EUROfusion

Emerging Breeding Blanket Variants for the EU DEMO

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Breeding Blanket Project in EUROfusion

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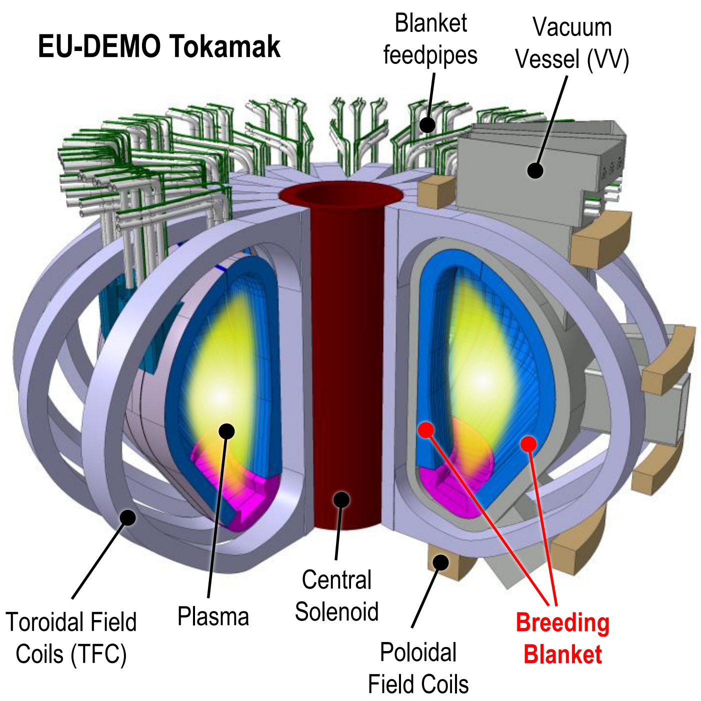
Outline

1. **Introduction. Breeding Blanket: the „core“ of a fusion reactor**
2. Reference BB concepts & motivation for variants
3. Emerging WCLL variant: the WCLL „double bundle“
4. Emerging HCPB variant: HCPB-HP
5. Emerging WCLL-HCPB hybrid variant: WLCB
6. Summary and Outlook

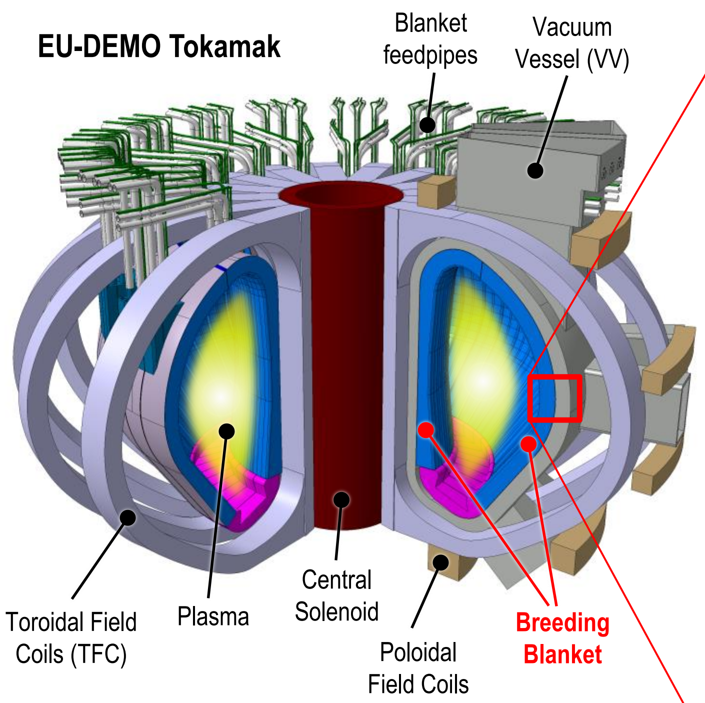
1. Introduction: The „core“ of a fusion reactor

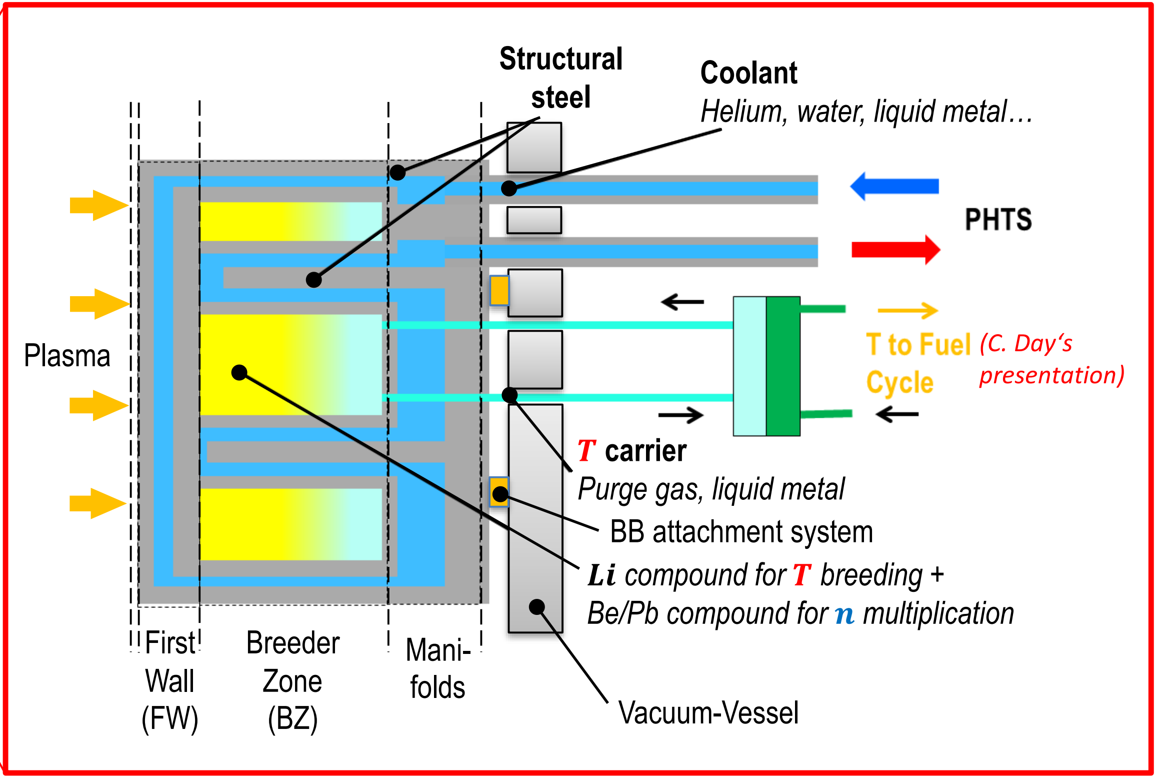


- D-T fusion reaction: $\boldsymbol{D} + \boldsymbol{T} \rightarrow {}^{4}He + \boldsymbol{n}$
  - $\boldsymbol{D}$ is abundant in nature
  - $\boldsymbol{T}$ is virtually inexistent in nature => we need to breed it *in-situ*
- $\boldsymbol{T}$ can be bred from *Lithium*: $\boldsymbol{Li} + \boldsymbol{n} \rightarrow {}^{4}He + \boldsymbol{T} + (\boldsymbol{n}')$
- However:
  - Some $\boldsymbol{n}$ are lost due to streaming, leaking and parasitic absorption
  - Some $\boldsymbol{T}$ are lost due to trapping in materials, decay or leaking
- We need to „multiply“ $\boldsymbol{n}$ to sustain $\boldsymbol{T}$ breeding from $\boldsymbol{Li}$ by means of a „neutron multiplier“:
  - ${}^{9}Be + \boldsymbol{n} \rightarrow 2\,{}^{4}He + \boldsymbol{2n}$
  - ${}^{m}Pb + \boldsymbol{n} \rightarrow {}^{m-1}Pb + \boldsymbol{2n}$
- The BB is the „core“ of a $\boldsymbol{D}-\boldsymbol{T}$ fusion reactor:
  1. The BB produces the reactor‘s own fuel $\boldsymbol{T}$
  2. The BB converts fusion energy (mostly $\boldsymbol{n}$) into high grade heat
  3. The BB contibutes to the n-shielding of coils and vacuum vessel

1. Introduction: The „core“ of a fusion reactor

- „Near-term“ Breeding Blanket atchitecture





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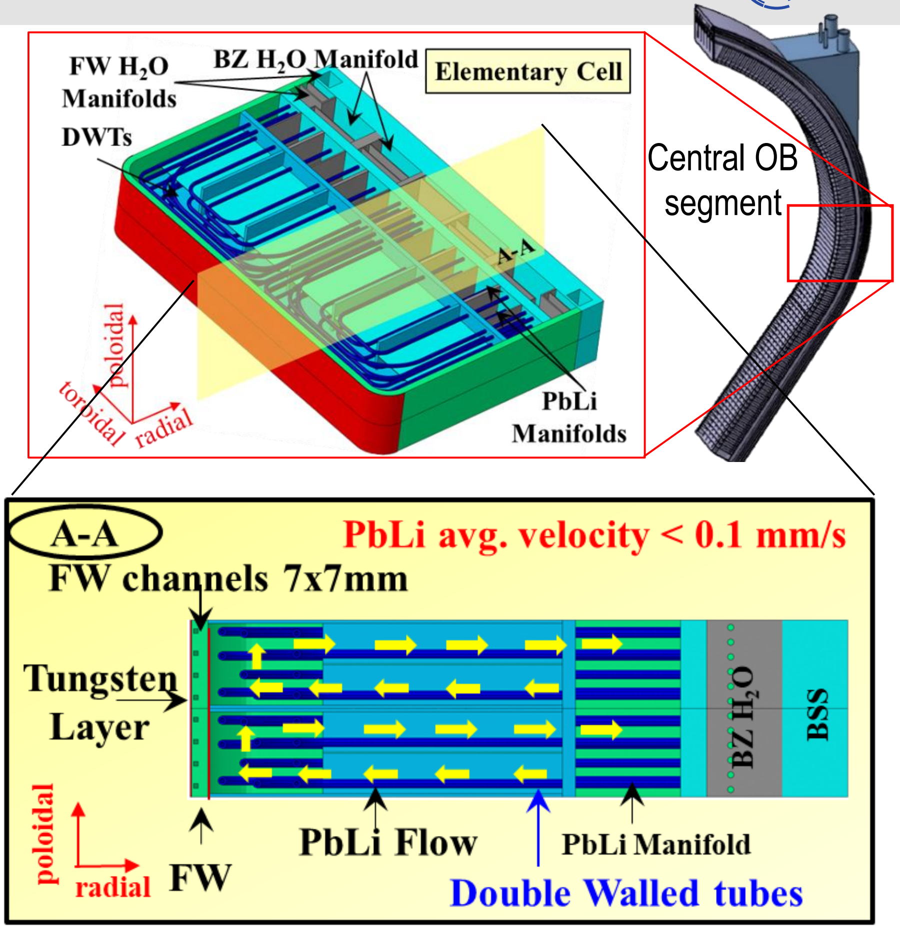
2. Reference BB concepts & motivation for variants

- Current WCLL baseline reference variant
  - DEMO: 16 sectors, 3 OBS + 2 IBS per sector, SMS segments
  - PWR water cooling (295-328°C, 15.5MPa), 2 loops (FW, BZ)
  - PbLi as n-multiplier, T-breeder and carrier
  - Unit cells cooled by radial Double Wall Tubes
  - PbLi radial flow in BZ, poloidal flow in manifold
  - Structural steel: EUROFER97, W-armor 2mm

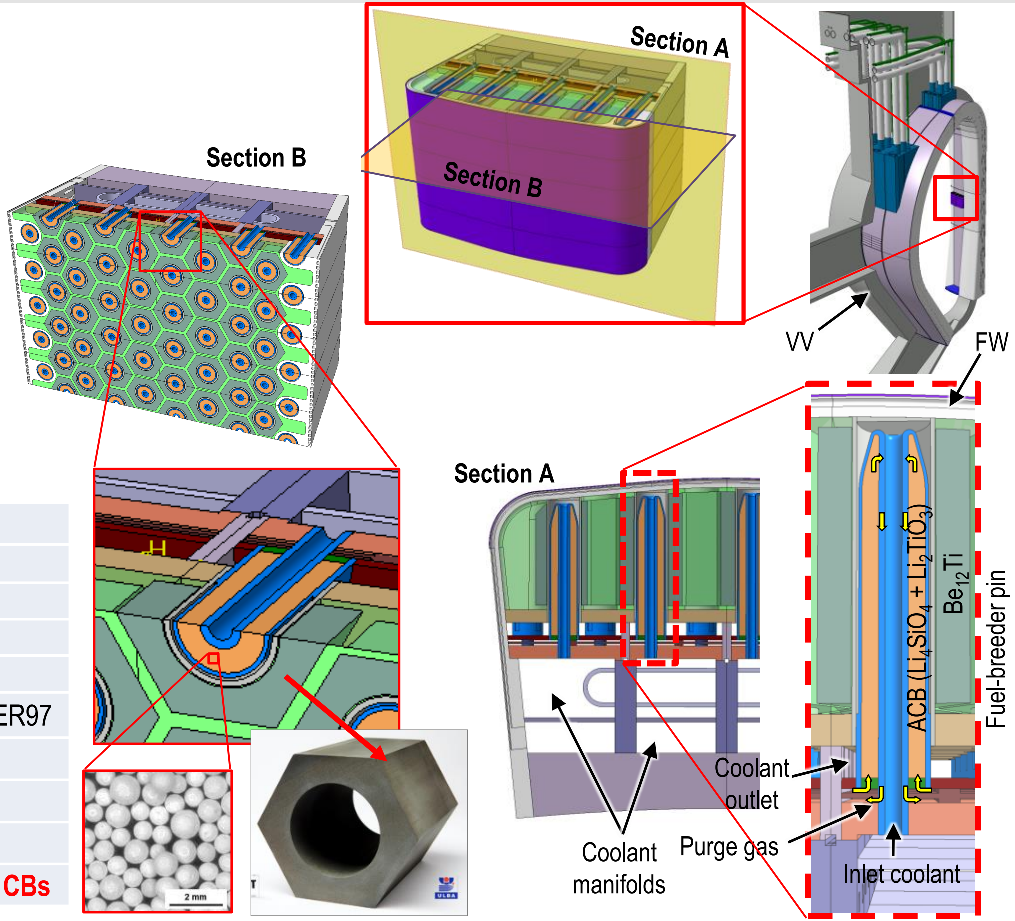


- Identified risks as of end pre-CD phase:

