Italian National Agency for New Technologies, Energy and Sustainable Economic Development

International Atomic Energy Agency
Technical Meeting on Tritium Breeding Blankets and Associated Neutronics

Current status and perspectives on DEMO WCLL BB design activities

IAEA Technical Meeting on Tritium Breeding Blankets and Associated Neutronic
Vienna, September 2nd – 5th, 2025

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EUROfusion
POWER PLANT PHYSICS & TECHNOLOGY DEPARTMENT

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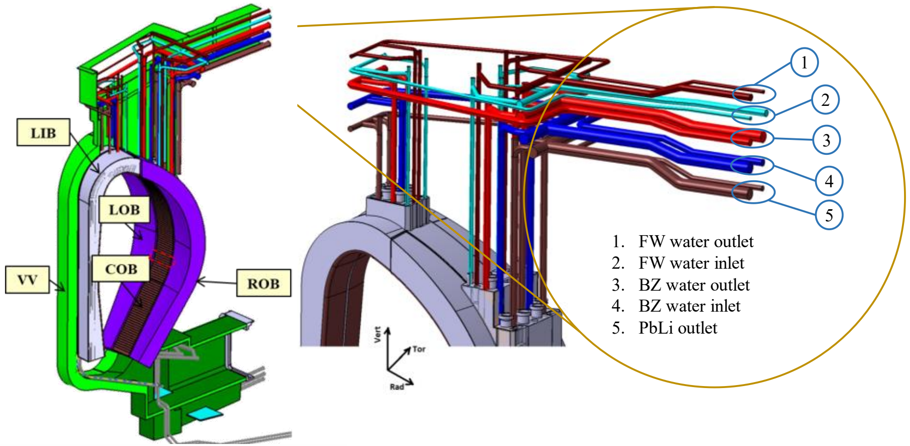
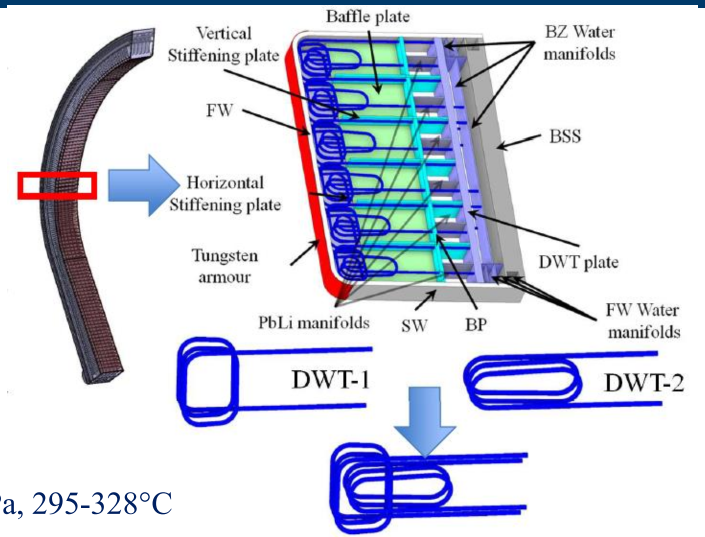
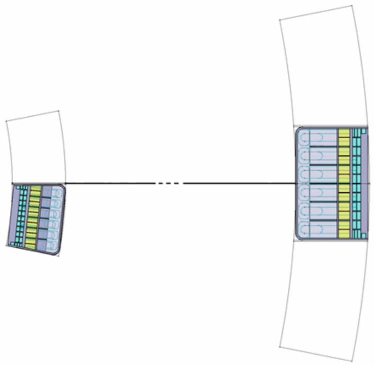
Outline

- WCLL BB architecture
- WCLL TER architecture
- Neutronic analyses
- Tritium transport simulations
- Thermo-hydraulic analyses
- Thermo-mechanical analyses
- Structural analyses
- MHD analyses
- Manufacturing activities
- Other simulations and experiments

WCLL BB architecture

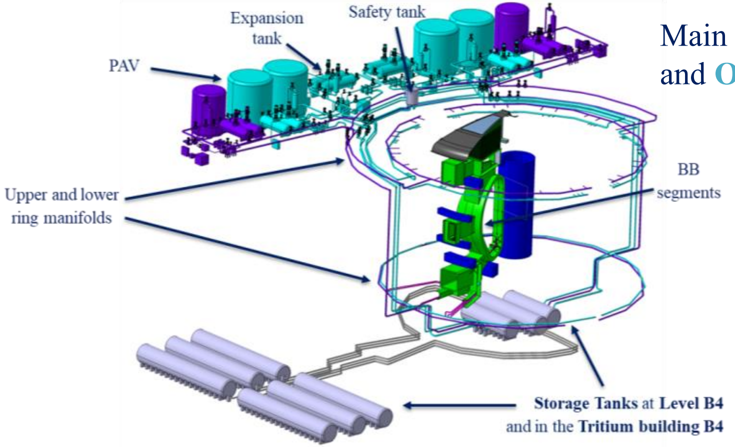




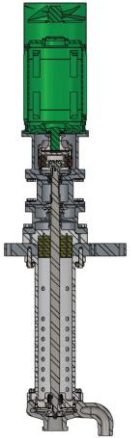


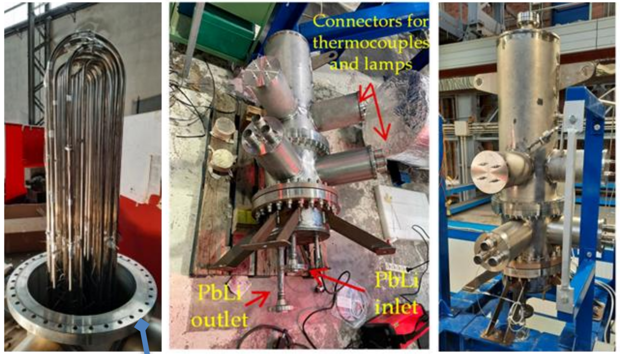
- ❑ Water in PWR conditions as coolant: 15.5 MPa, 295-328°C
- ❑ Dedicated water coolant circuits for FW (channels) and BZ (DWTs)
- ❑ Eutectic PbLi alloy as neutron multiplier (Pb), tritium breeder (6Li at 90% enrichment) and tritium carrier
- ❑ Single segment structure with elementary cell approach
- ❑ Eurofer as structural material, Tungsten coating in plasma facing surfaces

