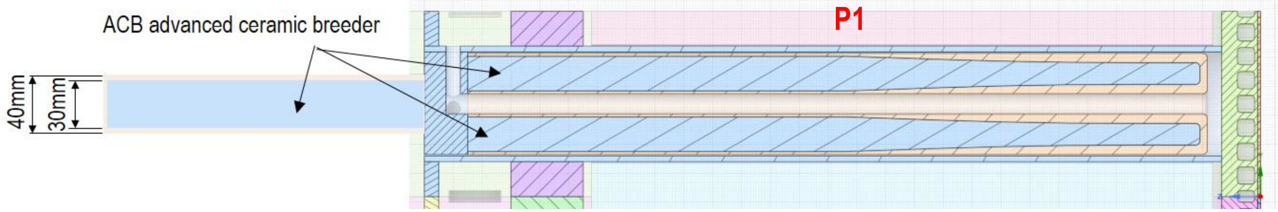
ANS

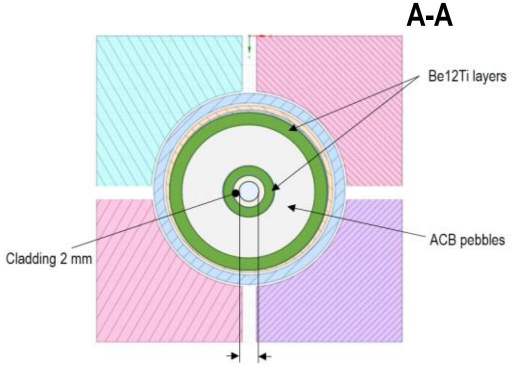
Tritium breeding ratio (TBR) optimization (2/2)

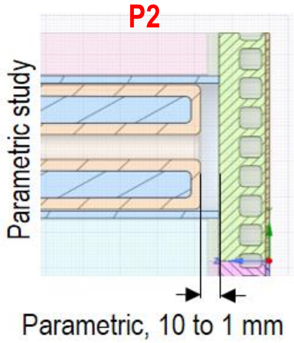
P1. Study influence of ACB in back side of the pin (whole length of back side of pin)
P2. Study reduction of the front pin cladding distance to FW
P3. Study influence of Be12Ti radial length
P4. Study influence of Be12Ti block gaps
P5. Starting from Option 1, introduction of a Be12Ti rod in the inner tube
P6. Introduce Be12Ti in pin in Option 1: pitch 128mm, inner cladding
P7. Like P6, but ACB thickness 35mm and introduce Be12Ti in pin front region 20mm thick
P8. Combined the positive effects