	Risk ID	Risk
WCLL	1	Low reliability of BB system
	2	Low efficiency of PbLi draining
	3	FW based on thin EUROFER + W-armor
	5	Low T breeding performance
	6	Large amount of transmutation helium in PbLi
	10	Large T permeation to coolant
	12	WCLL operating with EUROFER temp. irradiated <400 °C (DBTT shift)
	13	Pressure transient uncertainties due to PbLi-water interaction
	22	Diffusion of Li into anti-permeation barriers and production of T+He there

2. Reference BB concepts & motivation for variants

- Current HCPB baseline reference variant
  - DEMO: 16 sectors, 3 OBS + 2 IBS per sector, SMS
  - He cooling (300-520°C, 8 MPa), 1 loop (FW + BZ)
  - Be12Ti blocks as n-multiplier, Li_4SiO_4 + Li_2TiO_3 as T-ceramic breeder (ACB), He purge gas and T carrier
  - Unit : hexagonal fuel-breeder pin arrangement
  - Structural steel: EUROFER97, W-armor 2mm



- Identified risks as of end pre-CD phase:

	Risk ID	Risk
HCPB	1	**Low reliability of BB system**
	2	Limited heat flux removal capability of the blanket FW
	3	Loss of structural integrity Be12Ti blocks
	4&9	Low TRL industrial production Be12Ti blocks and CBs
	7	Reduction of structural integrity of BB due to DBTT shift of EUROFER97
	11	Large T permeation to coolant
	14	Low BB shielding capability
	18&19	Unknown behavior of Be12Ti and ceramic breeder under irradiation
	22	**Deterioration of mech. properties of EUROFER97 in contact w/ CBs**

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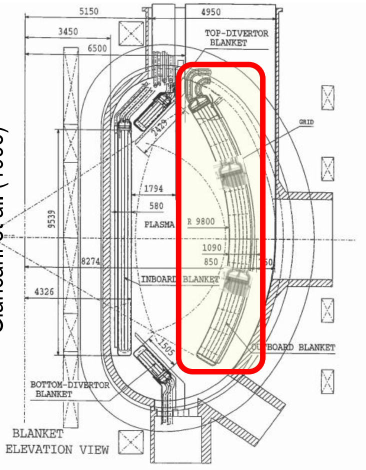
3. Emerging WCLL variant: WCLL "double bundle"

- Motivation:

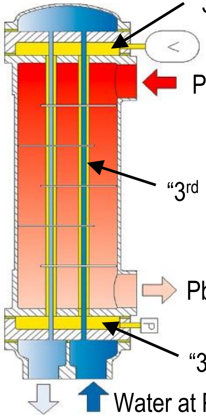
	ID	Risk	Addressed by
WCLL	1	**Low reliability of BB system**	(1)
	2	Low efficiency of PbLi draining	(4)
	3	FW based on thin EUROFER + W-armor	limiters
	5	Low tritium breeding performance	(3)
	6	Large amount of transmutation He in PbLi	
	10	**Large T permeation to coolant**	(2)(6)
	12	WCLL operating with EUROFER temp. irradiated <400 °C (DBTT shift)	
	13	**Pressure transient uncertainties due to PbLi-water interaction:**	(5)
	22	Diffusion of Li into anti-permeation barriers and production of He there	(2)(6) may avoid barriers

- Poloidal water tube distribution:
  - Poloidal tubes:
    - (1) Less tubes, less welds, ↑ **reliability**
    - (2) Less tubes, less surface, ↓ **T-permeation**
    - (3) Less tubes, less water, more PbLi, ↑ **TBR**
    - (4) Easier draining and less He accum. risks
  - BB similar to HX/SG => ↑ **TRL/RoX**
  - Segments split in several poloidal regions
    - – Limit heat flux per tube
    - – Allows systems integration (H/CD, limiters…) w/o splitting segments

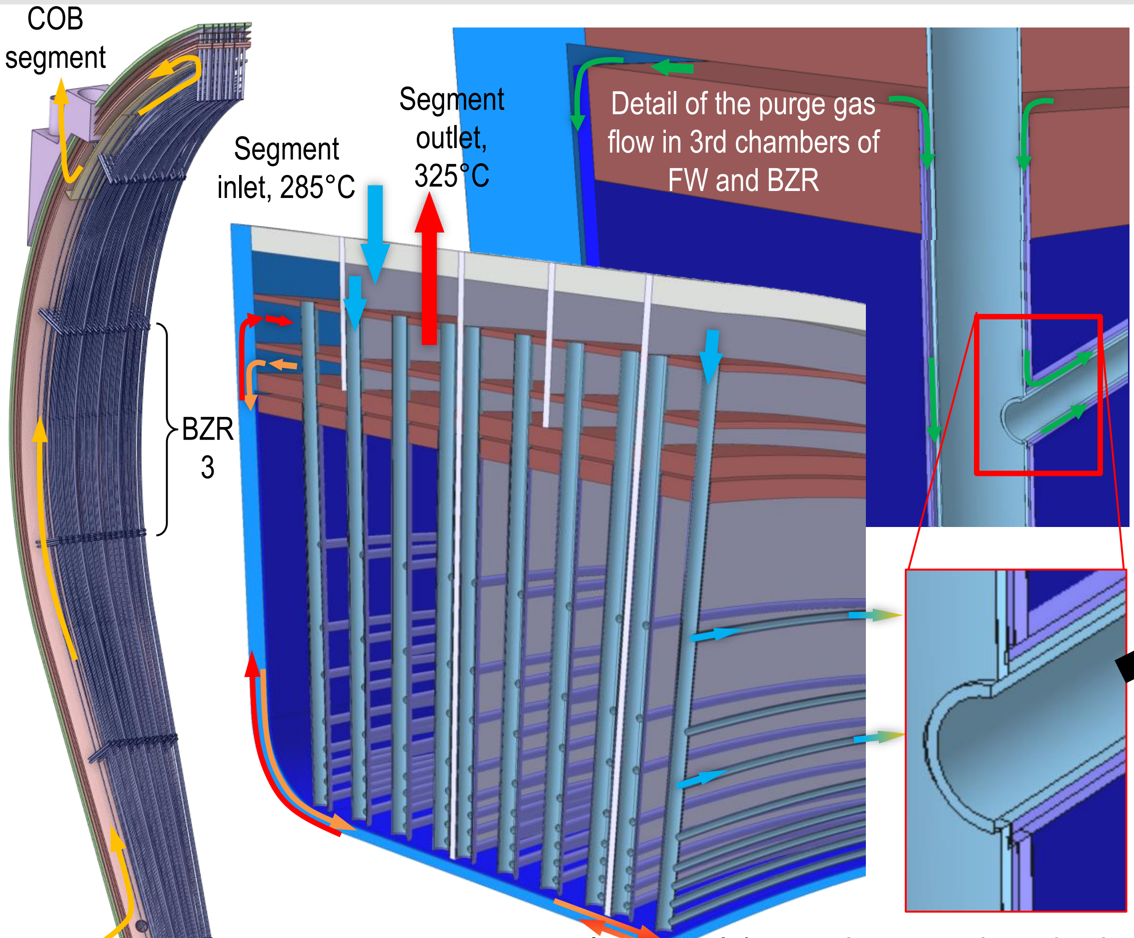


Giancarli et al. (1995)

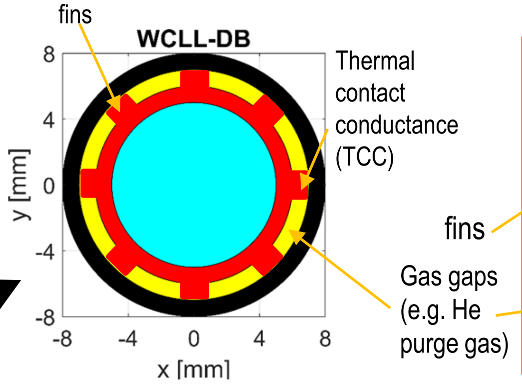
- „Double bundle" of simple tubes
  - 3-chamber idea of S&T HX (K.-H. Funke)
    - (5) Intermediate chamber between PbLi and water to avoid contact in case of internal LOCA
    - (6) 3rd chamber filled with He gas: used to remove permeated T before it reaches water

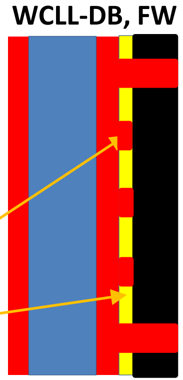


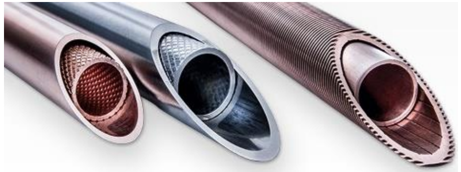
3. WCLL-DB: Conceptual design



- Design description:
  - PWR cooling (285-325°C, @15.5 MPa)
  - BZ and FW in series ($T_{in,FW}$≈315 °C)
  - 5 BZRs, poloidal PbLi flow
  - „3rd chamber“ between the double bundle, filled *with a He purge gas*



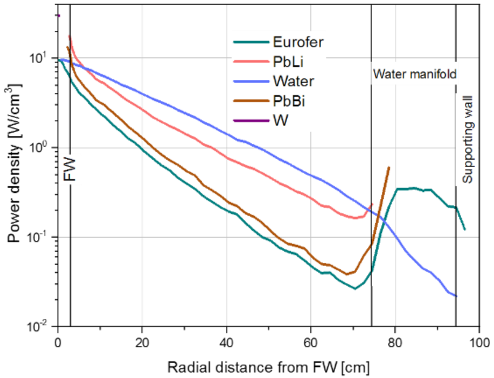


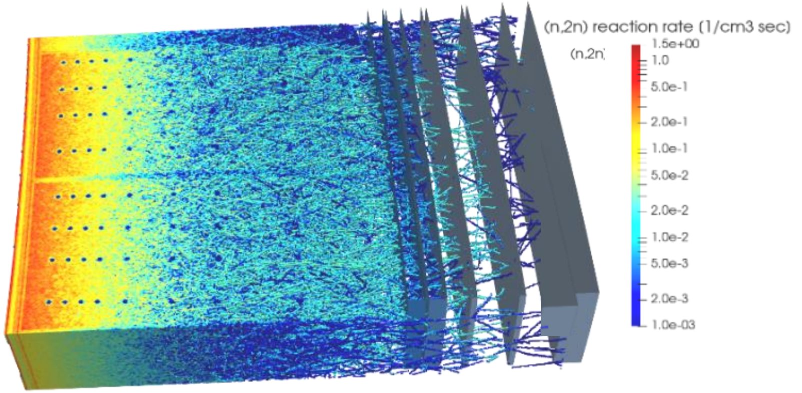


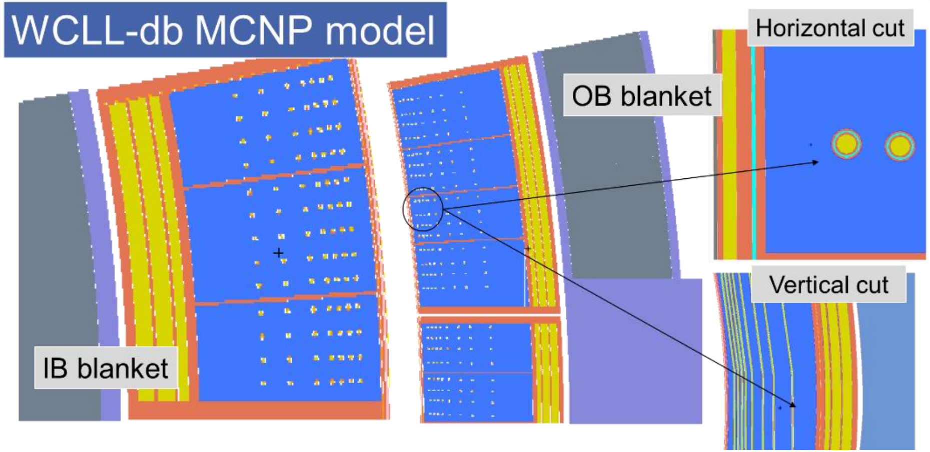
E.g. Wieland Safety Tubes: https://www.wieland-thermalsolutions.com

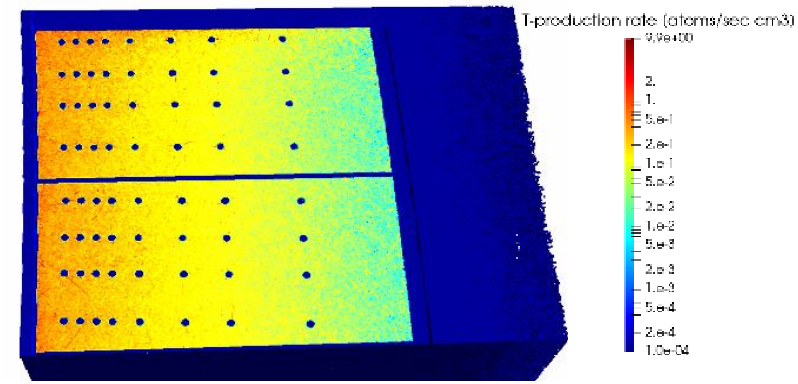
3. WCLL-DB: Neutronics

- **Summary 2021: Neutronics**
  - MCNP-6.2, JEFF-3.3 library
  - 3D WCLL DEMO sector (11.25°)
  - Fully heterogeneous model
  - **TBR = 1.16** (ref. 10 FW ch/BU)
  - **TBR = 1.17** (6 FW ch/BU)
  - Water manif. large => possibility to enlarge BZ (≈+0.01-0.02)