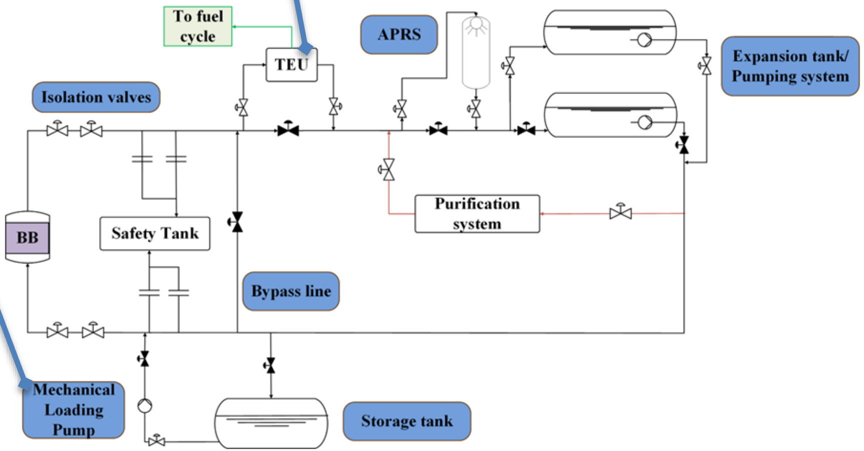
WCLL TER architecture



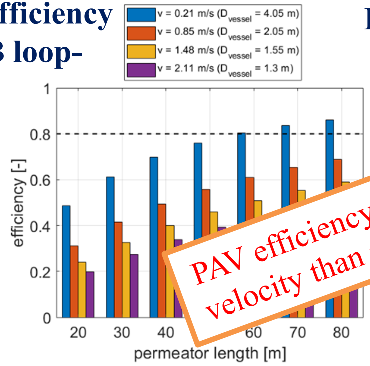
Main components of **Inboard** and **Outboard** loops (at L3)



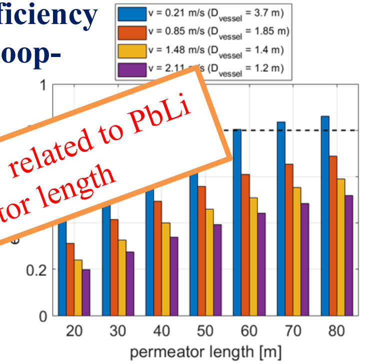




PAV efficiency -OB loop-

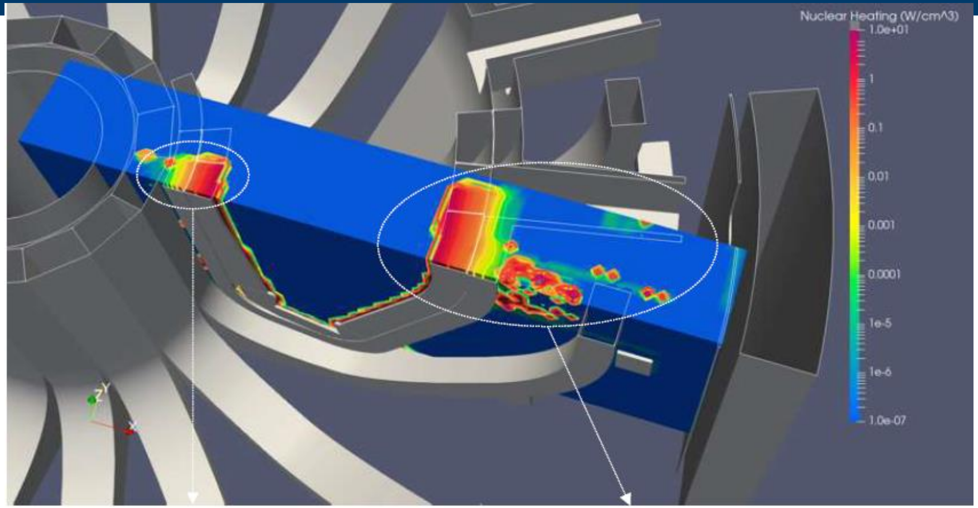


PAV efficiency -IB loop-

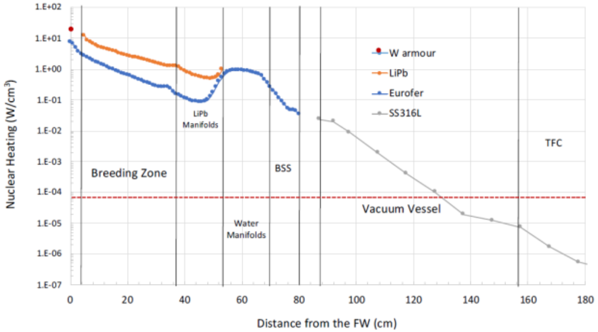


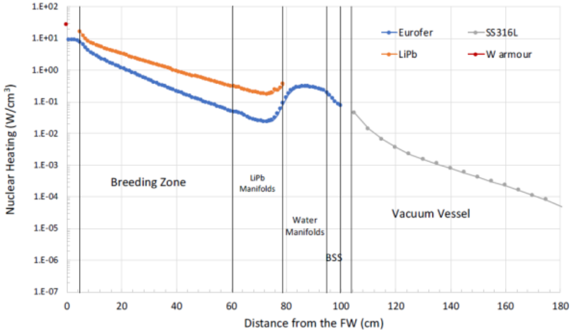
PAV efficiency mostly related to PbLi velocity than permeator length