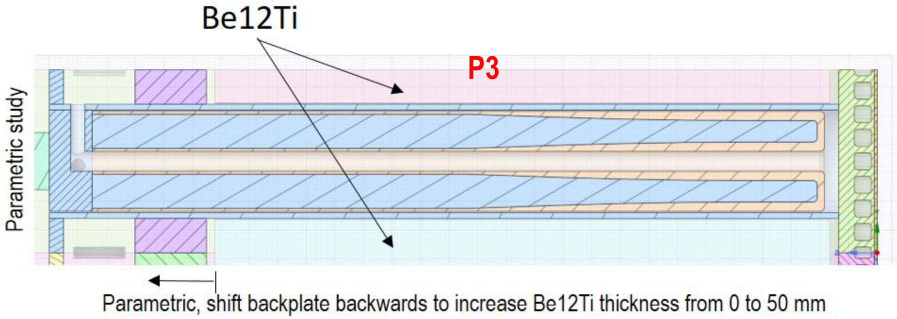


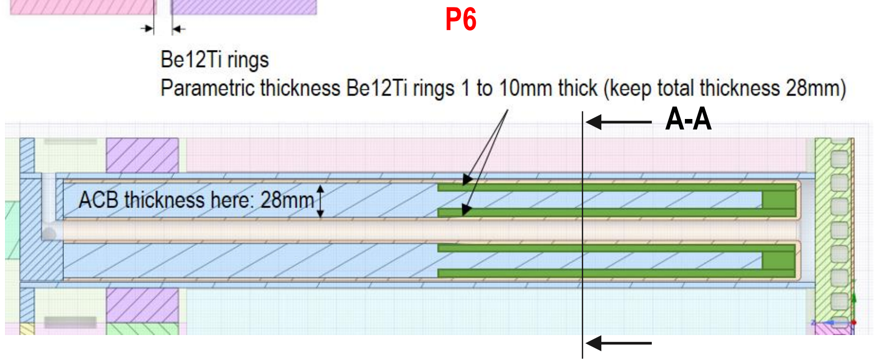


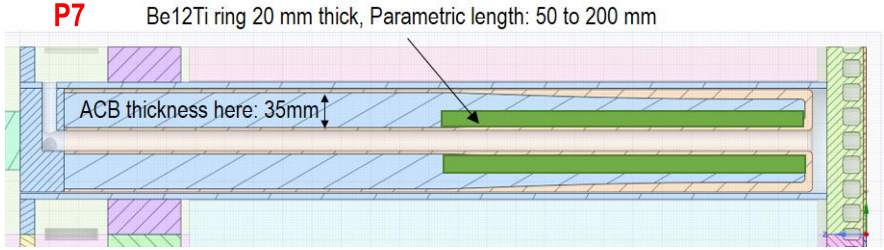






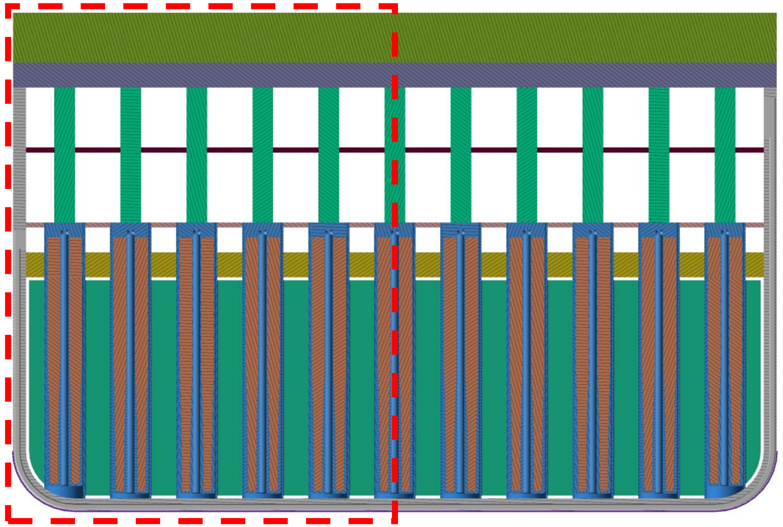




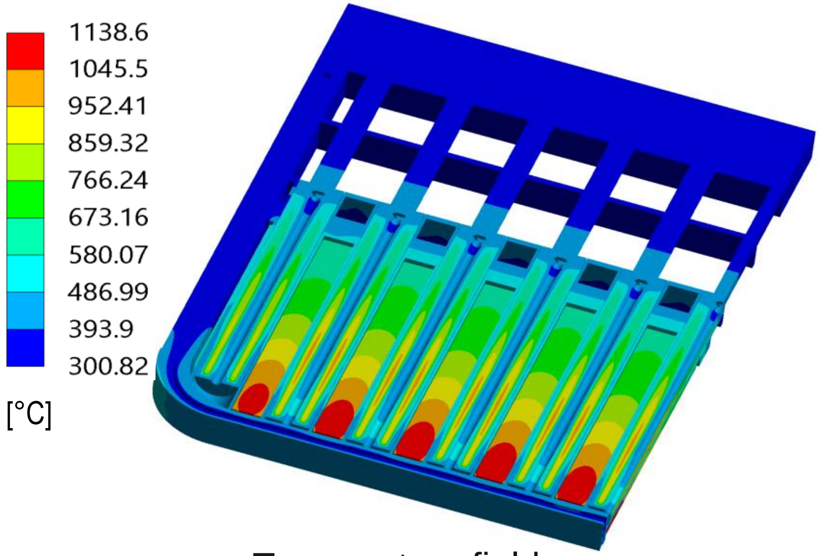


- Combined all positive effects, TBR = 1.17

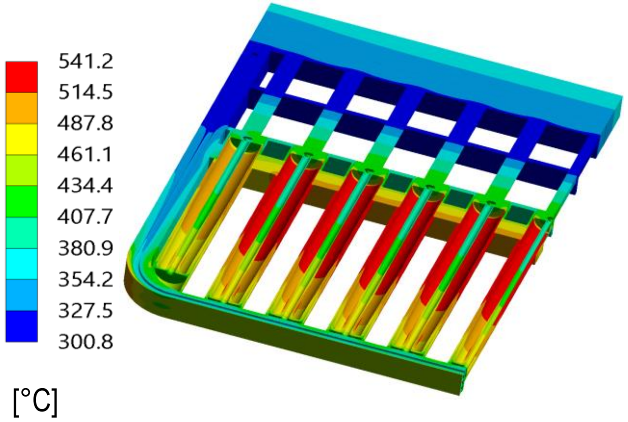
Thermal and structural analysis

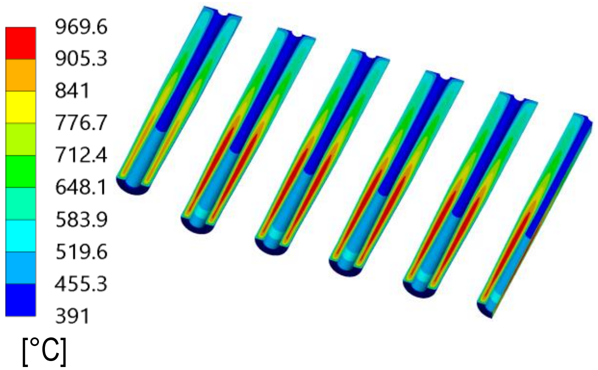


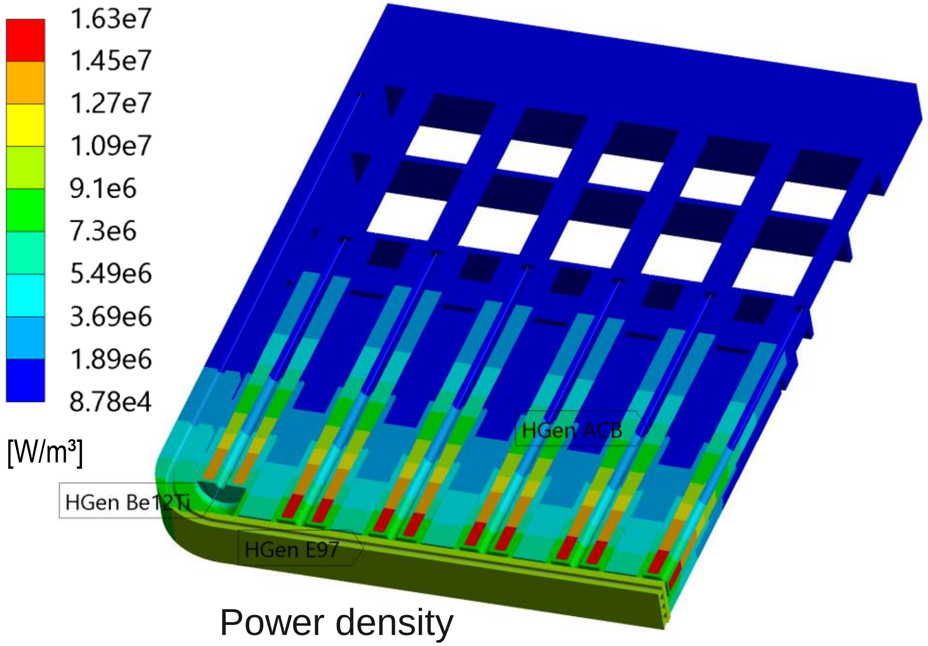
FEM model



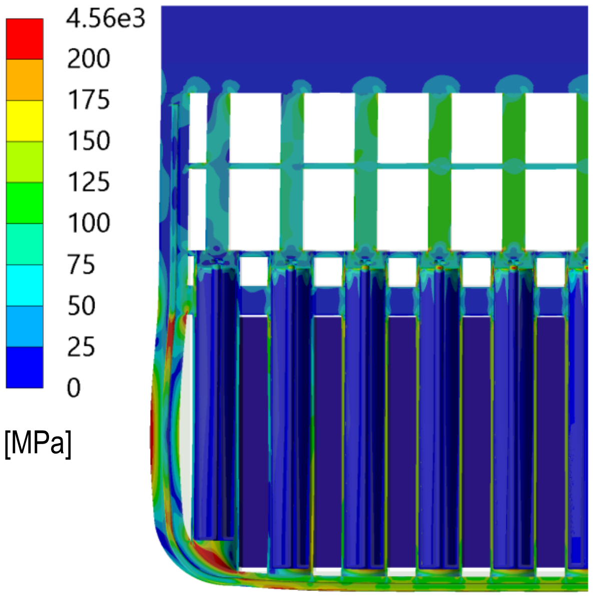
Temperature field







Power density



Stress field (P)

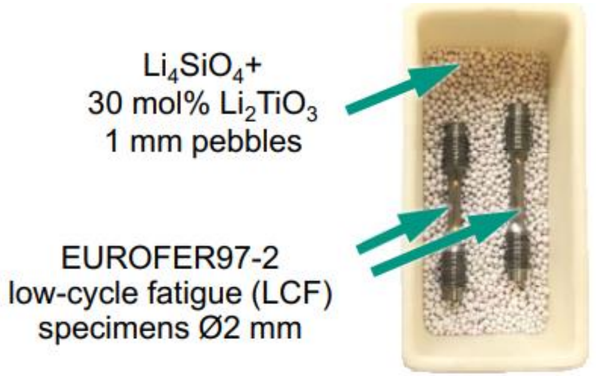
Tin / Tout = 300 / 530 °C

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

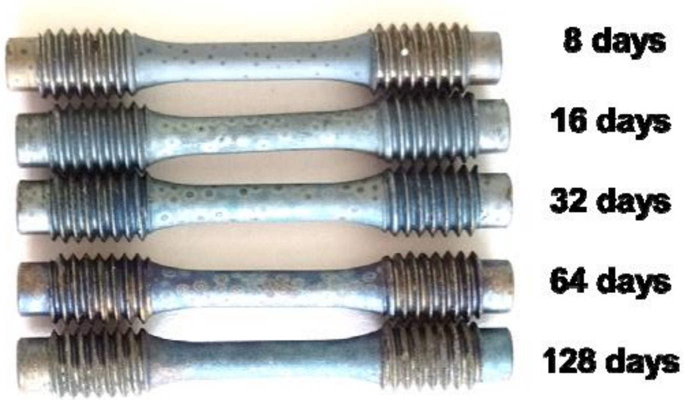


Interaction conditions:

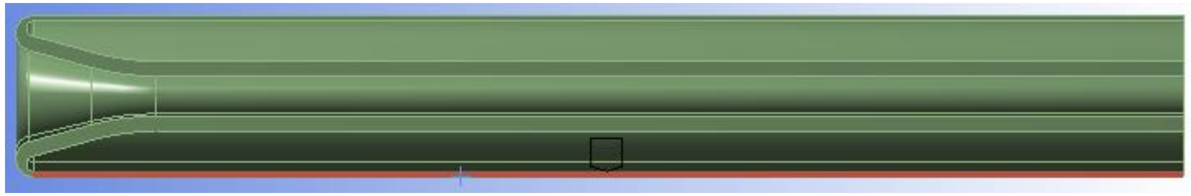
T=550°C

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

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

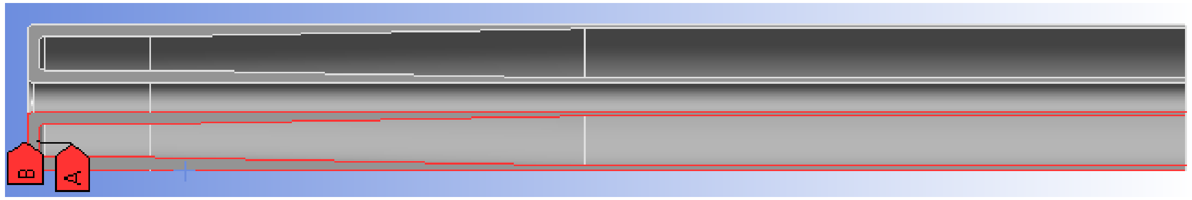


- Creep-Fatigue-Assessment tool [2] used to assess different design options (0.2 MPa vs 8 MPa purge gas)



0.2 MPa purge gas

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



8 MPa purge gas

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

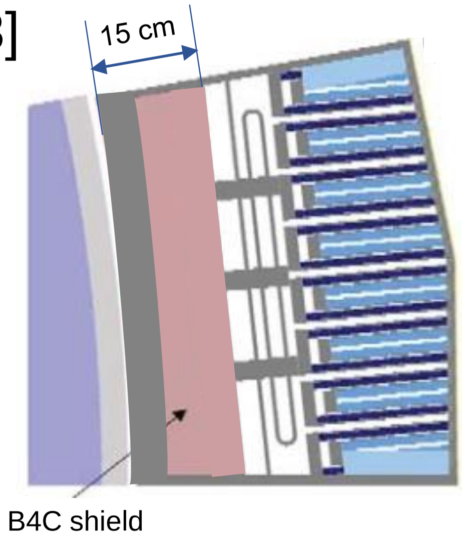
- New design able to improve lifetime.

[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

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.

Shielding design (2/2)

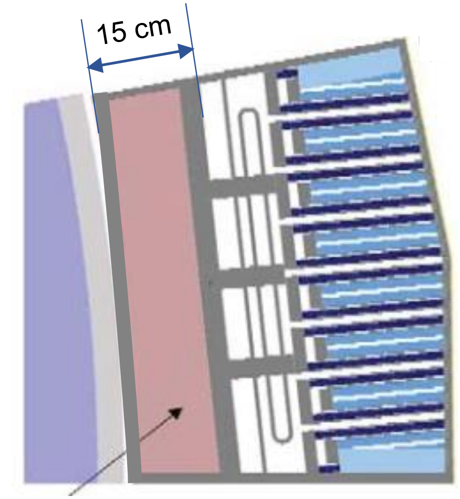
- Structural design

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

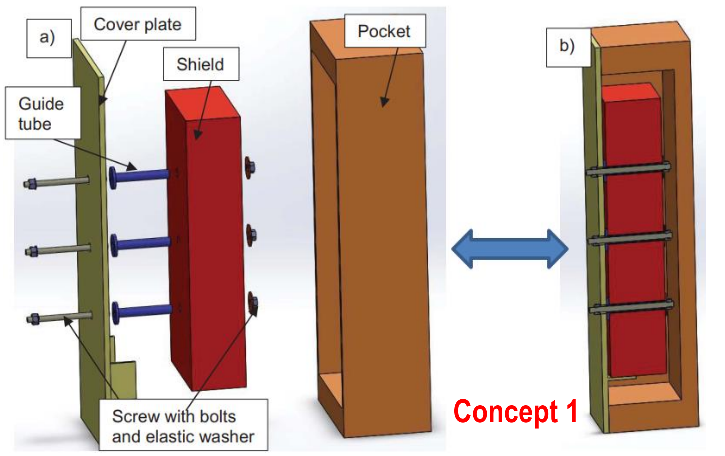
Concept 1: Radiation, shield fixed to cover plate

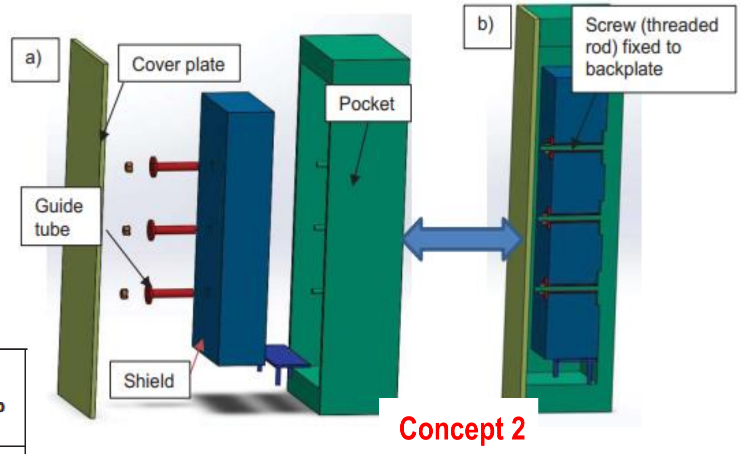
Concept 2: Contact, shield fixed to BSS backplate