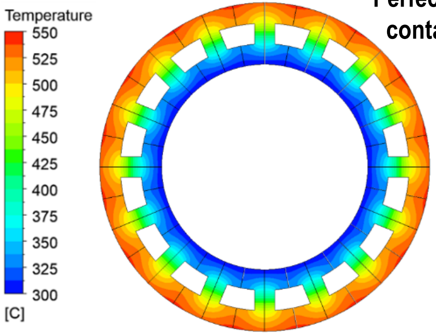


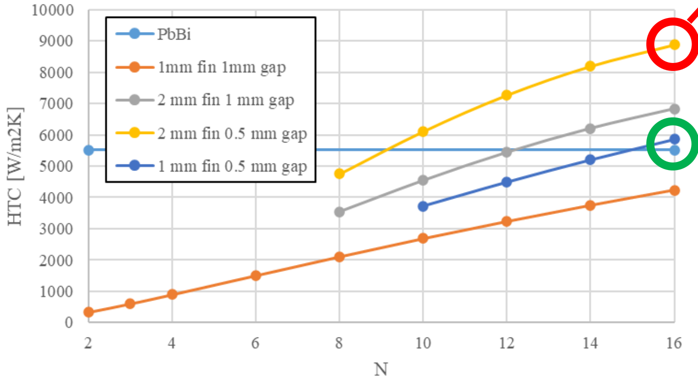


3. WCLL-DB: Thermal-hydraulics

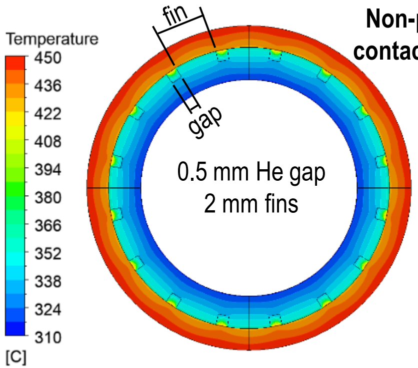
- Parametric study changing #fins (2 - 16), their thickness (1; 2 mm) and gap height (0.5; 1 mm)
- Each HTC_{global} (gap + fins) compared to initial 2021 baseline design (PbBi interlayer)

Perfect (bonded) contact in fins

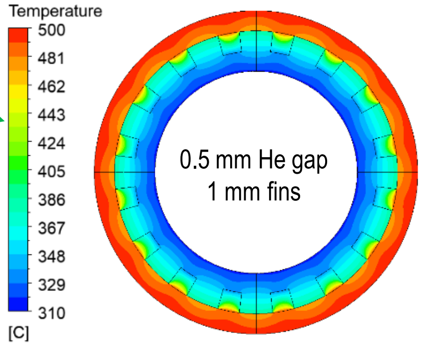




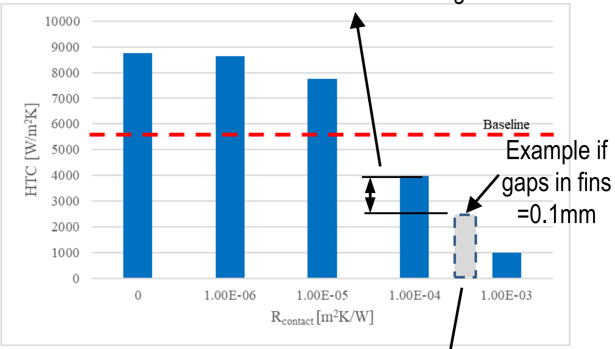
Non-perfect contact in fins

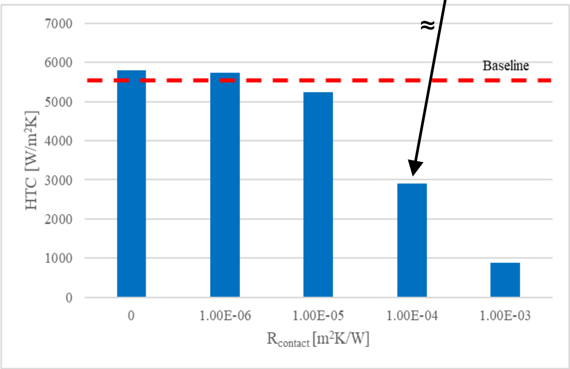


$R_{contact}$ = 1.0E-04 m^2K/W



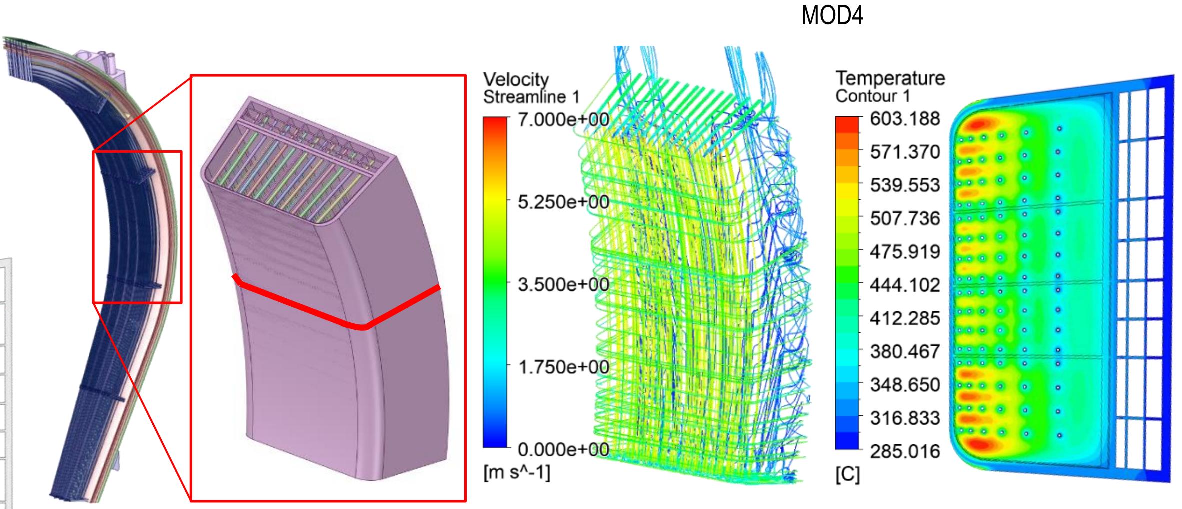
Drawback: HTC (temp.) very sensitive to tolerance setting

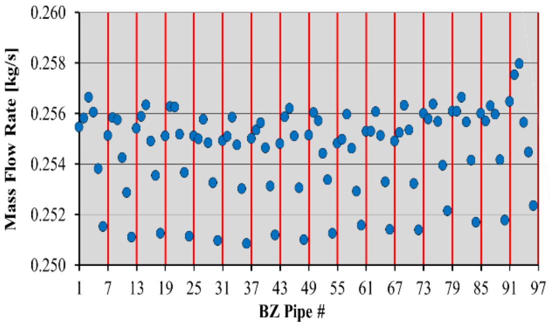


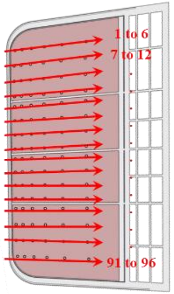


3. WCLL-DB: Thermal-hydraulics and mechanics

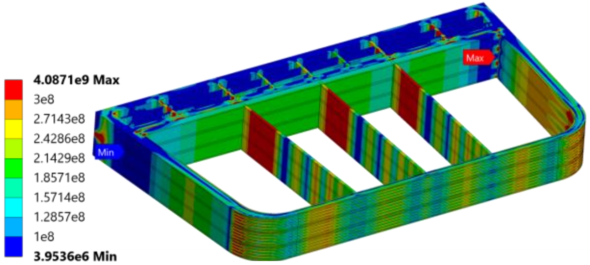
- **Summary: Thermohydraulics**
  - BZR3: Δp_{FW} = 0.555 bar, Δp_{BZ} = 0.693 bar
  - Mass flow distribution homogeneous
  - Heat transfer through fins demonstrated

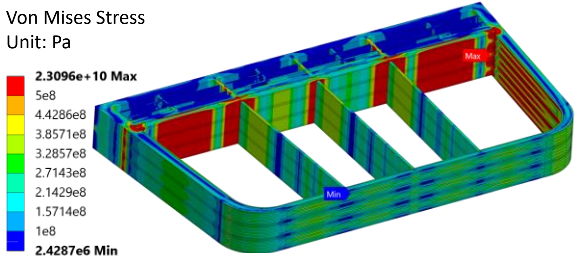






- **Summary: Thermomechanics**
  - Parametric assessment for NO and OP
  - Problematic regions seem easily solved by local reinforcement of structures

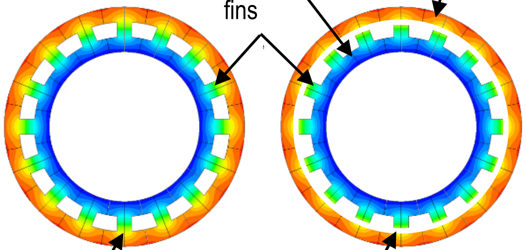


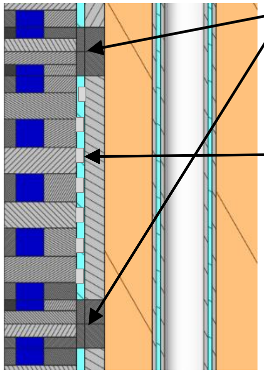


3. WCLL-DB: Tritium transport analyses

- **Simplified T-transport analyses**

Permeation rates to water circuits (g/d)	WCLL reference model (PRF = 1)	Stagnant purge gas	Flowing purge gas ($\dot{m}$ as in HCPB pin)				
		495 °C	495 °C	330 °C	495 °C	330 °C	
		Perfect contact in fins	Perfect contact in fins	Perfect contact in fins	No contact in fins	No contact in fins	No contact in fins, 10x $\dot{m}$ HCPB pin
Water tubes	44.18	27.668	7.071	2.194	8.2E-02	2.5E-02	2.4E-03
Feeding manifolds	--	4.878	9.0E-01	2.7E-01	9.3E-03	2.8E-03	2.7E-04
First wall	2.38	4.330	5.2E-01	1.4E-01	5.3E-01	1.3E-02	1.3E-02
Back wall	--	5.8E-01	2.2E-02	1.1E-02	3.5E-03	1E-02	1E-02
Total	**46.56**	**37.458**	**8.515**	**2.614**	**6.3E-01**	**1.7E-01**	**1.5E-01**





- Conclusions:
  - Stagnant PG, modest reduction (≈ 1.24x)
  - Temperature has a significant effect (≈3x)
  - Flowing PG and perfect contact in fins, significant reduction (≈5x - 18x)
  - Flowing PG and imperfect contact in fins, massive reduction (**≈74x - 319x**)
    - Potential to eliminate barriers, but HTC very sensitive to fins tolerances
  - Dominant perm. path => FW/back wall structural ribs, impact of PG $\dot{m}$ limited

3. WCLL-DB: Reliability analysis

Summary

- Most scenarios show low yearly FR <10^{-2}, but some cases (table below) requires attention
- Multiplicities: WCLL-ref > WCLL-DB > WLCB. Yearly FR has to be read together with ist consequence

Failure and element		WCLL-Ref			WCLL-DB			Consequence	
		FR min [1/y]	FR max [1/y]	Multip.	FR min [1/y]	FR max [1/y]	Multip.		
Leak/rupture F/T pipe PbLi		4.91E-02	4.09E-01	416	6.56E-02	5.47E-01	416	In-VV leak	
Leak/rupture of poloidal welds between LiPb-BP and FW		2.57E-01	3.69E+00	72576	N/A			In-box LOCA	
Leak of the LiPb-BP double welds		2.10E+00	2.33E+00	354816	N/A			In-box LOCA	
Leak/rupture of pol. and tor. welds in the LiPb outlet manif.		2.34E+00	3.36E+01	661248	3.03E-04	4.34E-03	64	Bypass	
Leak/rupture of weld of water pipes with water feed in/out feeder manifold halves	sw	N/A			3.62E-01	5.19E+00	76544	In-tube LOCA	DWT + dw recommended
	dw				3.62E-02	5.19E-01			
Leak/rupture weld of purge gas pipes with purge gas in/out feeder manifold halves	sw	N/A			3.62E-01	5.19E+00	76544	In-tube leak PbLi	DWT + dw recommended
	dw				3.62E-02	5.19E-01			
Leak/rupture of purge gas feeder manifold		N/A			2.78E-01	7.41E+00	11008	In-tube leak PbLi	C-shaped DWT recommended
Leak/rupture of purge gas chamber in FW		N/A			1.10E+00	2.94E+01	10000	In-tube leak PbLi	FW purge gas chambers HIPed
Leak/rupture of purge gas poloidal tubes	ST	N/A			3.62E+00	9.66E+01	38272	In-tube leak PbLi	DWT recommended
	DWT				2.11E-03	3.62E-02			
Leak/rupture weld connection of the manif to the manif. from next breeder zone region	sw	N/A			2.72E-02	3.25E-01	4800	In-box LOCA	
	dw				2.72E-03	3.25E-02			
Loss of structural integrity of the purge gas chamber		N/A			N/A			In-VV leak p.g.	
Leak/rupture of structural weld of water manif. to the water CPs		N/A			N/A			In-box LOCA	

sw = single welds

dw = double welds (with DWT)

ST = Simple Tube

DWT = Double Wall Tube

Recommendations & outlook:

- Implement C-shaped DWT with dw (instead of ST+ feeders) to decrease FR of these elements

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4. Emerging HCPB variant: HCPB "high pressure"

- Motivation:

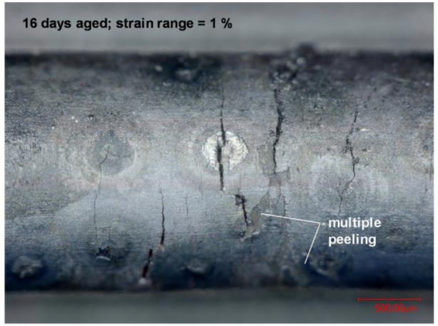
	ID	Risk	Addressed by
WCLL	1	Low reliability of BB system	(1)
	2	FW based on thin EUROFER + W-armor	limiters
	3	Loss of structural integrity Be12Ti blocks	R&D
	4& 9	Low TRL industrial production Be12Ti blocks and CBs	R&D
	7	Reduction of structural integrity of BB due to DBTT shift of EUROFER97	design option
	11	Large T permeation to coolant	-
	14	Low BB shielding capability	design option
	18 &19	Unknown behavior of Be12Ti and ceramic breeder under irradiation	R&D
	22	Deterioration of mech. properties of EUROFER97 in contact w/ CBs	(2)