Neutronic analyses 1/2

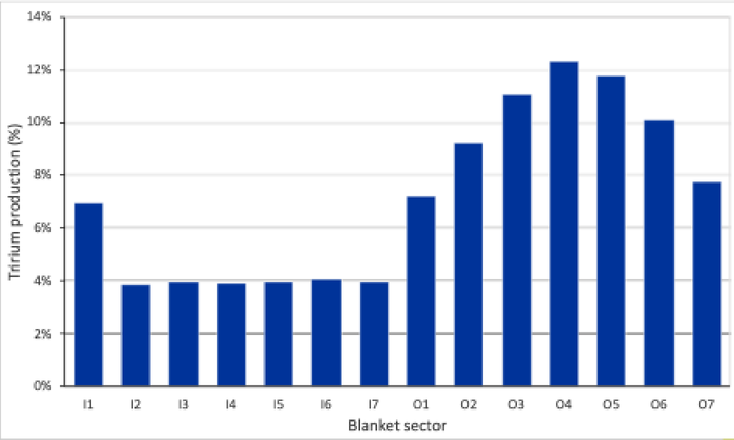


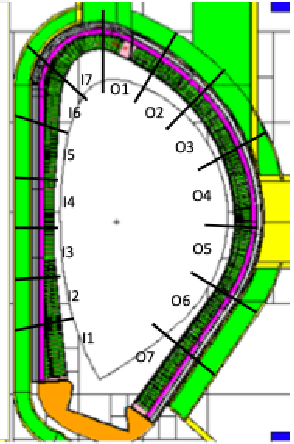
- Nuclear analysis performed on a fully heterogeneous model set-up with MCNP5v1.6 Monte Carlo code
- Nuclear quantities as nuclear heating, neutron fluxes, tritium generation rate, He generation and damage (dpa) calculated
- Shielding requirements on TFC (109 n/cm^{2}s) and Vacuum Vessel (5·10-5 W/cm^3) fully satisfied
- Tritium Breeding Ratio (TBR) slightly increased from 1.14 to 1.142, closer to the target value of 1.15



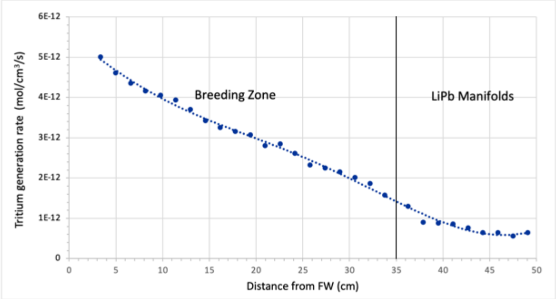


Neutronic analyses 2/2

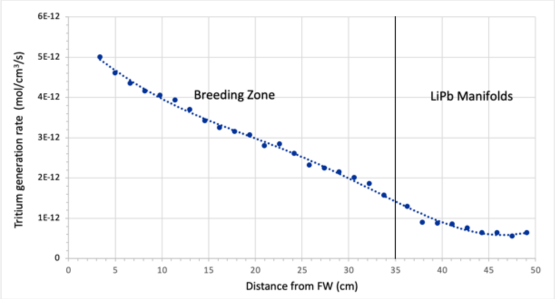




- IB & OB TGR radial profiles @ equatorial BUs, show similar behaviour with a maximum behind the FW ($5 \cdot 10^{12}$ mol/cm^3/sec vs 5.5 mol/cm^3/sec) and constant reduction of the TGR along BZ and LiPb manifold
- TGR poloidal profile on BZ only, shows most of the Tritium is produced in the Outboard sector, with a peak on OB4 due to harder neutron spectrum impinging on the equatorial outboard
- Sensitivity analyses on TBR vs BZ DWTs location: analyses confirm that a 15 mm radial displacement allows to achieve the TBR design target (1.15)



IB equatorial BU

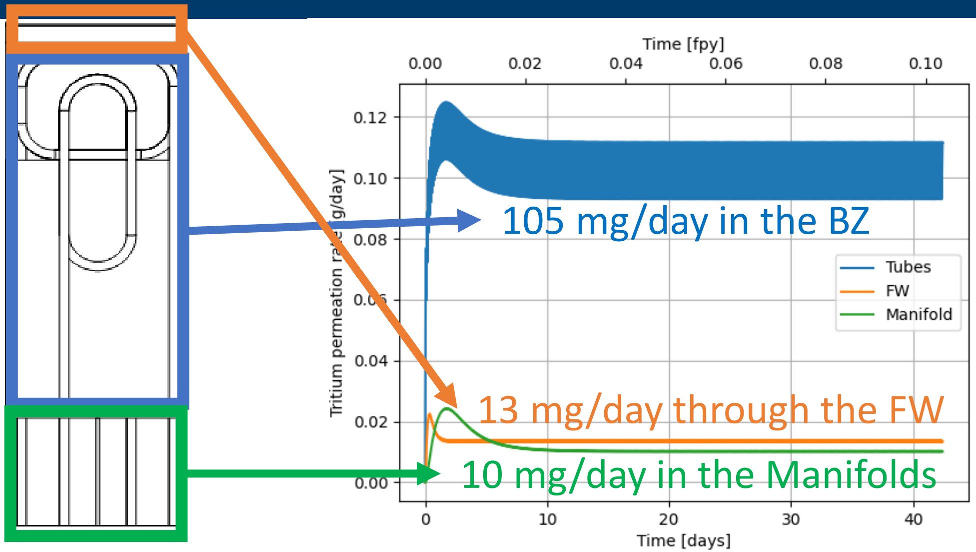


OB equatorial BU

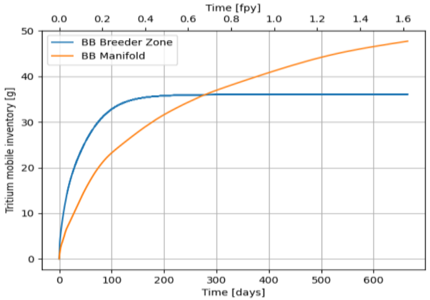
BZ cooling pipes radial shift [mm]	Total TBR [-]
0	1.142
5	1.144
10	1.147
15	1.5
20	1.155

Tritium transport simulations

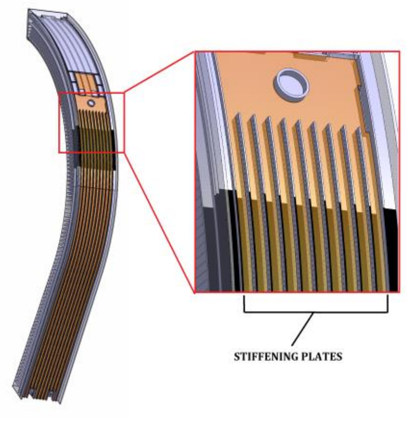
Parameter	Value
Blanket T generation rate [g/day]	320.26
In-vessel PbLi volume [m³]	878.56
Ex-vessel PbLi volume [m³]	508.84
Total PbLi mass flow rate [kg/s]	954
In-vessel water volume [m³]	195.31
Ex-vessel water volume [m³]	324.29
Total water mfr[kg/s]	9936
Permeation surface in OB slice [m²]	1.4
PRF in wetted surfaces [-]	100
TES extraction efficiency [%]	80
CPS extraction efficiency [%]	$6.58\ 10^5$