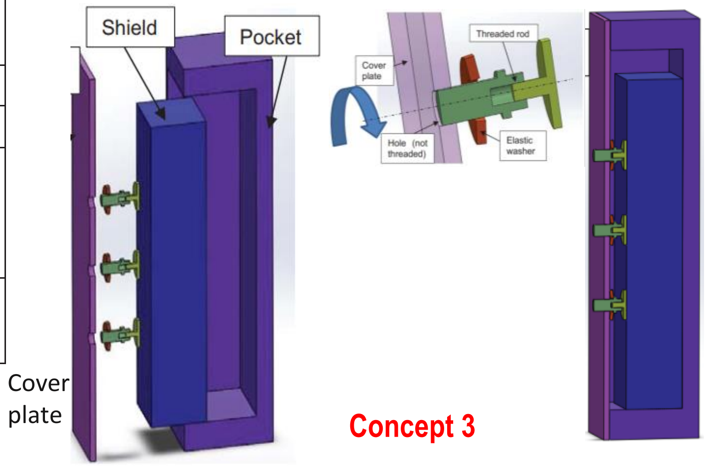
Concept 3: Contact, shield fixed to BSS backplate with external clamping



B4C shield



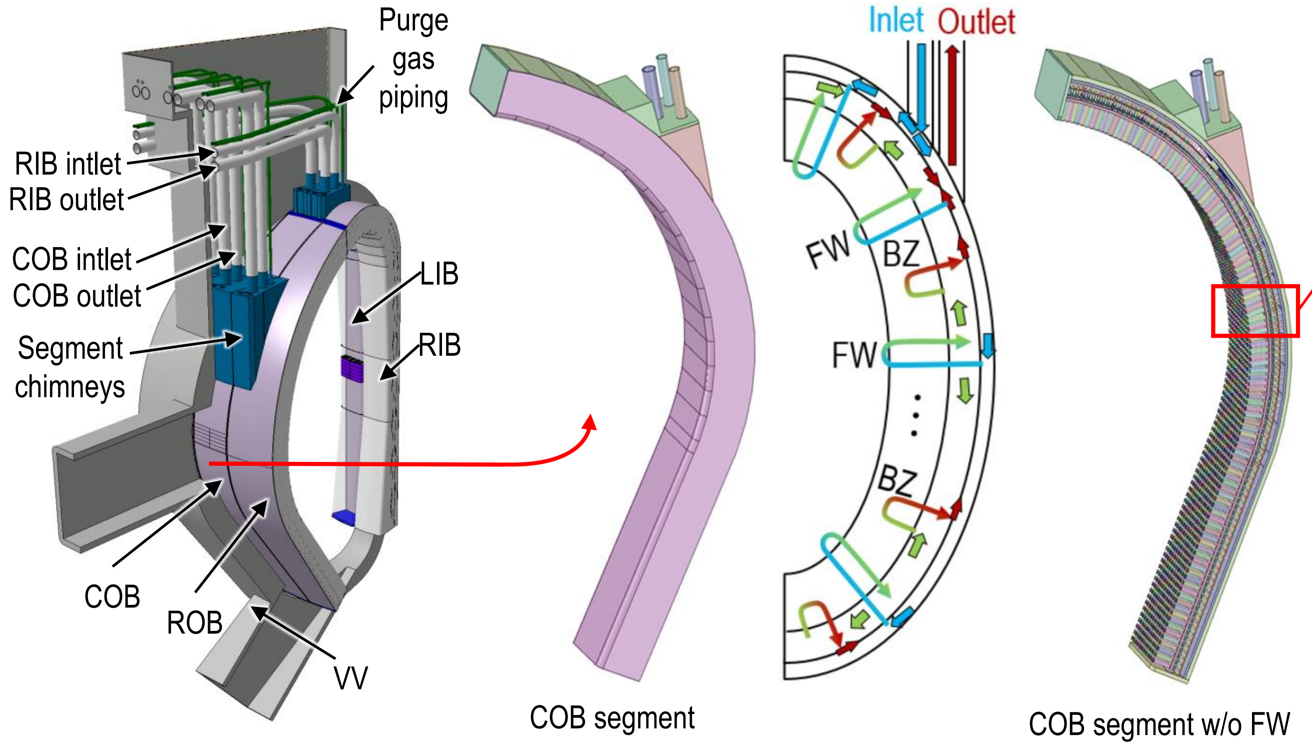




			Cover plate	Shield	BSS
Concept 1	Tmax	°C	795 > 450°C → **significant creep**	950°C	364 < 375°C → negligible creep
	Tmoy ΔT	°C	791 5	935 54	343 48
	Max($\bar{\sigma}$)	MPa	9	124	89
	$\overline{Q_m + Q_b} = \overline{\Delta Q}$	MPa	8 → low value	-	109
	Applied design criteria		Simplified analysis with 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**

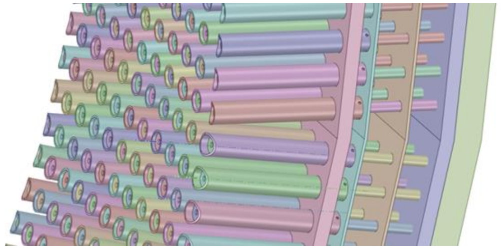
Concepts 2 & 3	Tmax	°C	426 < 450°C → negligible creep	467	382 > 375°C → **significant creep**
	Tmoy ΔT	°C	425 1	443 85	353 62
	Max($\bar{\sigma}$)	MPa	2	156	113
	$\overline{Q_m + Q_b} = \overline{\Delta Q}$	MPa	2 → low value	-	132
	Applied design criteria		Ratcheting: $\overline{P_m + P_b} + \overline{\Delta Q} < 3\,Sm$	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**

Global segment hydraulics



COB segment

COB segment w/o FW



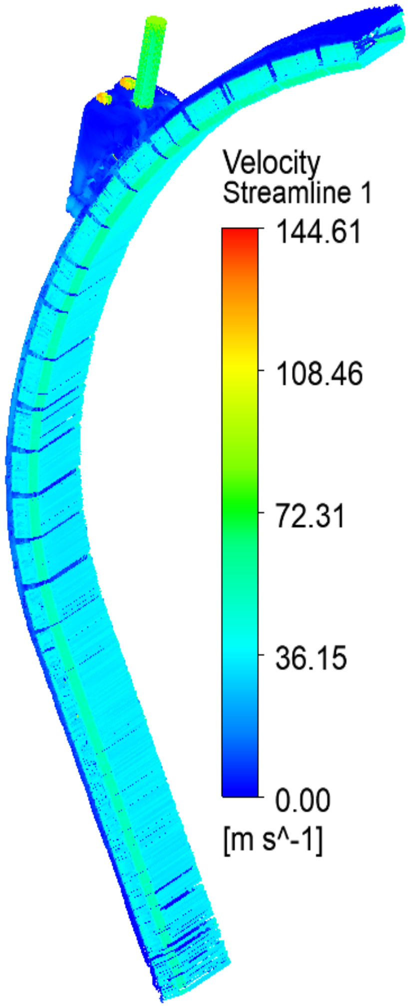
Porous media approach [4]