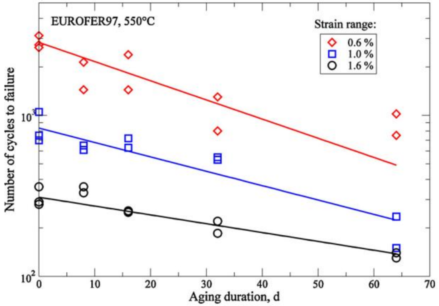
- Make coolant and purge gas virtually the same fluid (He 8 MPa):
  - Internal welds acting against in-box LOCA become irrelevant (but segment working at 8 MPa in normal operation)

(1) Design becomes a „fault tolerant", only welds against in-VV LOCA matter

T. Pinna, Fusion Eng. Des. 111937, 2020

(2) Reduction in lifetime of EUROFER97 of interfacing cladding not anymore important (both sides same pressure, no primary stresses)



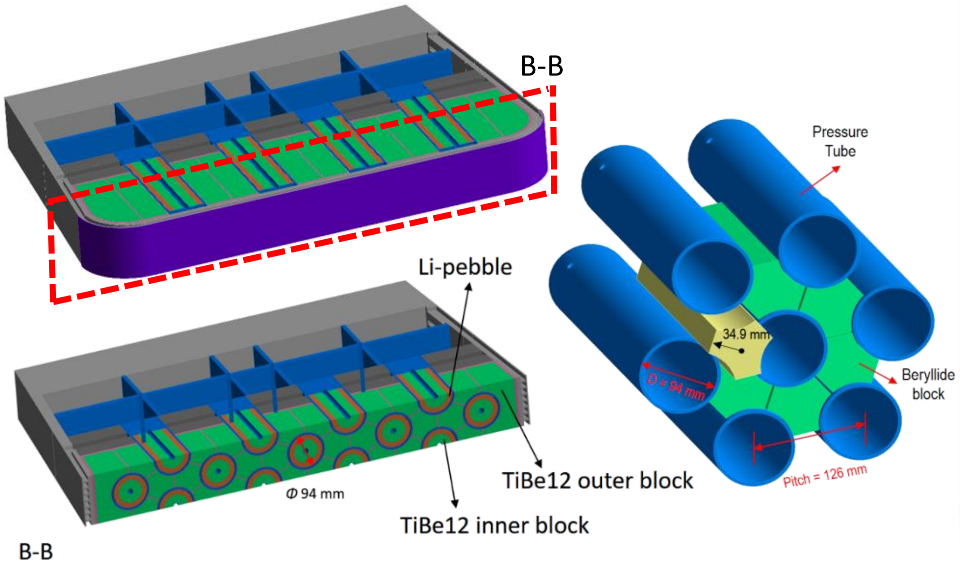


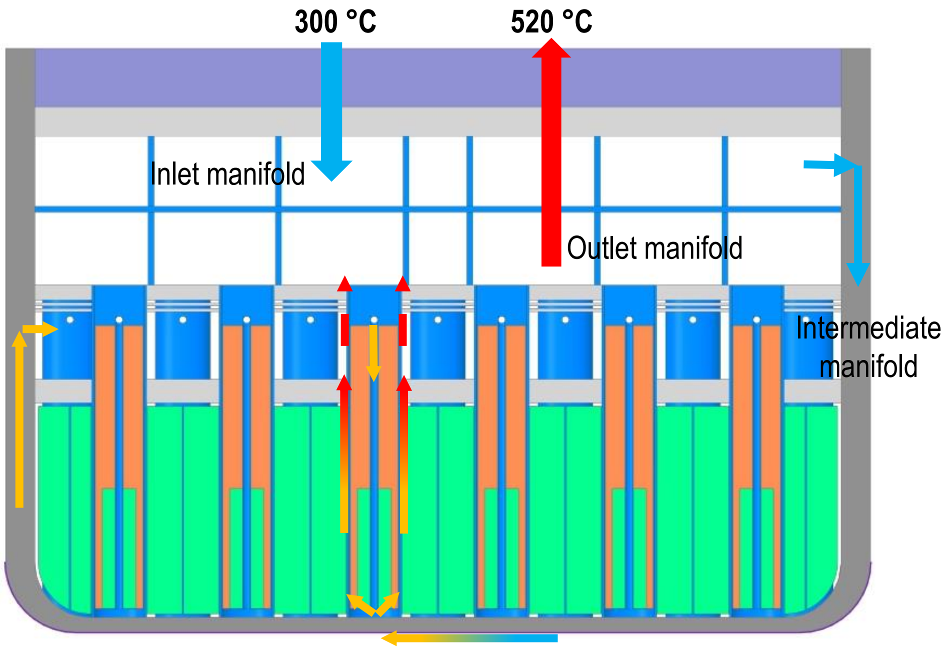
J. Aktaa, Fusion Eng. Des. 157 (2020)

E. Gaisina, Fusion Eng. Des. 564 (2022)

4. HCPB-HP: Conceptual design

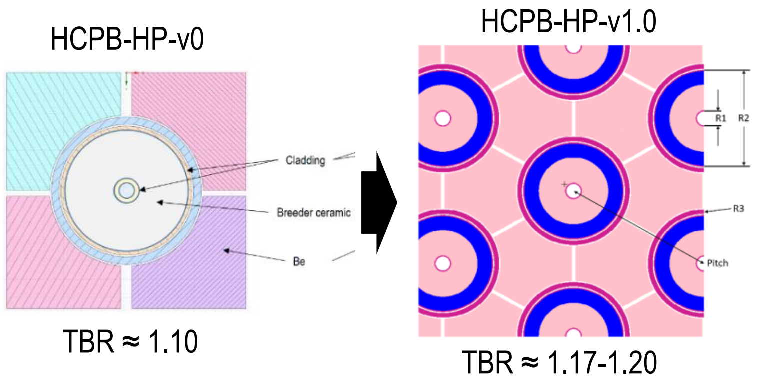
- Same HCPB architecture, but purge gas and coolant working at same pressure
  - Segment must work at an in-box LOCA conditions in normal operation
    - reinforcement of structures, design iterations to enhance tritium breeding capability to compensate higher steel amount
    - rearrange cooling internals to cool key structures with fresh He (higher stress limits at lower temperatures)
  - TER HCPB at high pressure: R&D to demonstrate technical feasibility of key subsystems working at 8MPa

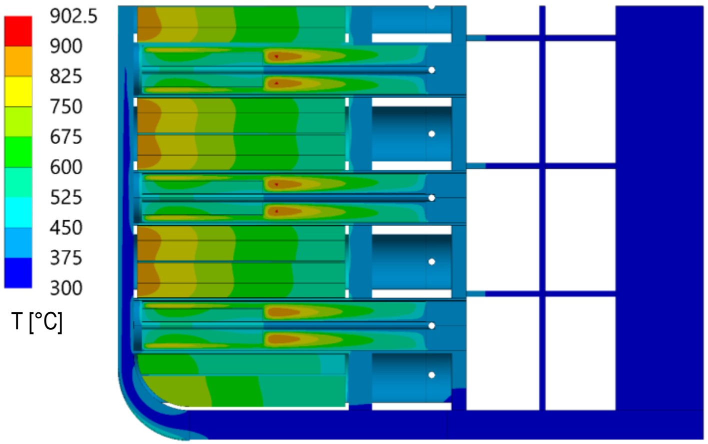


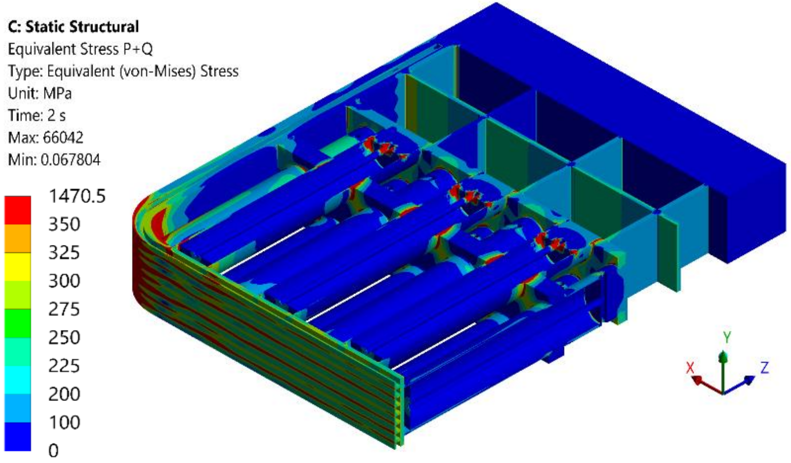


4. HCPB-HP: Neutronics, termal-hydraulics-mechanics

- Neutronics optimization
  - Thicker FW and BZ structural elements
  - Parametric studies, many design iterations
  - Similar shielding performance as former design
- Thermal and structural analyses
  - Temperature of materials within design limits
  - Colder key structural elements
  - Stress linearization: IPFL not anymore dominant, but IPI/IPC







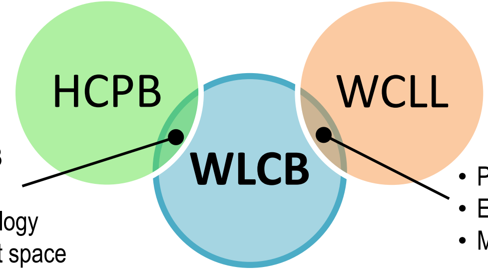
Outline

1. Introduction. Breeding Blanket: the „core“ of a fusion reactor
2. Reference BB concepts & motivation for variants
3. Emerging WCLL variant: the WCLL „double bundle“
4. Emerging HCPB variant: HCPB-HP
5. **Emerging WCLL-HCPB hybrid variant: WLCB**
6. Summary and Outlook

5. WLCB: Initial conceptual design

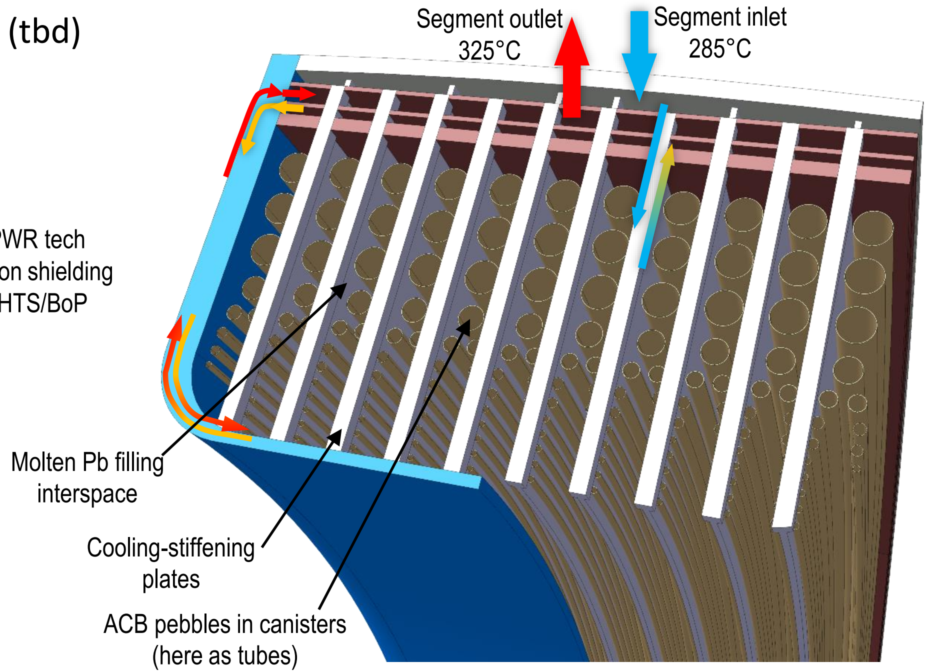
- Trade-off between HCPB and WCLL:
  - Mitigate n-shielding issues, n-mult. tech. and high costs of HCPB
  - Mitigate T-permeation issues and tech. risks on PbLi TER
  - Reduce dependency on anti-permeation barriers in BB (tbd)

- T extraction from ACB
- Low T permeation
- Available TER technology
- Good TBR in compact space



- Proven water PWR tech
- Excellent neutron shielding
- More mature PHTS/BoP

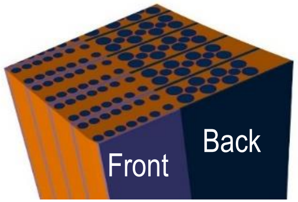
- Initial conceptual Idea
  - PWR cooling (285-325°C @155bar)
  - BZR: BZ and FW in series (as in WCLL-db)
  - Purge gas: He + %H2/H2O @2bar (tbd)
  - Radial cooling plates to withstand in-box LOCA
  - ACB pebble beds for T-breeding in canisters (tbd)
  - Molten Pb (n-multip) filling interspaces of BZR



WLCB COB, BZR3

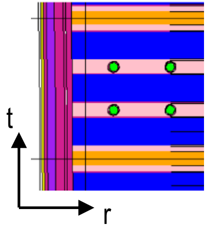
5. WLCB: Neutronics campaign

- ACB in poloidal configuration

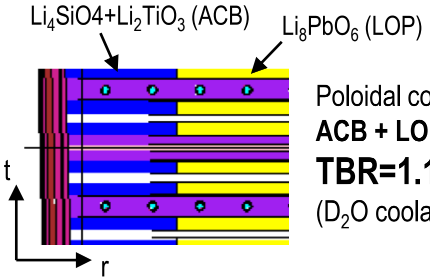


v7. CP: 50-25-25%
(E97-H2O-Pb)
Front & Back zones
TBR= 1.098

- ACB in radial configuration

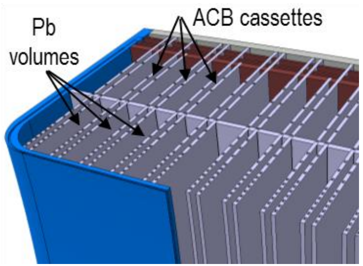


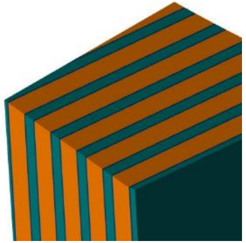
Poloidal cooling tubes
ACB, Li-6 90%, PF=64%
TBR=1.11

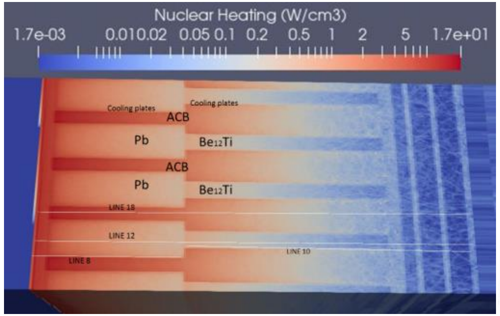


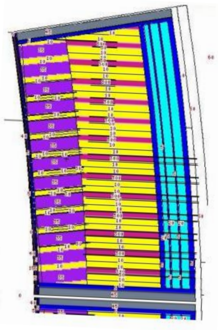
Poloidal cooling tubes
ACB + LOP, Li-6 90%, PF=64%
TBR=1.14
(D_2O coolant: TBR=1.17)