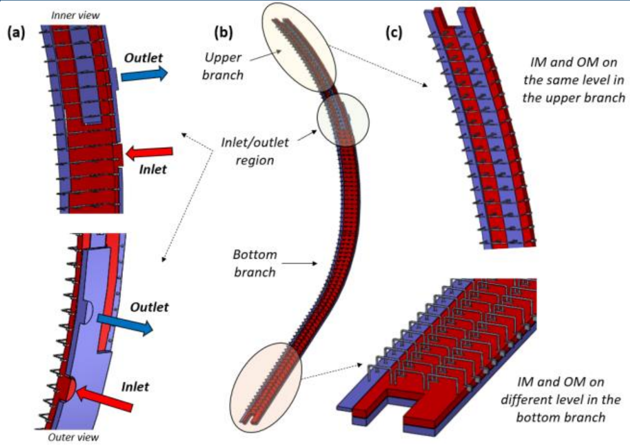


- Tritium transport models at system level developed with EcosimPro to study effect of the helical tube-layout and manifold arrangement
- 3-trap model featuring two high energy traps were adopted
- Smaller permeation surface and colder PbLi temperature reduced tritium permeation rates from PbLi to water of a factor 2.2. Similar trend observed in the FW, reduction of a factor 1.33 calculated
- Trapped inventories (~100g) are highly dependent on high energy trap density and hydrogen dynamics. Hydrogen competes with Tritium to fill the traps

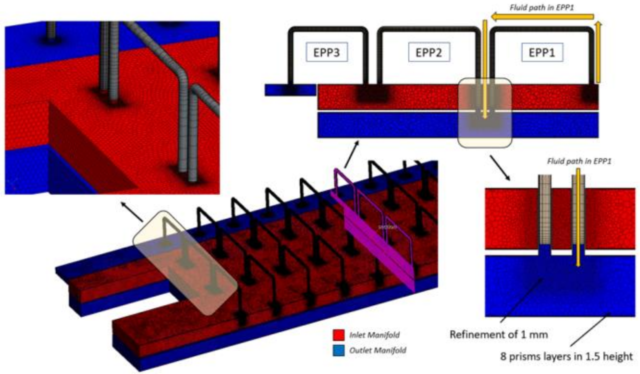


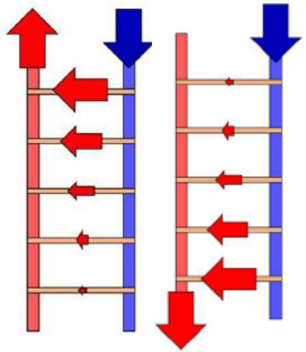
Thermo-hydraulic analyses: Segment



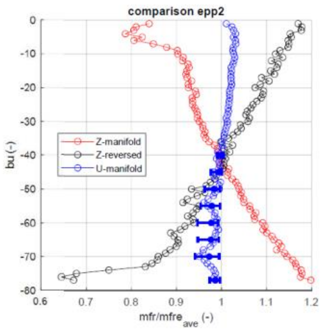


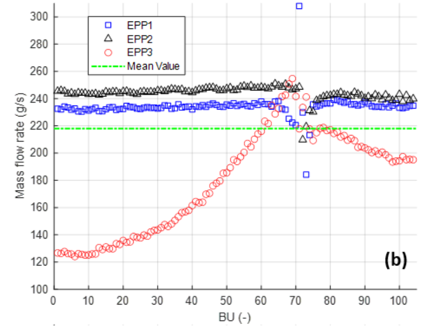
- Original layout (Z-manifold) led to un-even mass flow distribution along the poloidal abscissa.
- The new U-manifold improve the flow distribution in the BUs
- Different CFD sensitivity analyses were performed to evenly distribute the BZ inlet water at the different cells (EPP1, EPP2, EPP3)
- Further numerical work is needed to better calibrate EPP3 water mass flow rate



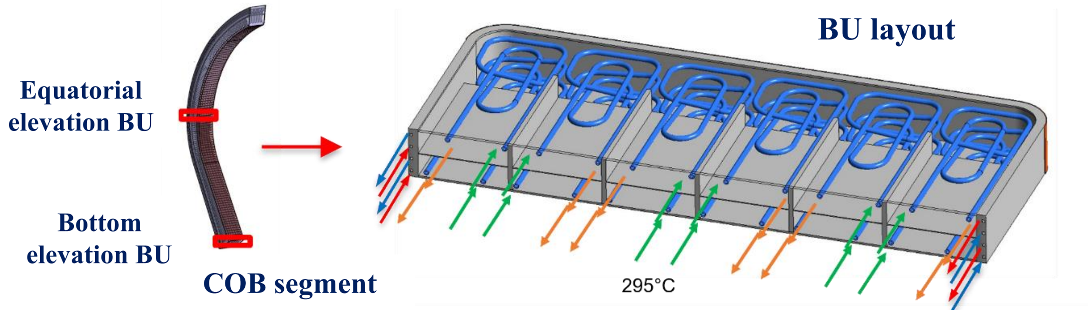


U-manifold Z-manifold

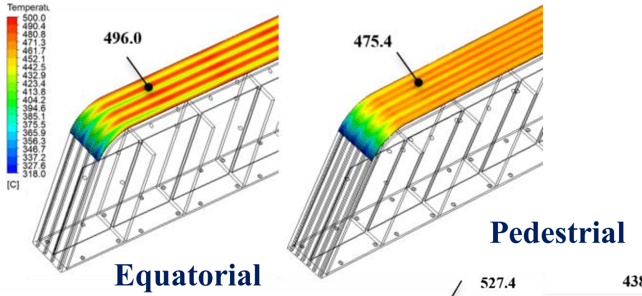




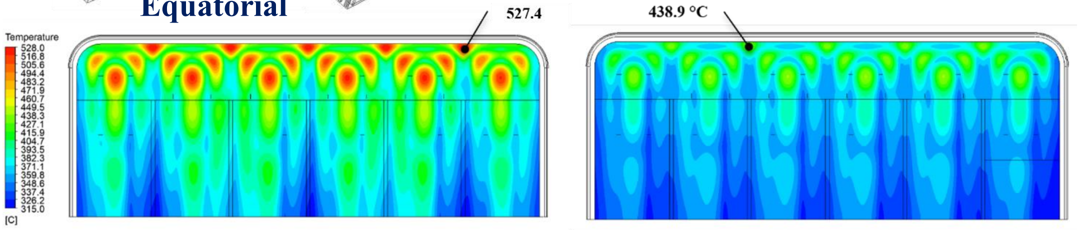
Thermo-hydraulic analyses: Breeding Unit