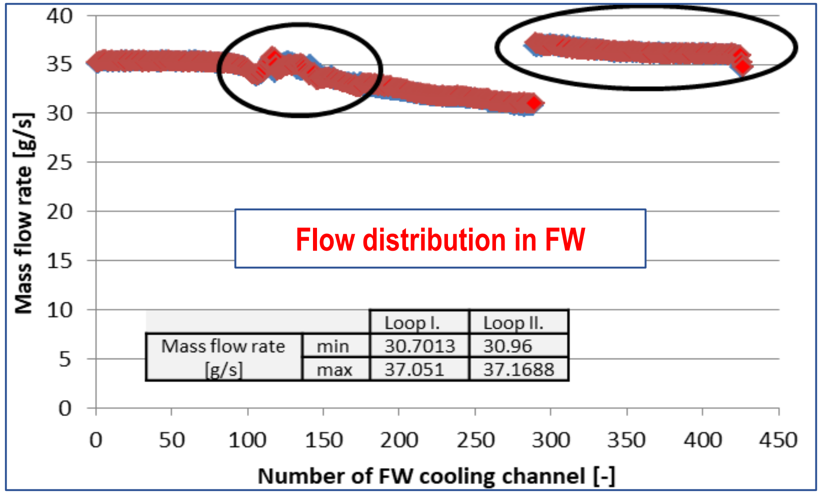
Totally in COB

- 1232 pins
- 860 FW channels

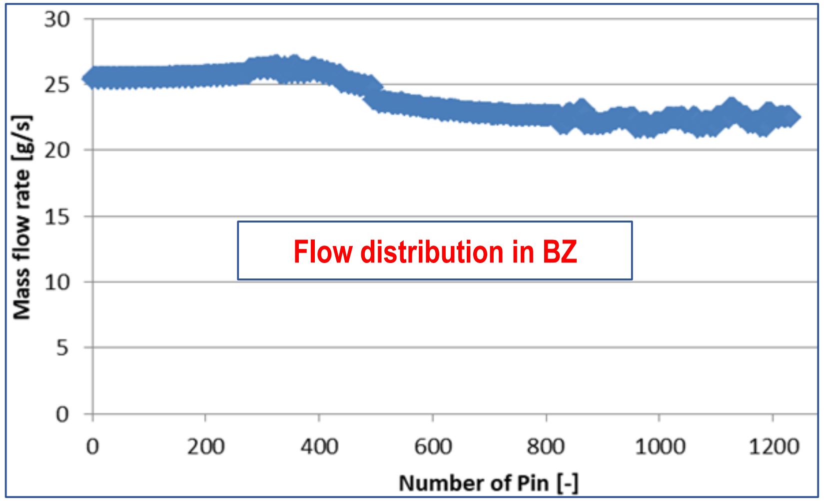
Pressure drop: 0.96 bar

Flow distribution relative OK





Mass flow rate [g/s]		Loop I.	Loop II.
	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 Q_2 on the Cryogenic Molecular Sieve Bed (CMSB) at 77 K.

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

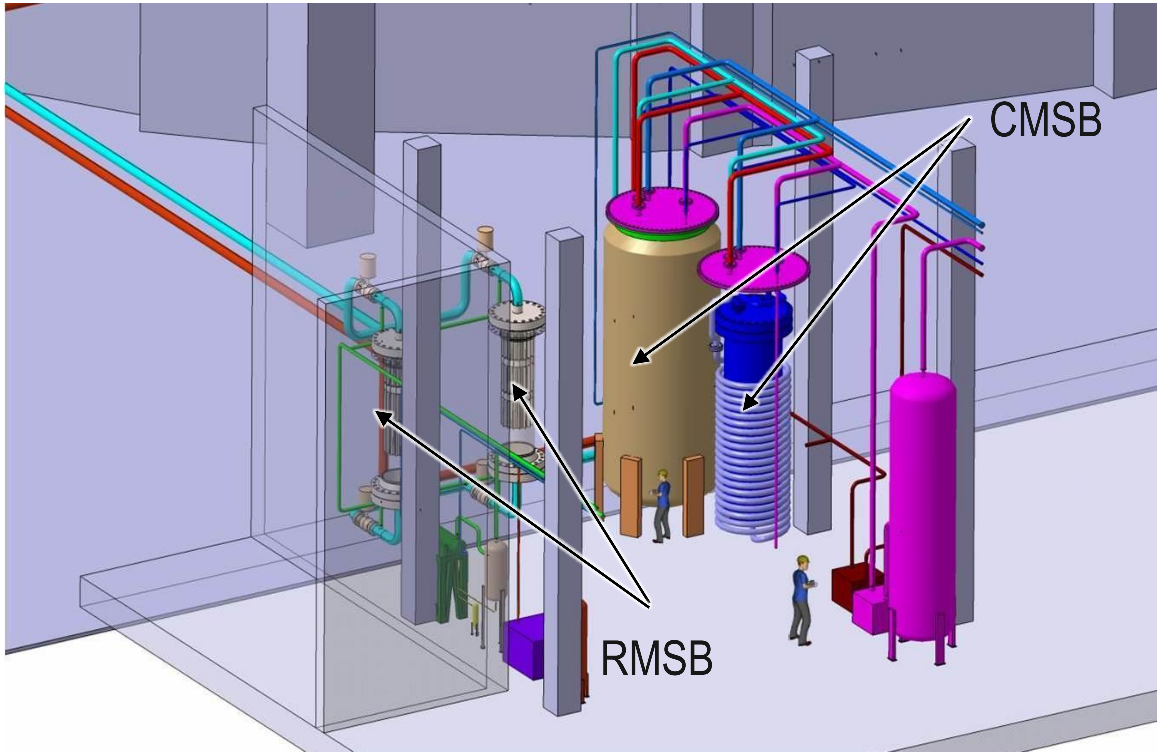
➢ Extrapolated to DEMO scale is realized with industry.

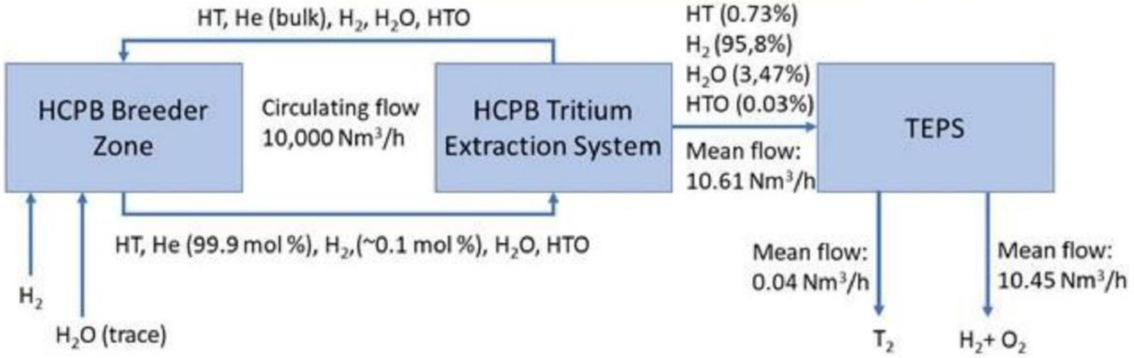
- Outlook

➢ 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.

➢ 8 MPa purge gas, introduced to improve reliability of BB, results show that TER operating at 8 MPa not a issue.