- ACB and NMM in cassettes



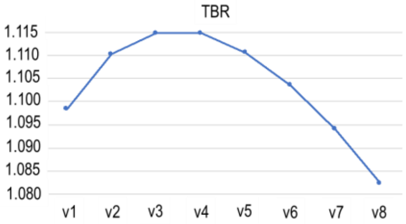






Front & Back zones
CP: 50-25-25% (E97-H2O-Pb)
ACB, Li-6 90%, PF=64%
TBR=1.137

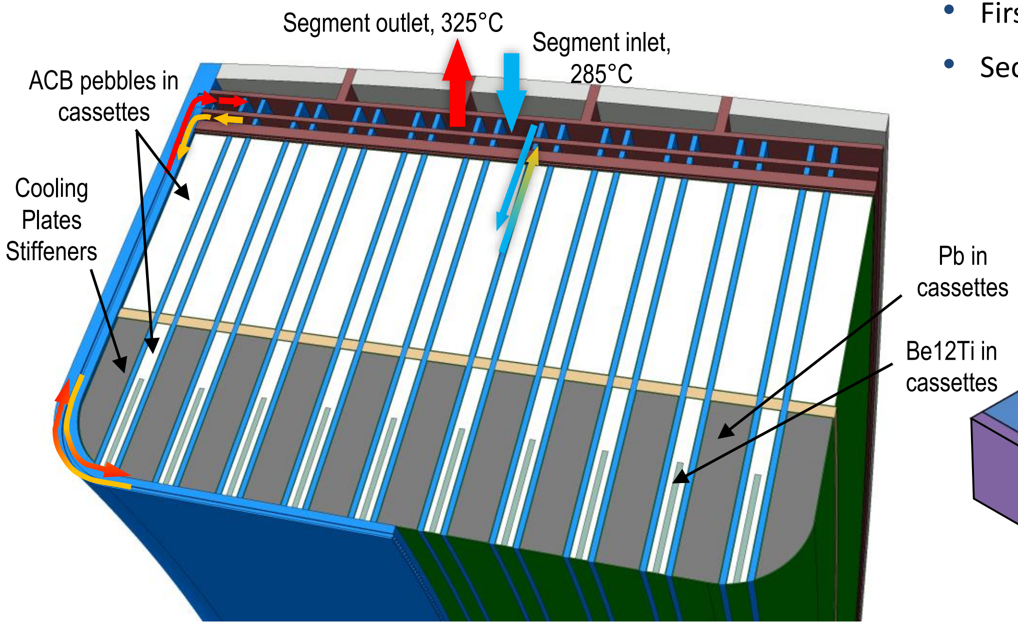
ACB+LOP, Li-6 90%, PF=64%
TBR≈1.168



Rad-pol ACB cassettes
CP: 50-25-25% (H2O-st-Pb)
ACB, Li-6 90%, PF=64%
TBR=1.115

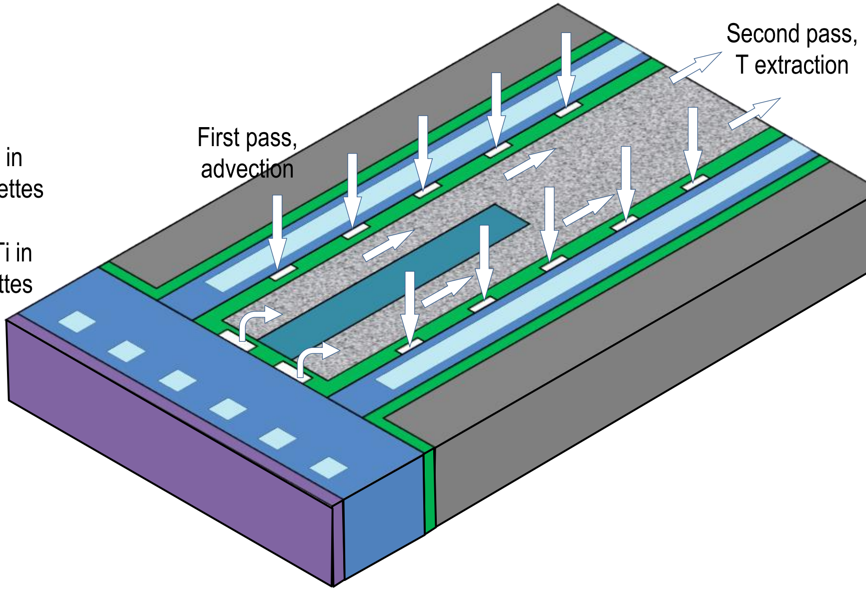
- Conclusions
  - Neutron economy in radial configuration better, more flexible
  - Pb not efficient after 20cm: studies filling it with ACB or mult./reflector
  - Addition of high Li density Li_8PbO_6 ceramics (LOP) in cold (back) BZ region can be key to add margins and/or reduce Li-6 % enrichment

5. WLCB: Maturated conceptual design



WLCB COB, BZR3

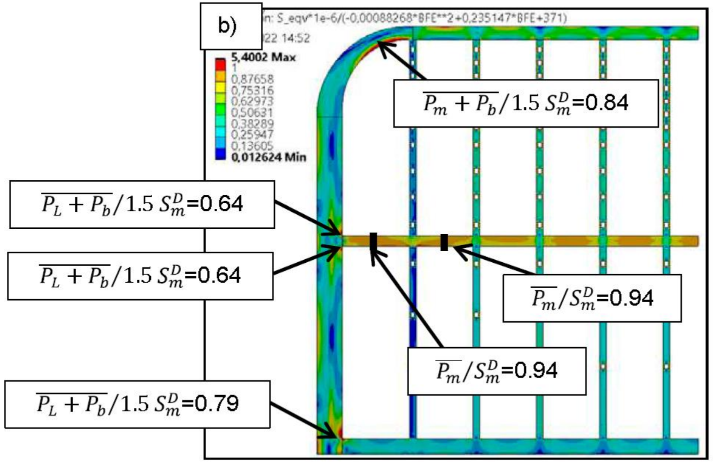
- First pass: high speed purge gas through fins
- Second pass: purge gas low speed sweeping ACB pebble bed

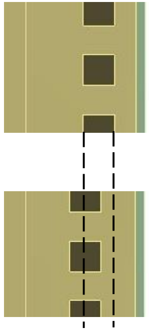


- **Characteristics:**
  - All functional material enclosed in cassettes (no segment pipe for Pb),
  - Finned contact with purge gas flow through interspace: same idea as WCLL-db to mitigate T permeation issue & leak detection method
  - Finned contact may faster pressure relief after in-box LOCA, maybe lower design pressure of the segment
  - R&D need: thermal management of BZ through finned contact needs to be qualified by testing

5. WLCB: Thermo-mechanics und Thermo-hydraulics

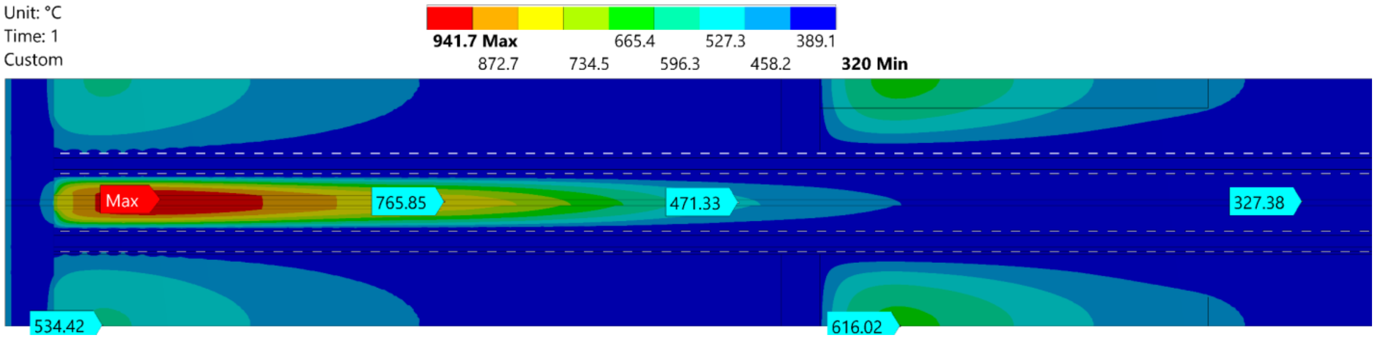
- TM analyses on first WLCB design (tubes)
  - Dimensioning the BZ key structures (CPs, toroidal stiffener), ignore CB tubes
  - Results:
    - (1) Q stress on toroidal SP (NO) and between channels on radial SPs (NO)
    - (2) FW cooling channels (OP): resulting stress exceed the criteria

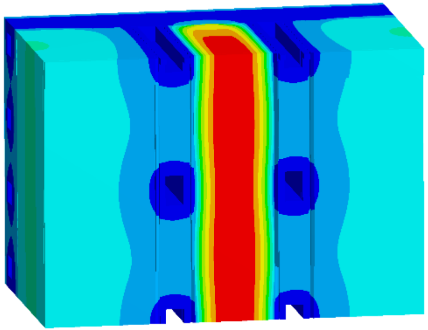




Shift channels 2mm inwards

- Simplified TH on maturated WLCB design (cassettes)





3. The WCLL-db: Reliability analysis

Summary

- Most scenarios show low yearly FR <10^{-2}, but some cases (table below) requires attention
- For first time, a design keeps yearly FR < 10^{-1} for <u>all</u> failure modes => potential to meet availability targets

Failure and element		WCLL-Ref			WCLL-DB			WLCB			Consequence
		FR min [1/y]	FR max [1/y]	Multip.	FR min [1/y]	FR max [1/y]	Multip.	FR min [1/y]	FR max [1/y]	Multip.	
Leak/rupture F/T pipe PbLi		4.91E-02	4.09E-01	416	6.56E-02	5.47E-01	416	N/A			In-VV leak
Leak/rupture of poloidal welds between LiPb-BP and FW		2.57E-01	3.69E+00	72576	N/A			N/A			In-box LOCA
Leak of the LiPb-BP double welds		2.10E+00	2.33E+00	354816	N/A			N/A			In-box LOCA
Leak/rupture of pol. and tor. welds in the LiPb outlet manif.		2.34E+00	3.36E+01	661248	3.03E-04	4.34E-03	64	N/A			Bypass PbLi
Leak/rupture of weld of water pipes with water feed in/out feeder manifold halves	sw	N/A			3.62E-01	5.19E+00	76544	N/A			In-tube LOCA
	dw				3.62E-02	5.19E-01					
Leak/rupture weld of purge gas pipes with purge gas in/out feeder manifold halves	sw	N/A			3.62E-01	5.19E+00	76544	N/A			In-tube leak PbLi
	dw				3.62E-02	5.19E-01					
Leak/rupture of purge gas feeder manifold		N/A			2.78E-01	7.41E+00	11008	N/A			In-tube leak PbLi
Leak/rupture of purge gas chamber in FW		N/A			1.10E+00	2.94E+01	10000	N/A			In-tube leak PbLi
Leak/rupture of purge gas poloidal tubes	ST	N/A			3.62E+00	9.66E+01	38272	N/A			In-tube leak PbLi
	DWT				2.11E-03	3.62E-02					
Leak/rupture weld connection of the manif to the manif. from next breeder zone region	sw	N/A			2.72E-02	3.25E-01	4800	1.97E-02	2.82E-01	4160	In-tube/box LOCA
	dw				2.72E-03	3.25E-02		1.97E-03	2.82E-02		
Loss of structural integrity of the purge gas chamber		N/A			N/A			4.38E-01	4.38E-01	400	In-VV leak p.g.
Leak/rupture of structural weld of water manif. to the water CPs		N/A			N/A			5.75E-02	8.24E-01	12160	In-box LOCA

Outline

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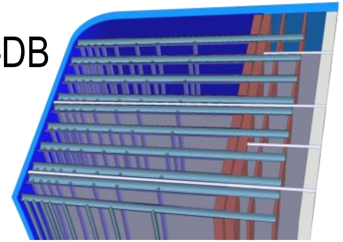
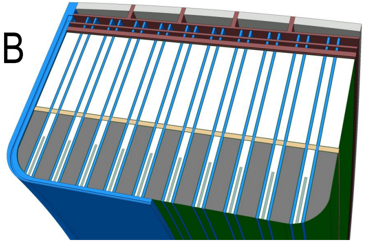
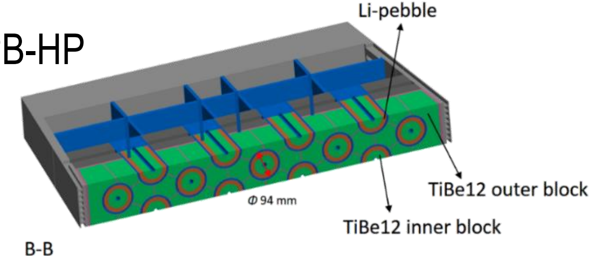
4. Emerging HCPB variant: HCPB-HP
5. Emerging WCLL-HCPB hybrid variant: WLCB
6. **Summary and Outlook**

4. Summary and Outlook

WCLL-DB 

WLCB 

HCPB-HP 

- Summary

WCLL-DB
- First set of NK, TH/TM, T-transport and MHD studies prove potential, improving figures of WCLL
- Reliability not significantly better than WCLL-ref, only improves when DWT (double welds) are introduced

HCPB-HP
- No showstoppers identified for operation at 8 MPa (full segment analyses under VDE ongoing)
- Reliability analyses pending, but in-box LOCA does not exist, it should be a fail-tolerant concept

WLCB
- Decision for cassette configuration: better NK, feasible TH/TM, similar T-transport as WCLL-db
- For first time, a blanket concept scores 10^{-1} yearly failure frequency

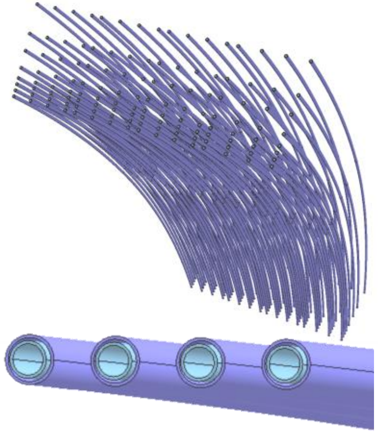
- Outlook:
  - Introduction of the WCLL-DB in the baseline, later in the year also WLCB
  - High pressure purge gas setting to become a reference for HCPB
  - Optioneering among WCLL-ref, WCLL-DB and WLCB for future reference selection

Backup slides

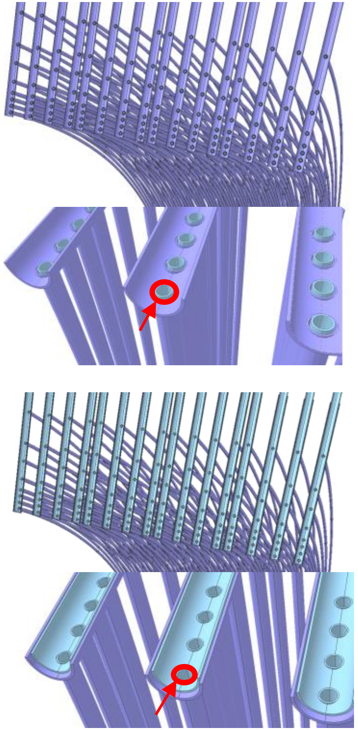
Summary 2021: Manufacturing and Assembly

Why is this important so early?