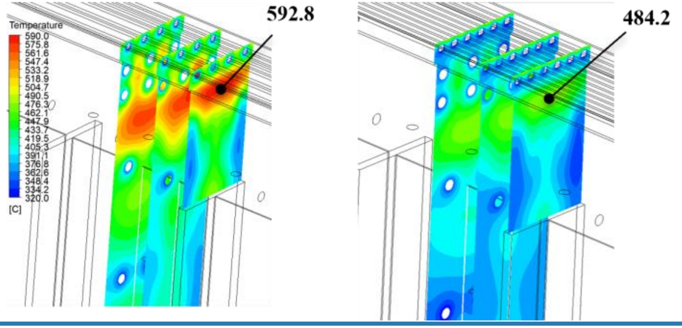


- Detailed CFD analyses: slices at equatorial (IB and OB) and pedestrial slice (OB - close to divertor area)
- Ansys-CFX code calculation
  - equatorial level 4 FW channels/slice, pedestrial slices 6 FW channels/slice
  - steady-state calculation assuming solid PbLi
  - k-ω SST turbulence model in water
  - inlet water T in FW channels and DWTs of 295 °C
  - inlet mass flow rate is optimized to obtain outlet averaged T of 328 °C

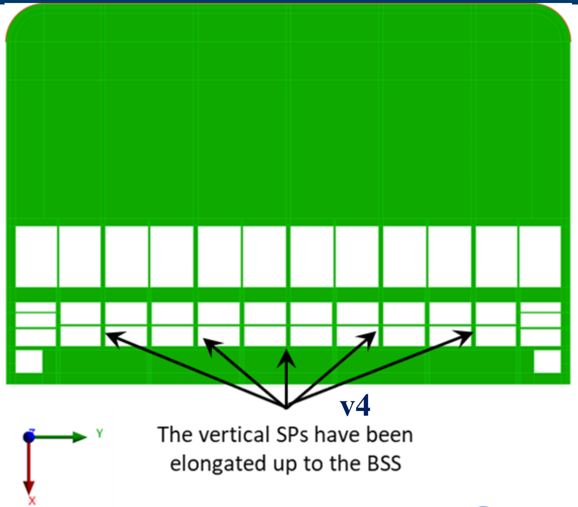


Region	Heat fluw [MW/m2]
OB equatorial	0.32
OB pedestrial	0.59

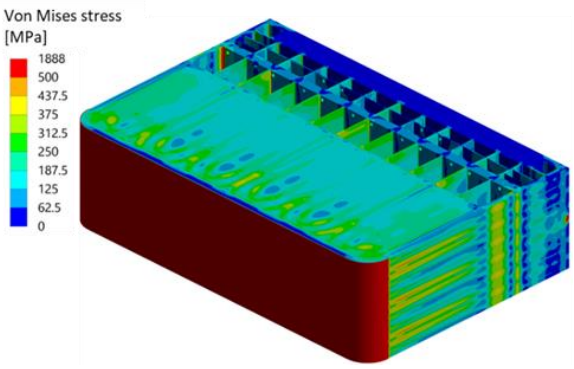


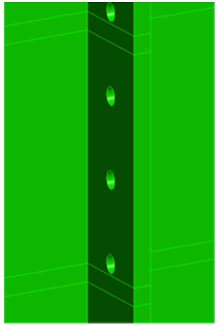


Thermo-mechanical analyses

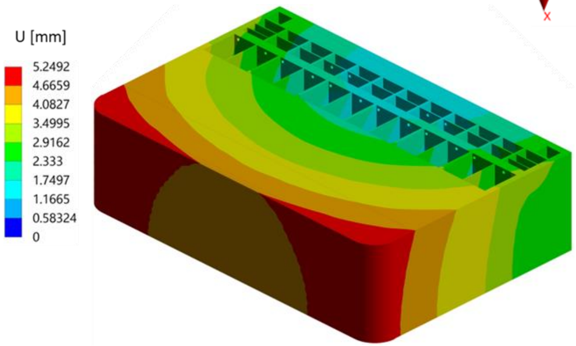


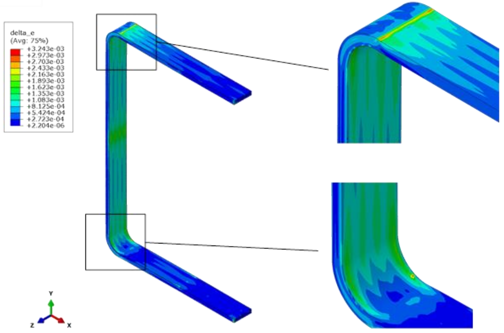
- Behaviour of the PbLi and Water Manifold region, to optimise its geometrical layout. Results confirms that the "model v4" shows a good structural behaviour fulfilling every criterion within all paths with a large margin over the limit imposed by the standard
- Equalize pressure in each water manifold chamber, plates pierced to evaluate the impact of the holes number, diameter and location. Configurations equipped with 3 holes per cell, with a diameter equal to 10mm, withstand the loads and boundary conditions related to the NO and OP loading scenarios
- Numerical assessment of ratcheting, fatigue and creep-fatigue of the WCLL BB FW