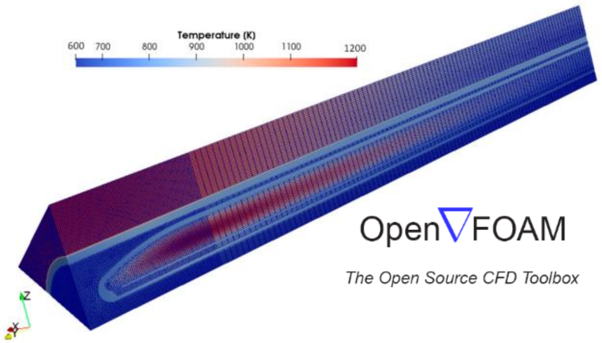


[5] I. Cristescu et al., Fusion Eng. Des. 158 (2020) 111558.

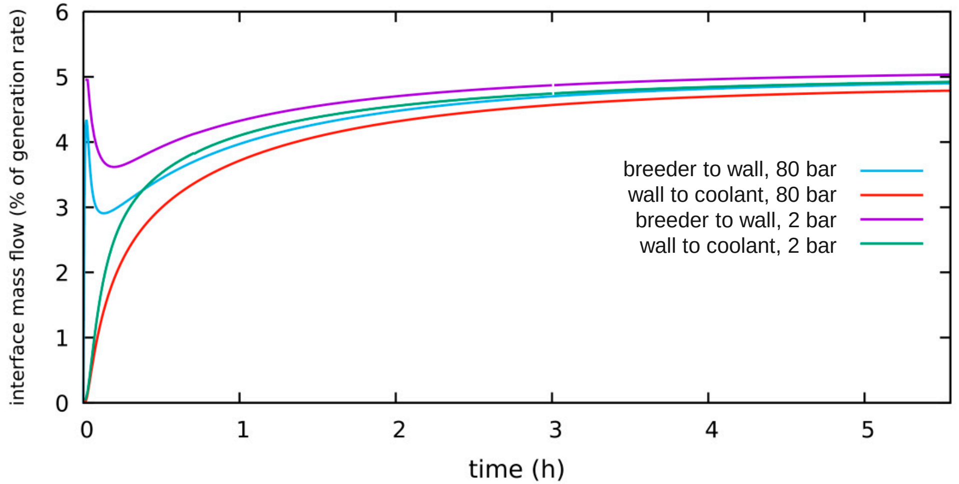
Tritium permeation analysis

- 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]

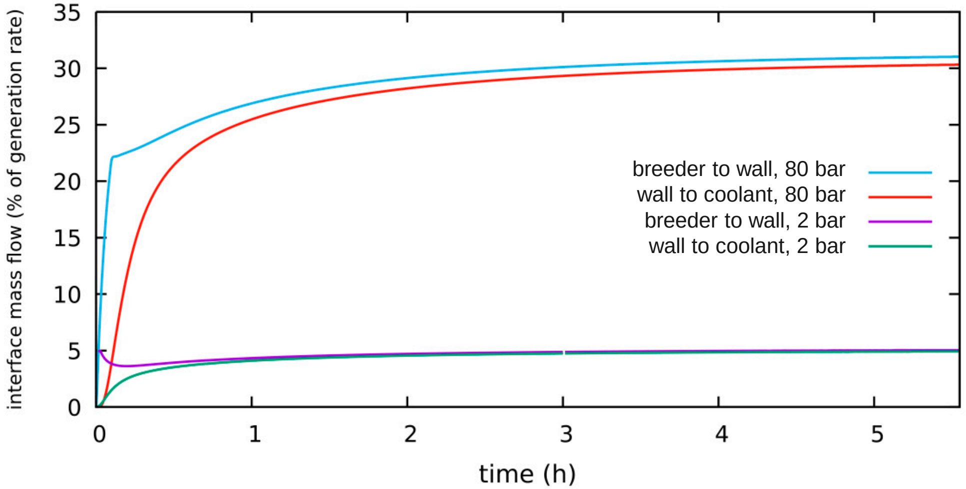


Temp. field of 1/6 fuel-breeder pin



Permeation under equal volumetric flow

- T permeation analysis
  - T permeation analysis under 0.2 MPa pressure purge gas vs 8 MPa pressure purge gas, with same H2 partial pressure
  - Wetted purge gas vs dry purge gas



Permeation under equal mass flow

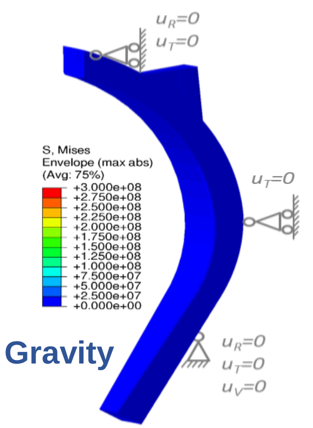
Purge gas	Permeation to coolant	Wall T inventory
200Pa H2, no H2O	0.077% of T generation 290 mg/d	65 ng
200Pa H2 + 200Pa H2O	0.022% of T generation 83 mg/d	19.2 ng

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

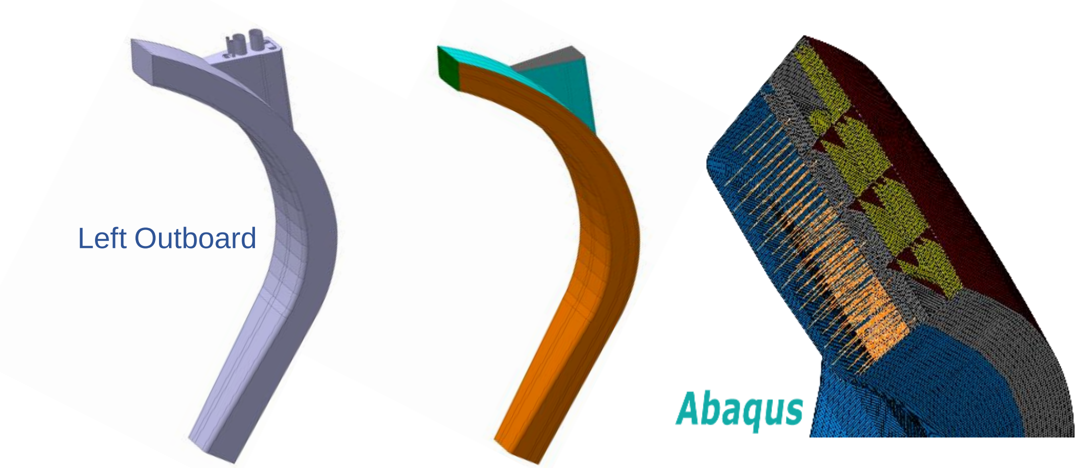
Optioneering of blanket attachment (1/2)

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

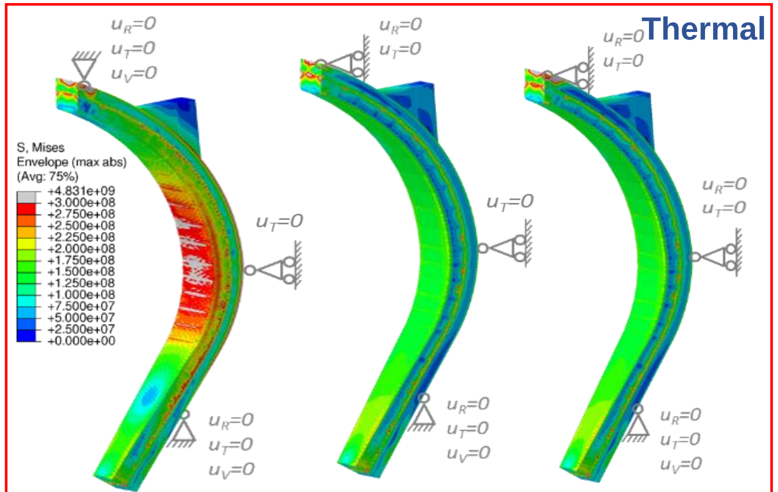
Equivalent shell and beam elements used to get quick feedback



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.