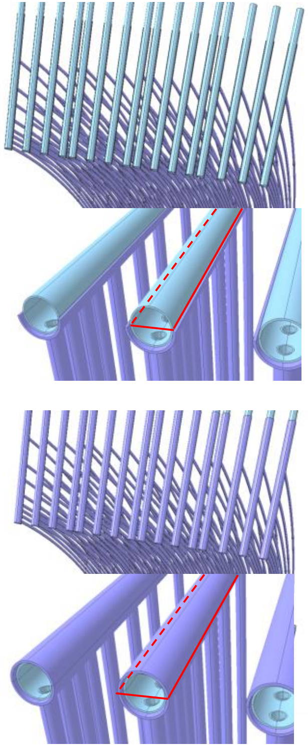
- Design for manufacturability
- Understanding architecture and estimation of number of welds is essential for RAMI analyses



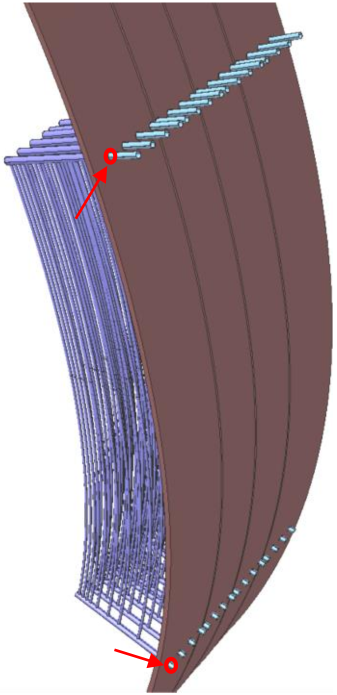
1. Manufacturing of double bundle tubes (planar curvature)



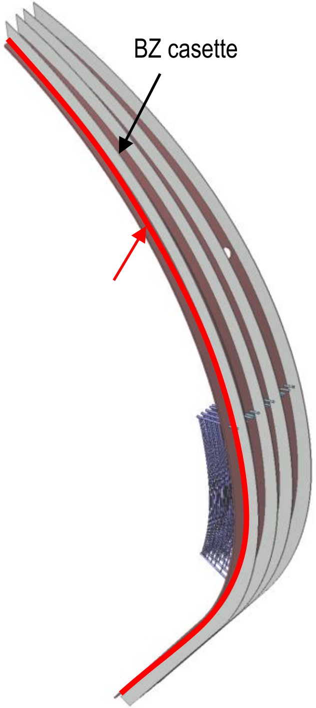
2. TIG/laser weld of double bundle tubes feeders halves



3. TIG/laser weld of feeders halves



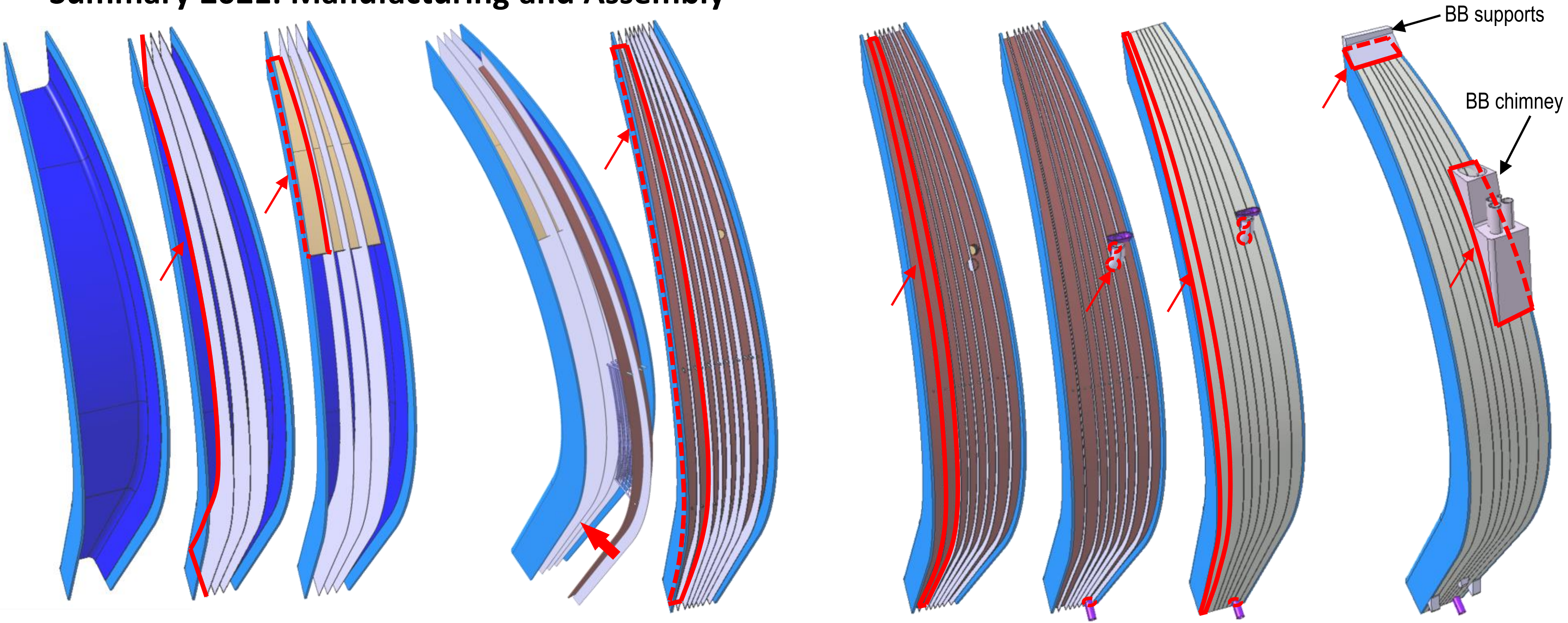
4. Orbital TIG weld of feeders to 1st BB manifold backplate to produce BZ cassettes



5. TIG weld of manifold stiffeners

3. Exploring variants: WCLL "double bundle"

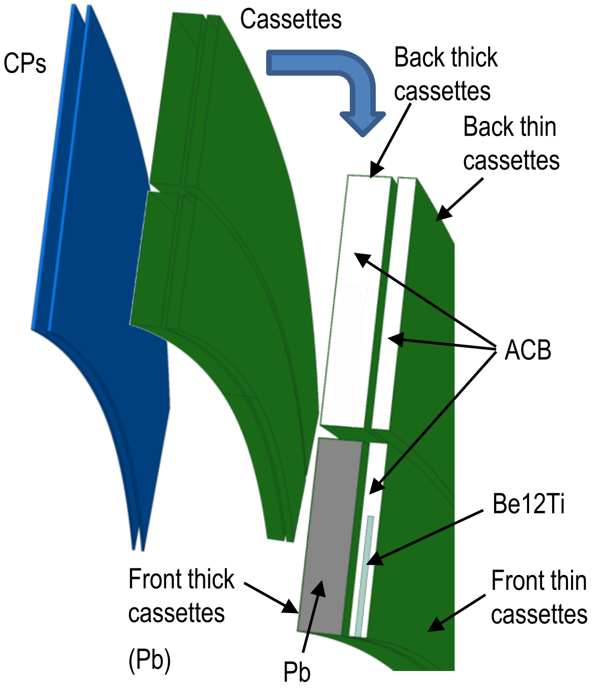
- **Summary 2021: Manufacturing and Assembly**

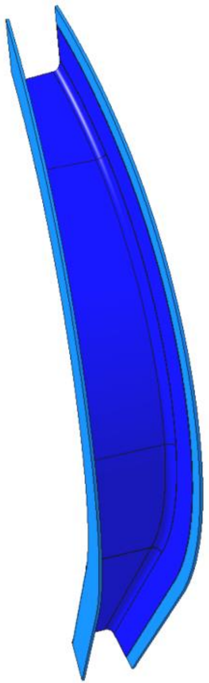


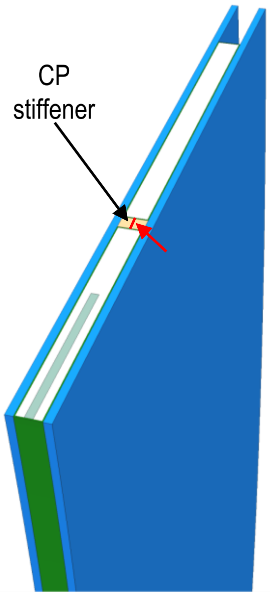
8. FW and caps production and assembly, with gas gap chamber and TIG/laser weld of stiffening plates (shown as continuous plates, but continuity not necessarily needed)
9. Insertion of BZ cassettes and TIG/laser weld to FW+caps assembly
10. TIG/laser weld of back manifolds, inlet and outlet segment pipes
11. Chimney and segment supporting structures assembly TIG weld

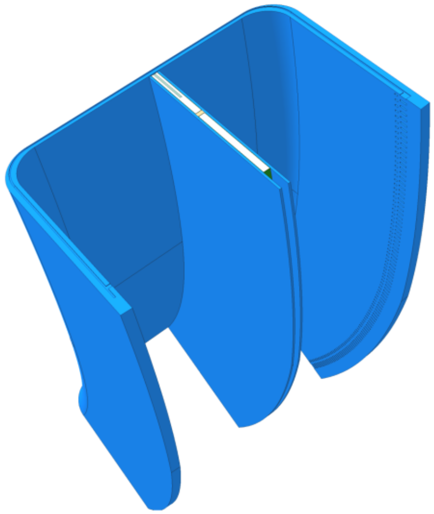
WLCB: Manufacturing considerations

- Manufacturing and assembly sequence





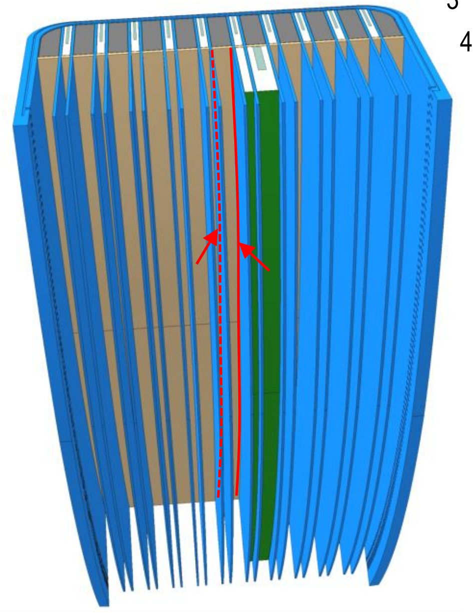




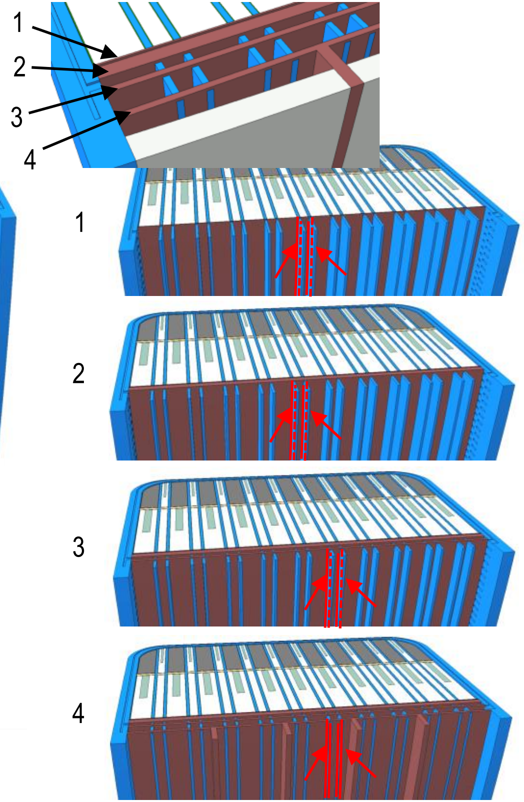
1. Production of BZ elements:
   - Production of CPs and cassettes
   - Production of ACB and NMM
   - Cassettes filling
2. Production of FW in 5 parts and TIG/laser weld of caps (not shown)
3. EB weld of CP thin stiffener of adjacent CP, insertion of thin front and back cassettes
4. Weld of CP with thin cassettes to FW