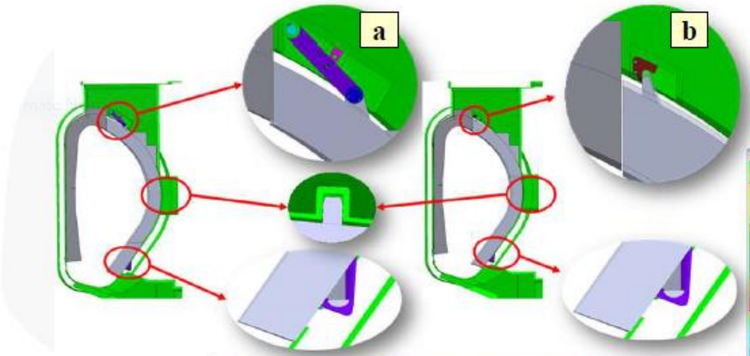
"v4_holes2"
3 holes per cell with a diameter of 10mm



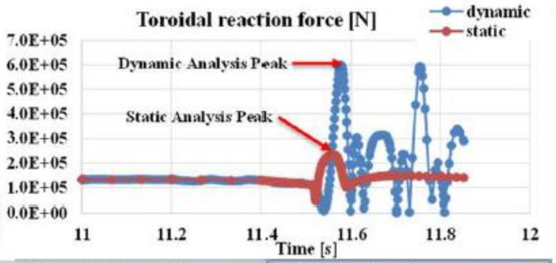


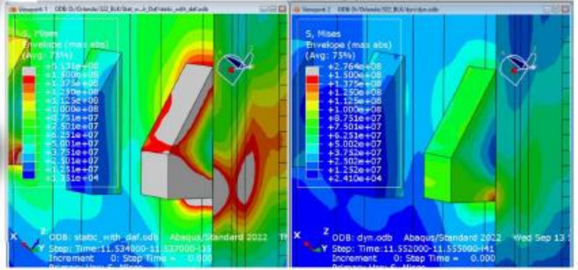
Structural analyses 1/2

- Structural analysis of the COB segment and determination of the Dynamic Amplification Factors (DAF)
  - Computation of the DAF for the WCLL DEMO COB segment, in order to include dynamic effects of a plasma VDE-up in static analyses
- Structural analysis for the development of a BB attachment system to the Vacuum Vessel. A spherical bearing is envisaged in the bottom area of the segments (similar solution adopted for ITER cryostat). Two solutions are being studied for the upper area:
  a) Connecting rod
  b) Vertically guided system



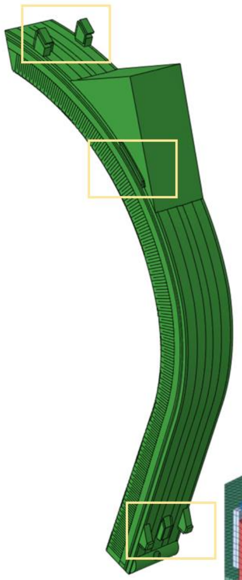
Spherical bearing in the bottom area





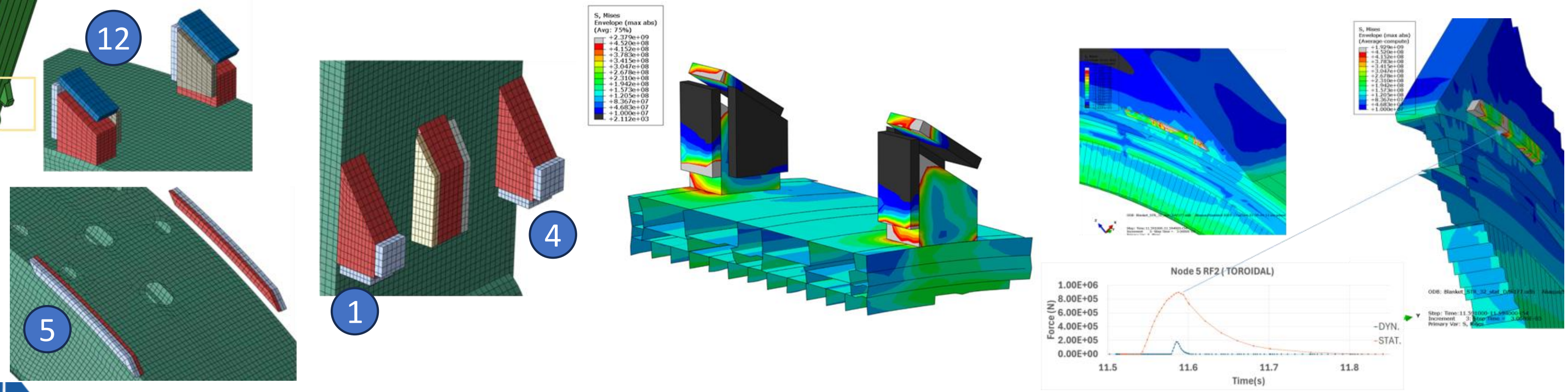
Support name	Analisys	Max response [MN]	DAF
Top right radial & toroidal	Dynamic	2.68	1.3
	Static	2.04	
Top right vertical	Dynamic	1.58	1.6
	Static	0.978	
Top left radial & toroidal	Dynamic	1.35	1.1
	Static	1.25	
Top left vertical	Dynamic	0.922	1.2
	Static	0.79	
Port right	Dynamic	0.625	2.3
	Static	0.270	
Port left	Dynamic	0.6	2.6
	Static	0.233	
Bottom right radial	Dynamic	1.85	1.1
	Static	1.68	
Bottom right vertical	Dynamic	1.75	1.0
	Static	1.73	
Bottom left radial	Dynamic	1.76	1.1
	Static	1.64	
Bottom left vertical	Dynamic	1.99	1.2
	Static	1.68	
Bottom toroidal	Dynamic	2.91	1.3
	Static	2.25	
max			2.6

Structural analyses 2/2

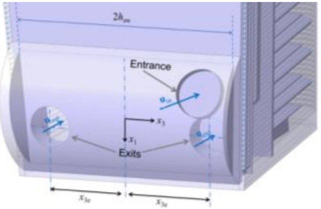


- All the supports of the blanket have been analyzed under both static and dynamic conditions, and for each, a Dynamic Amplification Factor (DAF) has been determined for the static analysis that best approximates the dynamic behavior

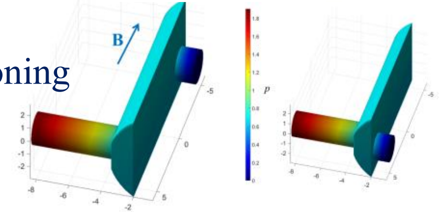
- For node 12, a DAF of 3.5 is required, whereas for the other nodes a DAF of 1.77 would have been sufficient. This highlights the need to differentiate between the type of constraints supports with a well-established, gap-free contact, and those with localized gaps in the upper section, as observed at node 12. The DAF values are high due to the geometry and the clearances in the supports.