Solid geometry | Surface bodies | Shell and beam elements

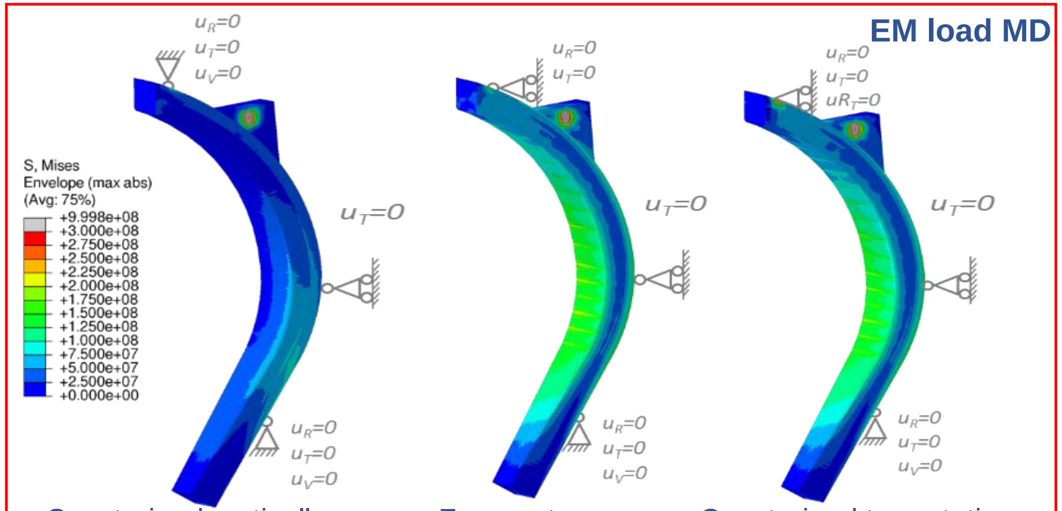


Constrained vertically | Free vertical expansion | Free vertical expansion

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

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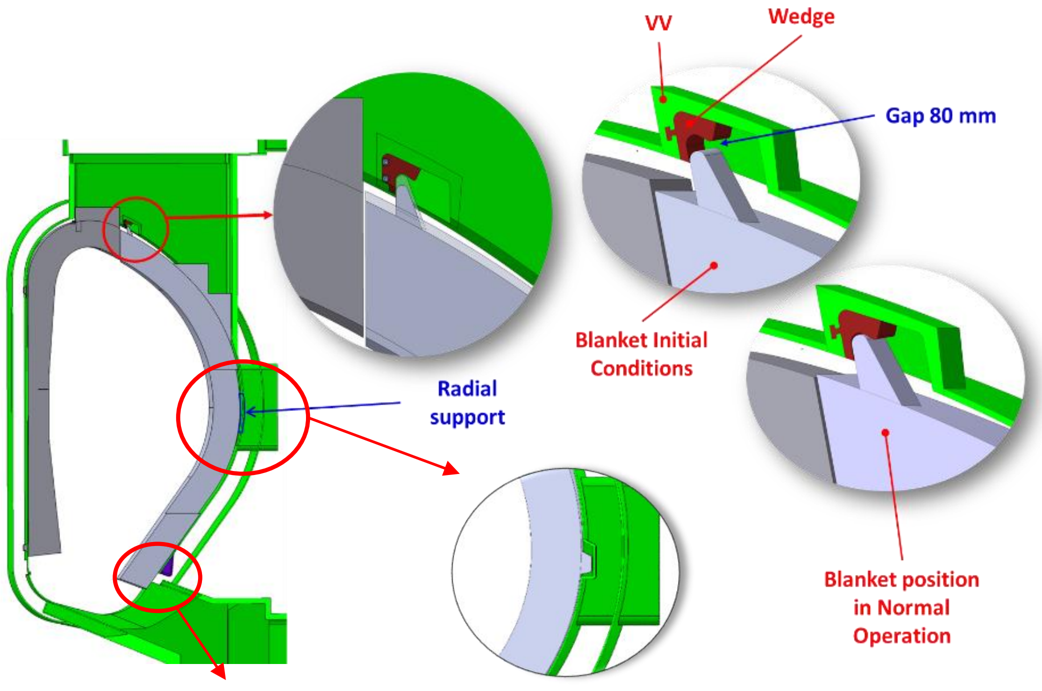
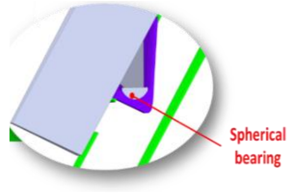
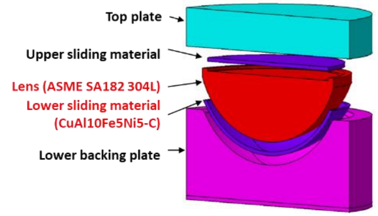
Optioneering of blanket attachment (2/2)