WLCB: Manufacturing considerations

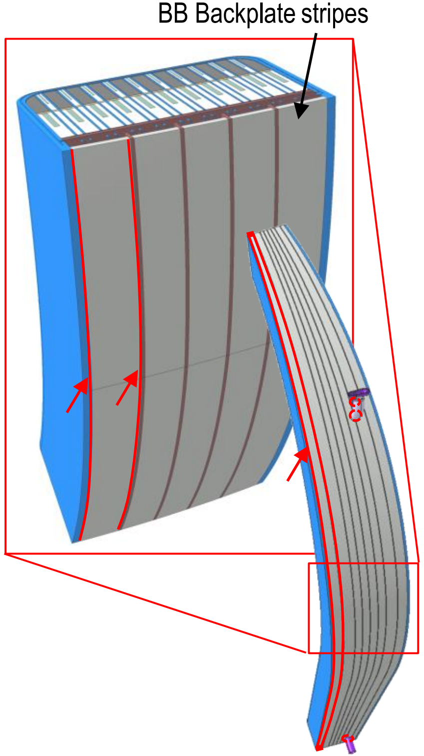
- Manufacturing and assembly sequence



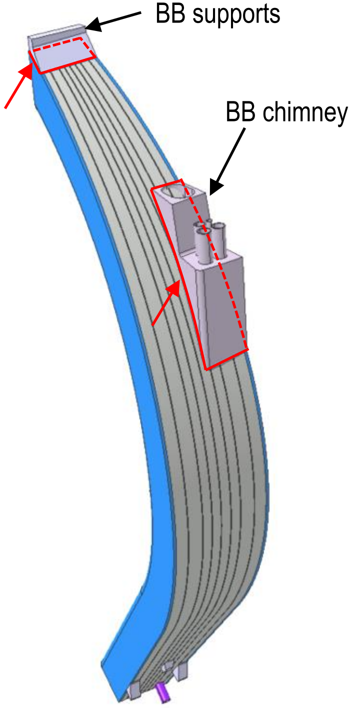
3. Insertion of front thick cassettes, weld of thick stiffener stripes and insertion of back thick cassettes



4. Insert and weld manifold plates. Only welds in 4 act against in-box LOCA.



5. TIG/laser weld of BB backplates to manifold stiffeners, FW & caps. Welds act against in-VV LOCA



6. TIG weld of chimney (welds act against in-VV LOCA) & BB supports to BB backplate.

WLCB: Relevant infos for reliability analyses

- Preliminary design specifications (v1.1, Pb also in cassettes, **preferred option**)

Component	COBS	LOBS/ROBS	LIBS/RIBS	Reactor total
FW	1	1	1	(1 x 3 + 1 x 2) x 16 = 80
FW channels	15000 / 24 = 625	15000 / 24 = 625	15000 / 24 = 625	625 x 5 x 16 = 50000
CP channels[a]	20 x 5 x 8 = 800	20 x 5 x 8 = 800	14 x 5 x 8 = 560	(800 + 2 x 800 + 2 x 560) x 16 = 56300
~~Welds against p.g leak in Pb~~[b]	~~(11 + 33) x 5 = 220~~	~~(11 + 33) x 5 = 220~~	~~(8 + 24) x 5 = 160~~	~~(220 + 2 x 220 + 2 x 160) x 16 = 15680~~
Welds against in-box LOCA[c]	(20+5) x 5 = 125	(20+5) x 5 = 125	(14+5) x 5 = 95	(125 + 2 x 125 + 2 x 95) x 16 = 9040
Welds against in-VV LOCA[d]	5 + 2 + 5 = 12	5 + 2 + 5 = 12	3 + 2 + 5 = 10	(12 + 2 x 12 + 2 x 10) x 16 = 896

[a]CP channels 20 x 5 x 8 = 800

20 = number of CPs in a BZR
5 = number of BZR
8 = number of cooling channels per CP (assuming a reasonable water speed of <4m/s, channels could be halved to get a max. water speed of ≈7m/s)

[b]~~Welds against p.g leak in Pb~~ ~~(11+11+20) x 5 = 210~~

~~11 = welds of BZ stiffeners to CPs at Pb region~~
~~33 = welds of adjacent CP collectors & distributors & CP poloidally at FW front side~~
~~5 = number of BZR~~
In this version there are no such welds because Pb is confined in cassettes

[c]Welds against in-box LOCA (20+5) x 5 = 125

20 = countour welds of CPs
5 = 1 external contour of backplate + 4 separation between BZR
~~20 = welds of adjacent CP collectors & distributors~~
5 = number of BZR

[d]Welds against in-VV LOCA 5 + 2 + 5 = 12

5 = poloidal closure stripes forming the back plate
2 = caps
5 = FW BZR

WCLL-db: Summary

Basic preliminary design specifications

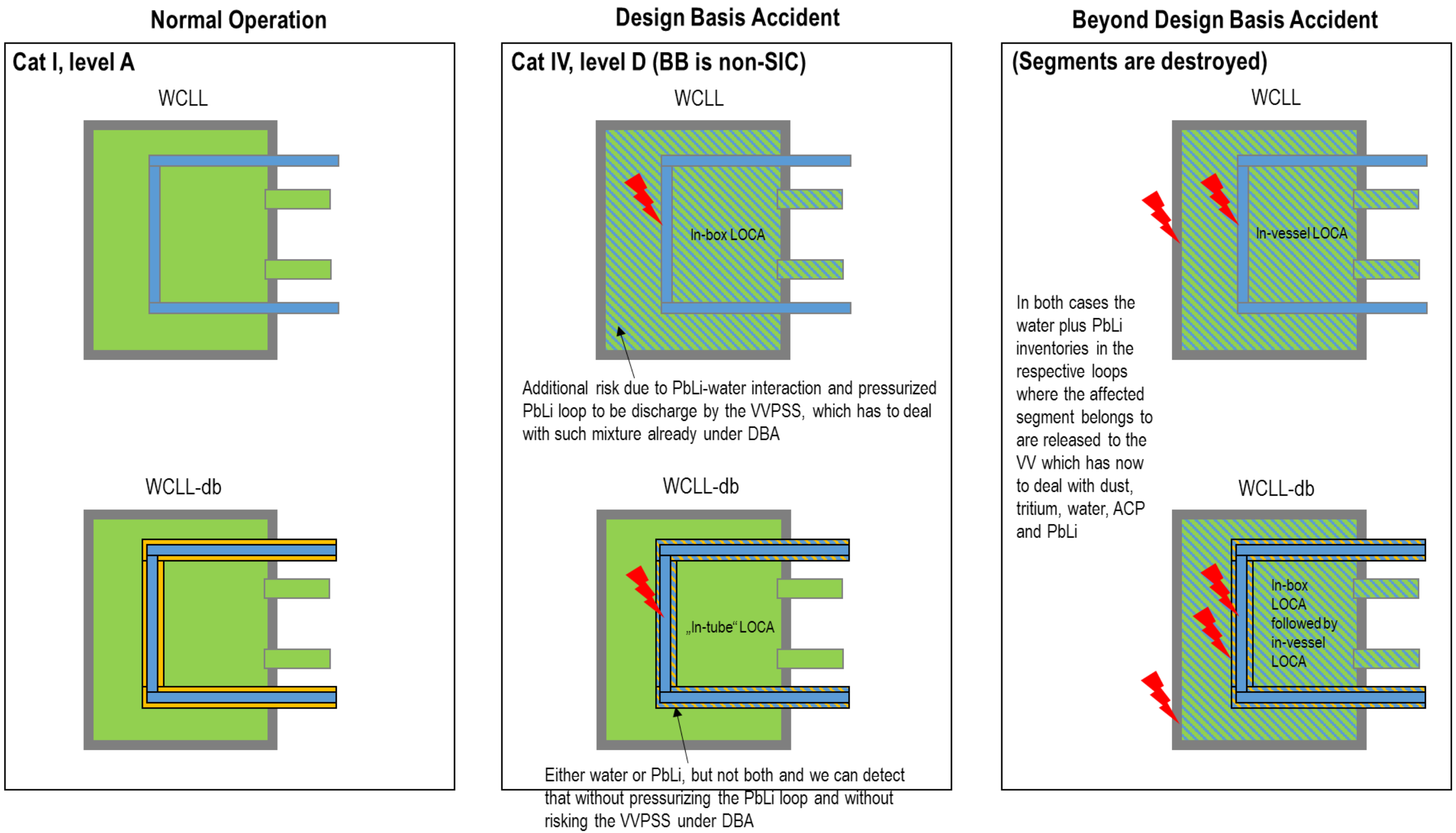
	WCLL-db
Coolant operating temperature [°C]	285 – 325
Coolant operating pressure [MPa]	15.5
Plant coolant mass flow [kg/s]	7450
Plant purge gas mass flow [kg/s]	0.5
Coolant feeding pipes, OB	Inlet: 1x DN200 Outlet: 1x DN200
Coolant feeding pipes, IB	Inlet: 1x DN200 Outlet: 1x DN200
Purge gas feeding pipes	Inlet: 1x DN80 Outlet: 1x DN80
~~Pb feeding pipe~~	~~TBD~~ ~~(Tentative 1x DN80)~~
Number of BZR per segment	5
Number CPs	≈ 7040
Number coolant feeding pipes	≈ 160
Number purge gas feeding pipes	≈ 160
Reactor inventory CB (ACB / mix ACB & Li8PbO8)	539.2 / 1772.8 ton
Reactor inventory Be12Ti	53.2 ton
Reactor inventory Pb	2470 ton
Reactor inventory Steel	2978 ton

Inventory does not take into account cut outs in segments. These can be significant specially at the OB (average whole BB -10%)

Segments inventory [ton]			
Material	**COB**	**ROB/LOB**	**RIB/LIB**
CB (KALOS / mix ACB & Li8PbO8)	8.5 / 28	7.4 / 24.4	5.2 / 17
Be12Ti	0.85	0.74	0.52
Pb	39	34	23.7
Steel	47	41	28.6
Total (per segment)	**95.4 / 114.9**	**83.1 / 100.1**	**58.0 / 69.8**

3. Exploring variants: WCLL “double bundle”

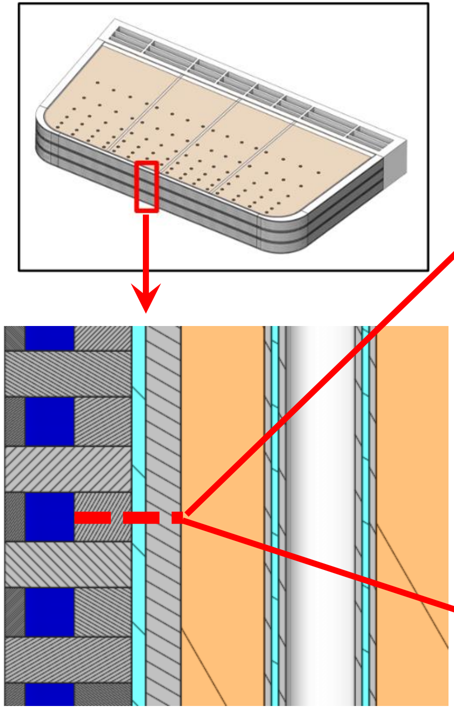
- **Initial work 2022: Workshop with Safety Office on WCLL-DB vs. WCLL Safety and Licensing Case**

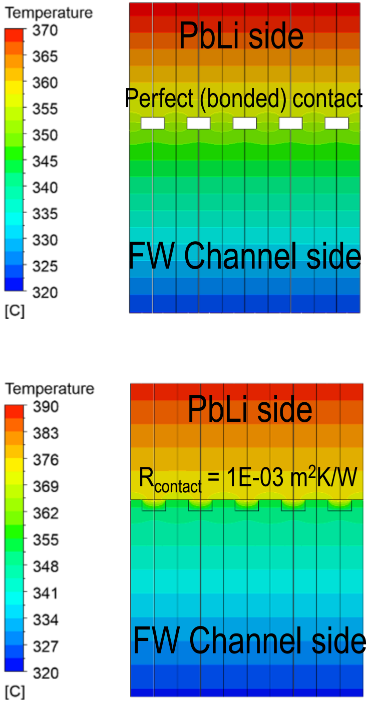


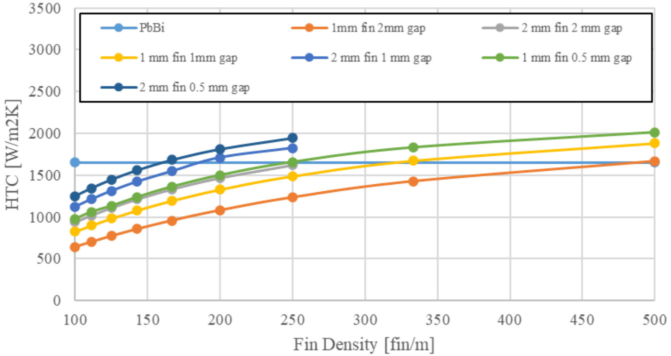
TH of WCLL-db with gas gap

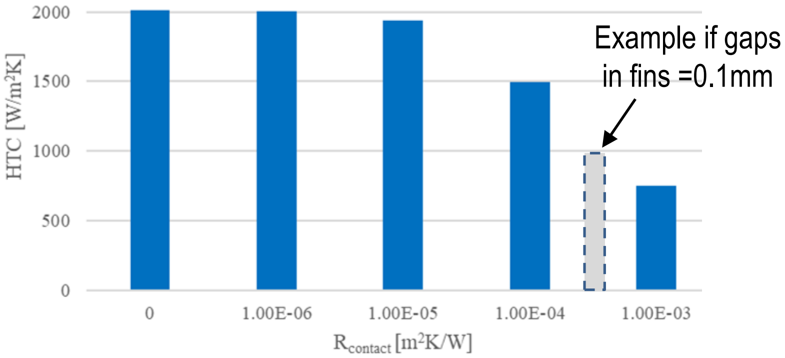
DES-ENG.MECHENG.MECHAN-T002
(P.A. Di Maio)

- Parametric study on HTC_{global} for the FW interlayer changing fin density and density and gap thickness
- Each HTC_{global} compared to the case with PbBi, He interlayer assumed adiabatic
- Sensitivity analysis also to evaluate the thermal contact resistance, considering the presence of He mitigating the HTC reduction.