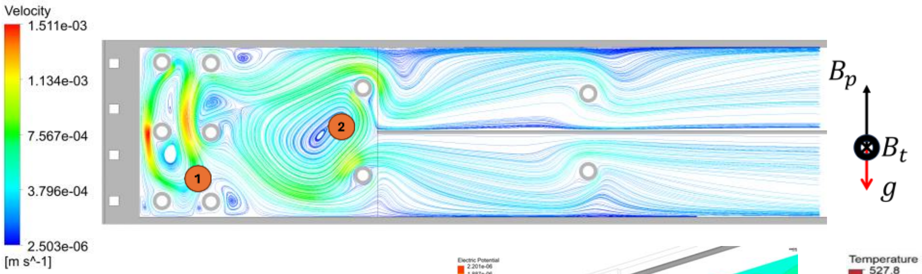


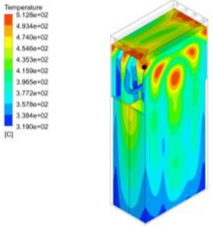
MHD analyses – Helical pipes and manifold

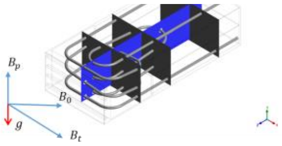


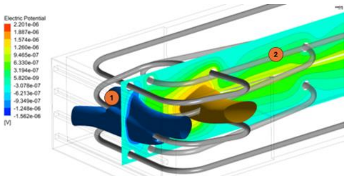
- Magneto-convective analysis of the OB equatorial cell equipped with helical-DWTs
  - Buoyancy responsible for two 3D convection cells adjacent to FW
  - Heat transfer consistent with previous predictions, higher margin on *T*max compared with pure conduction
- Hybrid analysis of the PbLi Manifold
  - Optimization of manifold and expansion chamber to reach uniform PbLi flow partitioning in all BUs