- Proposed concepts of BB-to-VV attachment

Bottom, middle and top supporting structures

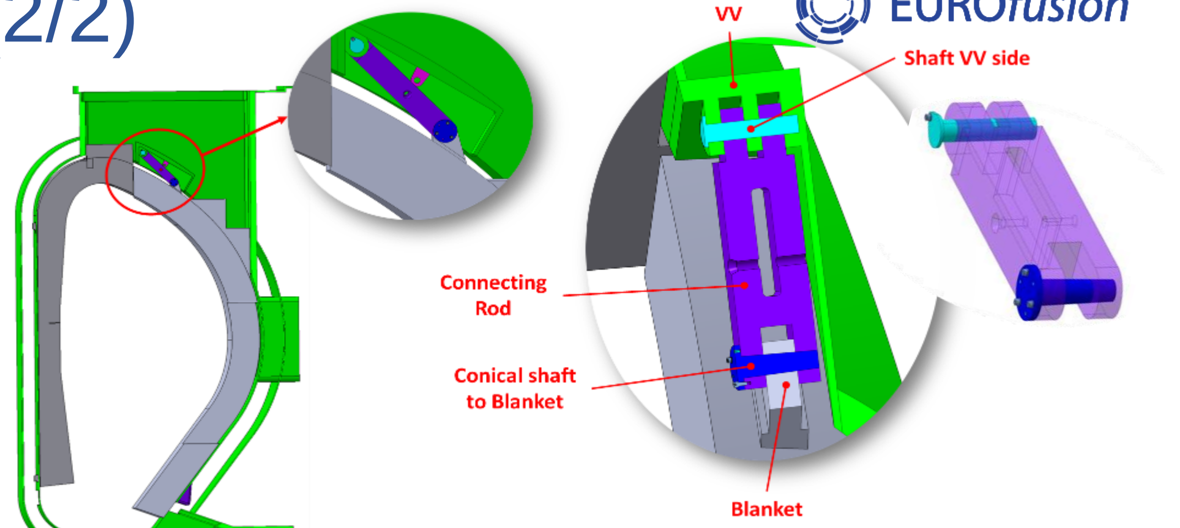






ITER Cryostat Support Bearings
to take 1100 tonnes

Proposal 1

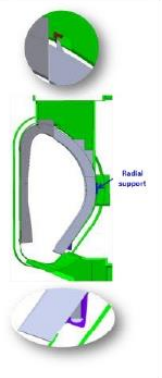
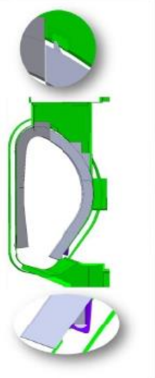
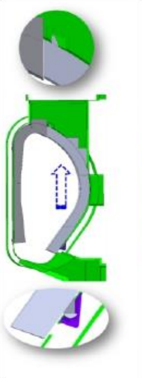
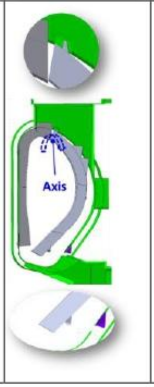
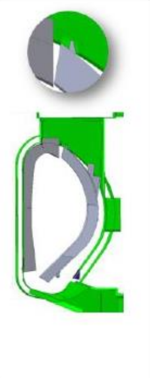
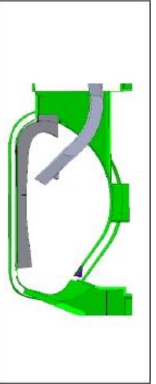


Proposal 2

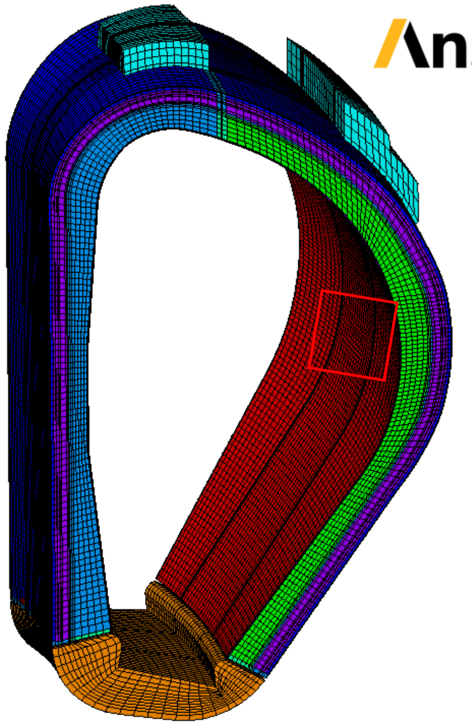
At bottom, spherical bearing similar to ITER Cryostat Support Bearings

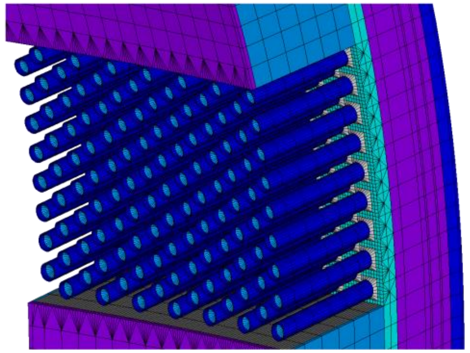
At midplane, toroidal key is proposed. The toroidal key has a toroidal gap to facilitate assembly by RH tools. The pocket at the VV allows sufficient vertical displacement (124 mm) of the segment for the assembly process.

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

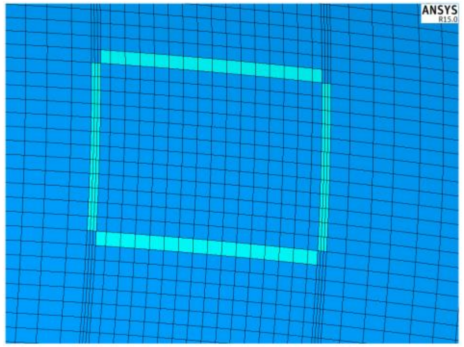
0. Initial conditions	1. Wedge removal	2. Segment lift	3. Segment rotation	4. Segment translation	5. Segment extraction
					

Advanced electromagnetic analysis procedure

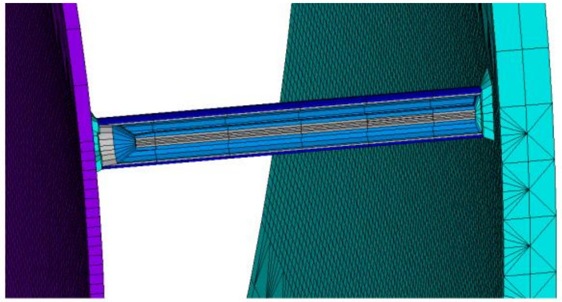


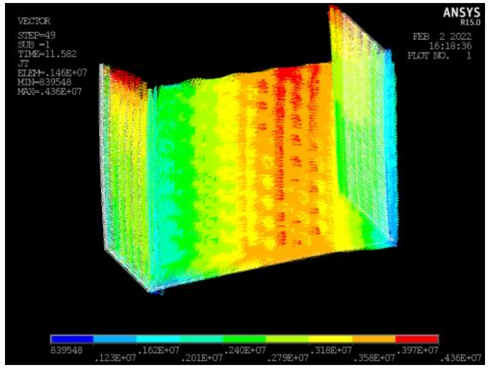


Submodelling

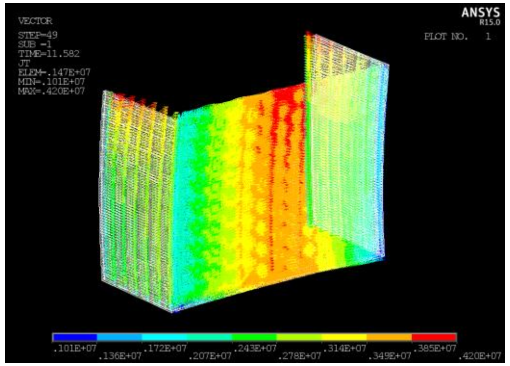


Model without detailed region





Model without detailed region



Submodelling

Current Density [A/m2]

- EM model that simulates a whole DEMO sector are usually limited by mesh dimensions and computational time.
- Homogenization of the BB structure, not allowing to calculate the EM loads on internal structure with an high precision.
- To overcome such a limitation, the EM submodelling procedure (using ANSYS solid236) to simulate the detailed internals of HCPB BB.
- Obtained results show that the method is realiable also in presence of non-linear magnetic behavior.

[8] I.A. Maione et al., SOFT 2022.

Outlook

EUROfusion

- 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.

ANS

Contributors & Acknowledgements

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Thank you for your attention!