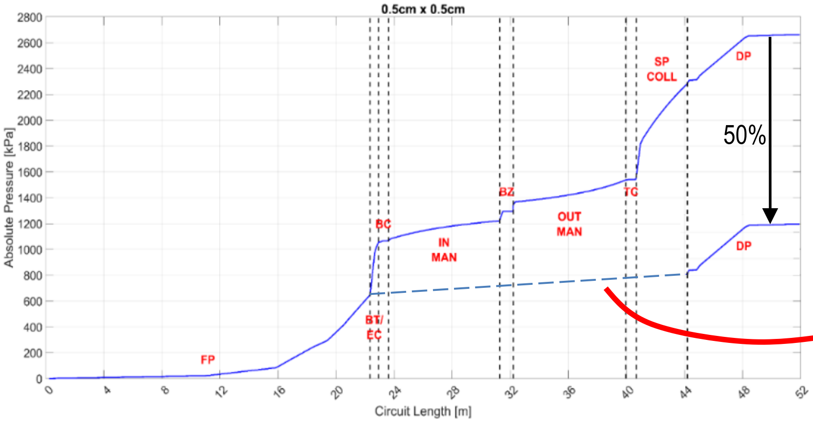


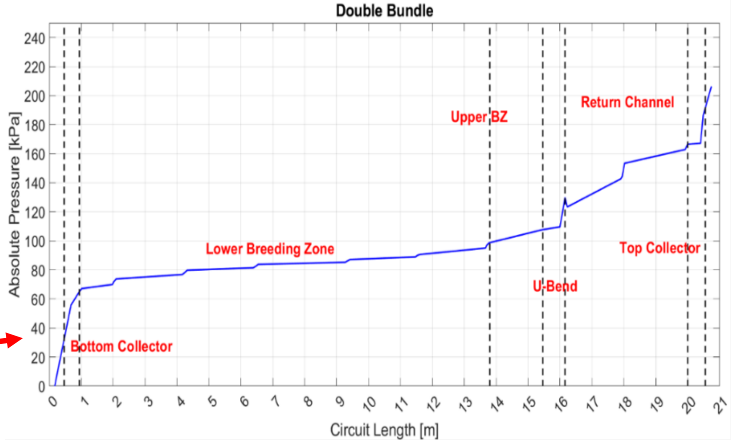


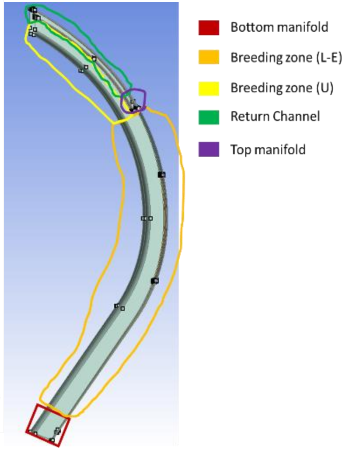


MHD of WCLL-db

DES-FS.BB.S-T002 (A. Tassone)







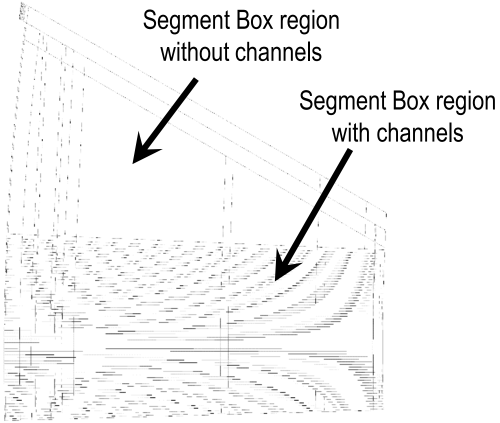
- Methodology
  - $\Delta p_{MHD} = \Delta p_{2D} + \Delta p_{3D}$ semi-emp. correlation + RELAP5 benchmark
  - PbLi flow: bottom + BZ (Low-Eq, upper, return) + top manifold
- Assumptions
  - Only toroidal field, no EM coupling between channels
  - Hydrodynamic friction and concentrated losses neglected, $T_0 = 600$ K
  - No effect of Δp due to streamwise obstacles (tubes)
- Outcome
  - $\Delta p_{WCLL-db} \approx 0.1\ \Delta p_{WCLL-db}$, R5 and correl. good agreement (ε ≈ 3%)

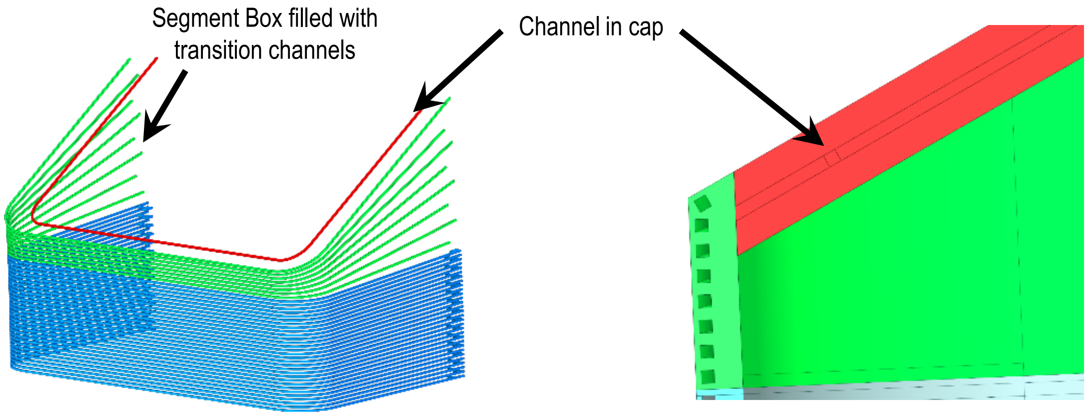
	WCLL-db	WCLL-db RELAP5*	WCLL [1]
Total Δp [kPa]	151.5	156.0	1512.0

*Reference side channel for WCLL-db
[1] 2022 WCLL Design Team Meeting

5. WLCB: Caps Thermo-mechanics

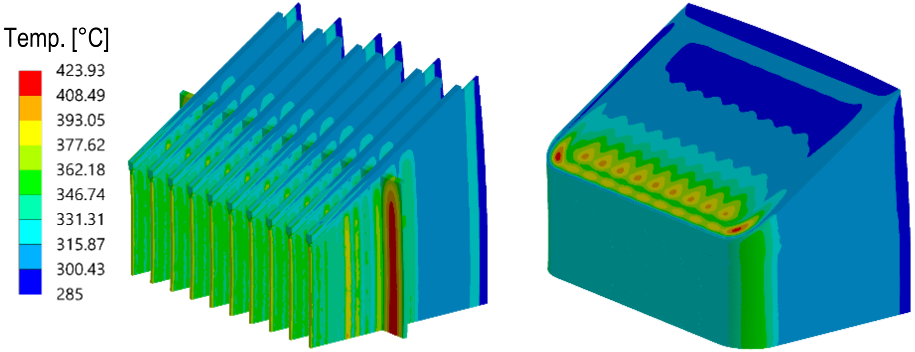
- Design of a feasible WLCB cap
  - Caps: segment endings close to ports
    - Historically problematic due to non-smooth transition of poloidal to radial plates with different thickness requirements and difficulty to place stiffeners => large bending stresses and stress concentration
  - 3D FEM set-up and tested, temperature dependent material properties
  - Coolant flow (CPs and Seg. Box in series) modelled with ANSYS «thermal fluids» feature
    - automatically calculating the mixing temperatures in the CPs collectors and Seg. Box inlet manifold.
    - Iterative approach has allowed characterizing the fluid to obtain the Seg. Box outlet coolant average temperature in the whole BZR1 equal to ~325 °C, integrating analysis results with analytical estimations.

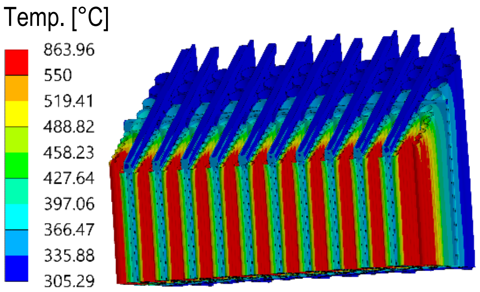


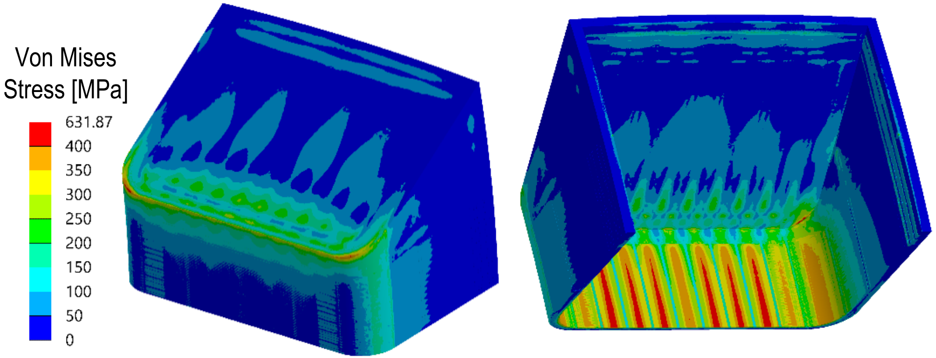


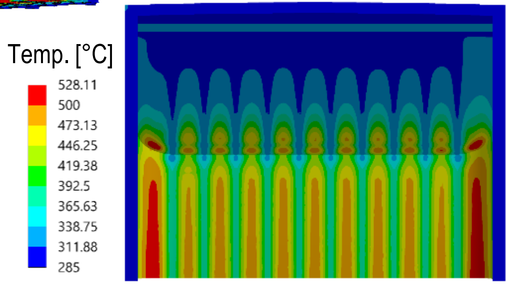
5. WLCB: Caps Thermo-mechanics

- Thermal field
  - Structural elements (CP and Seg. Box) below limits
  - BZ: temperatures beyond 550°C within ACB tubes
  - Revision of BZ needed after neutronics work finishes
- Stress field
  - TM analyses in normal operation and over-pressurization (17.8 MPa)
  - RCC-MRx criteria fulfilled with large margins in segment box and top cap, problematic regions limited to collectors and manifold









3. Exploring variants: WCLL "double bundle"

- **Initial work 2022: Safety and Licensing Case, Workshop with Safety Office**
  - Fundamental safety aspects of WCLL-DB vs. WCLL
    - DB interlayer can be used as monitoring point for leaks, early detection => safety characteristic to bring plant to safe state
    - LBB principle: Small LOCA leak detected before larger LOCA (this may help for event categorization, i.e. small vs. Large LOCA)
    - „In-tube" LOCA avoids H_2O + PbLi and PbLi loop pressurization + release to VVPSS regardless of the break size under DBA
    - DB: 2-layer redundant system (WCLL also a 2-layer redundant system, 2nd layer is the box itself) => rupture of the DB or box are extremely unlikely events => currently not postulated

- **2021 and 2022: Workshops with WPBB and implementation of feedback**
  - Points regarding safety considerations
    - WCLL-DB based on assumption that „DB" excludes LOCA, but not been demonstrated
      - „DB" failure would be a common failure mode of a redundant system: if working with PbBi as interlayer, after in-tube LOCA water contacts PbBi and series of pressure pulses will occur => this triggers series of pressure waves in PbBi that may overcome water pressure => „DB" failure => in-box LOCA in DBA possible => DB design assumption invalid, *but…*
      - If interlayer empty (i.e. gas) => interlayer pressure = coolant pressure, no pressure waves => possible solution
    - Inner tube breaks, banging/whipping against outer tube occurs => „DB" failure
      - With gas gap, fins are necessary => whipping mitigated

On Li8PbO6

journal J. Am. Ceram. Soc., 73 [6] 1710–13 (1990)

Investigation of Lithium Diffusion in Octalithium Plumbate by Conductivity and NMR Measurements

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Toru Matsuo
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Diffusion of lithium ion and tritium in octalithium plumbate (Li_8PbO_6) was studied. The electrical conductivity of the polycrystalline pellets measured by the two-terminal ac method in the temperature range of 300 to 973 K was one of the highest among oxide lithium ceramics. The temperature dependence of the conductivity is consistent with the nuclear magnetic resonance of lithium-7 powder samples, suggesting that the temperature dependence of the diffusion of lithium consists of three regions in this temperature range. Preliminary measurements of the diffusion coefficient of tritium in neutron-irradiated Li_8PbO_6 powder were also carried out. The resu[...] and the [...]

II. Experimental Procedure

(1) Sample Preparation

Samples of Li_8PbO_6 were sythesized by the solid reaction between Li_2O and PbO_2. Powders of Li_2O and PbO_2 were mixed at a ratio of 4 to 1 and agglomerated in dry argon atmosphere in a glovebox. The appropriate powder was pressed into cylindrical pellets of 6-mm diameter with a hydrostatic press at a pressure of 1.2 ton/cm². These pellets were loaded into a platinum crucible and were heated at 873 K in a dry oxygen stream for several hours. Reaction and sintering took place at the same time, and slightly yellowish sintered pellets

60 Journal of Nuclear Materials 170 (1990) 60–65
North-Holland

TRITIUM RELEASE BEHAVIOR FROM NEUTRON-IRRADIATED Li_8PbO_6

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Received 21 April 1989; accepted 1 August 1989

Chemical behavior of tritium produced in octa-lithium plumbate (Li_8PbO_6) crystals by the $^6Li(n, \alpha)T$ reaction has been investigated. Nearly 100% of the tritium in the crystals existed in the T^+ state. When the neutron-irradiated crystals were heated up to 1073 K under vacuum, almost all the tritium released in the chemical form of tritiated water (HTO(g)). The HTO(g) release rate was controlled by diffusion of tritium (T) in the crystals and the diffusion coefficient (D) determined in the temperature range from 580 to 670 K was

$$D = 1.1\times10^{-4} \exp\{-75.5(\text{kJ mol}^{-1})/RT\} \quad \text{cm}^2\ \text{s}^{-1}.$$

The observed tritium diffusivity in Li_8PbO_6 was the largest of the lithium-based oxide ceramics previously reported. This coincides with the fact that the diffusivity of lithium ion in crystals was the largest of these ceramics.

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Octalithium plumbate as breeding blanket ceramic: Neutronic performances, synthesis and partial characterization

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ABSTRACT

A neutronic assessment of the performances of a helium-cooled Li_8PbO_6 breeding blanket (BB) for the conceptual design of a DEMO fusion reactor is given. Different BB configurations have been considered in order to minimize the amount of beryllium required for neutron multiplication, including the use of graphite as reflector material. The calculated neutronic responses: tritium breeding ratio (TBR), power deposition in TF coils and power amplification factor, indicate the feasibility of Li_8PbO_6 as breeding material. Furthermore, the synthesis and characterization of Li_8PbO_6 by X-ray phase analysis are also discussed.

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First principles review of options for tritium breeder and neutron multiplier materials for breeding blankets in fusion reactors

F.A. Hernández, P. Pereslavtsev

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Abstract

The current breeding blankets proposed in the different conceptual fusion power plants are based mainly on the use of Li_4SiO_4 and/or Li_2TiO_3 as tritium breeder and $Be/Be_{12}Ti$ as neutron multiplier or an eutectic $Li_{17}Pb_{83}$ for as a hybrid tritium and