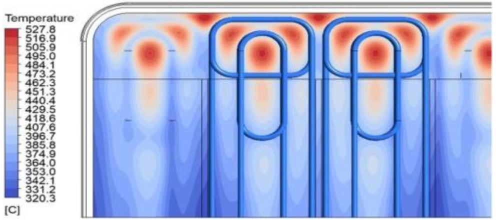


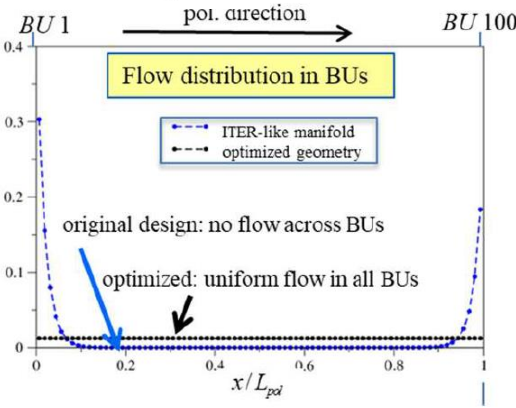




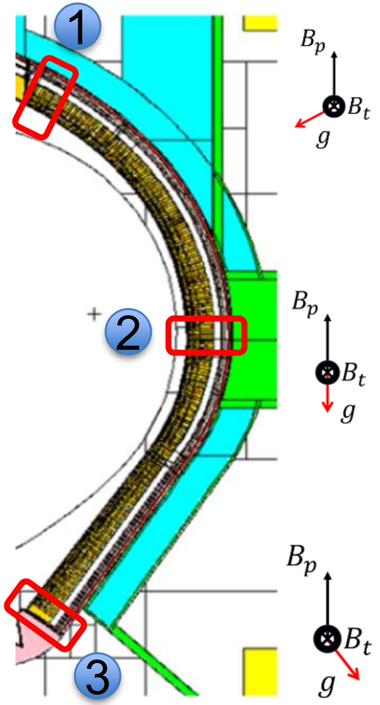


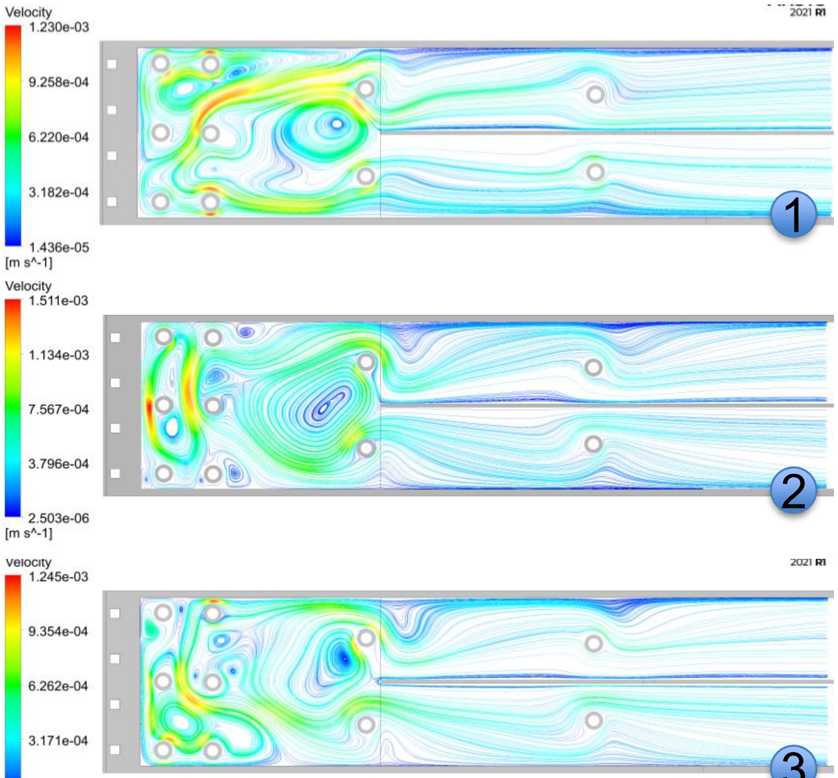






MHD analyses - Effect of gravity orientation on TH performance



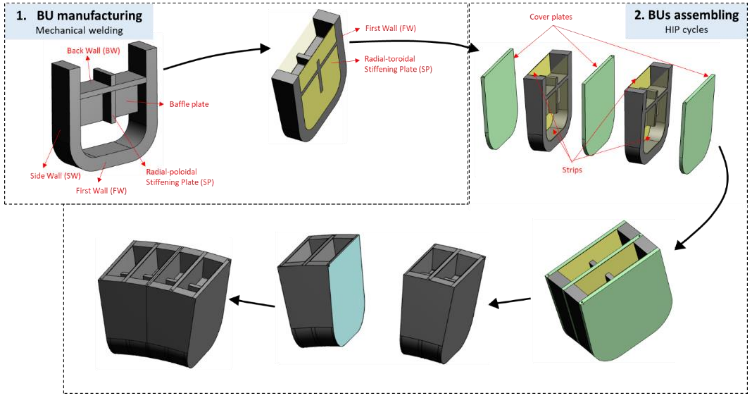


⚠ Thermal and electromagnetic BCs are equal across the 3 models ⚠

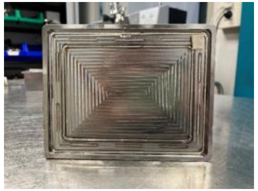
Cell position	Tmax Eurofer (°C)	$\Delta p/\sigma u_0 B_0^2$
1: Apical	515.5	0.10292
2: Equatorial	512.8	0.11125
3: Near-divertor	522.2	0.11584

- ❑ Orientation consistent with OB apical and near-divertor elementary cells
- ❑ Limited effect, increase in temperature for near-divertor cell

Manufacturing activities: FW/SP mock-ups by HIP process



- Manufacturing a mock-up with 2 breeding units
- Realization of a mock-up with 4 breeding units according this manufacturing route
- HIP process



1. CAD

2. Grade 91 material supply

3. Machining + welding
- Cutting sheet
- Grinding plates
  to remove oxides, scratches,...
- GTAW and Laser

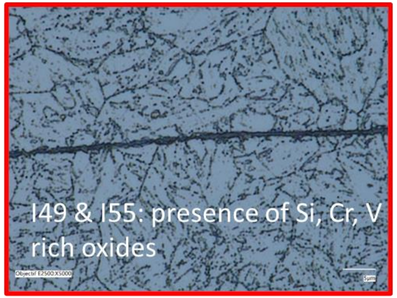
4. Cleaning
to remove oils, dirts,...

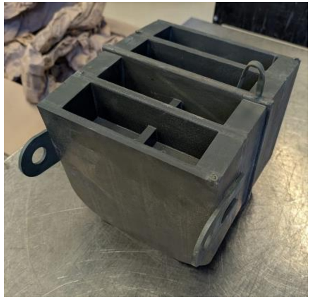
5. Canister operations
(loading, degassing, welding, thightness test)

6. HIP cycle

7. Post HIP heat treatment

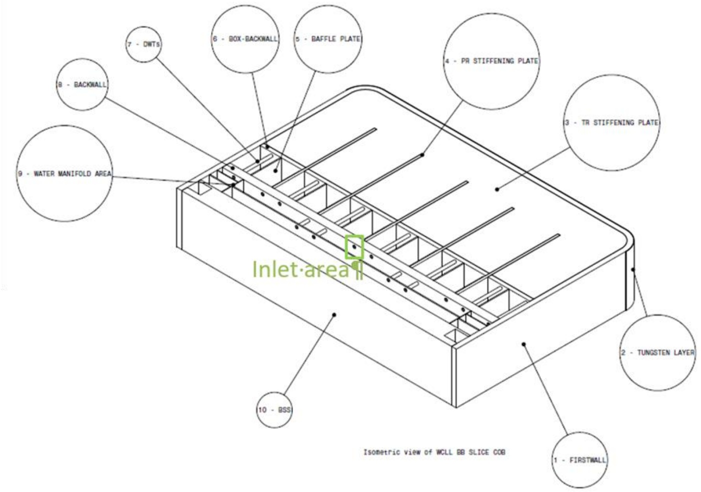
8. Characterizations

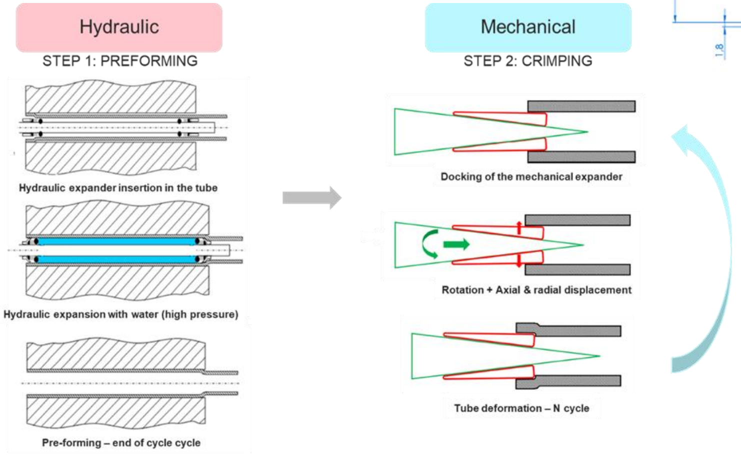


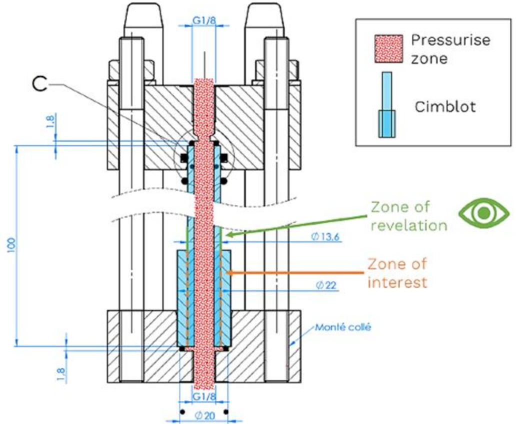


Manufacturing activities

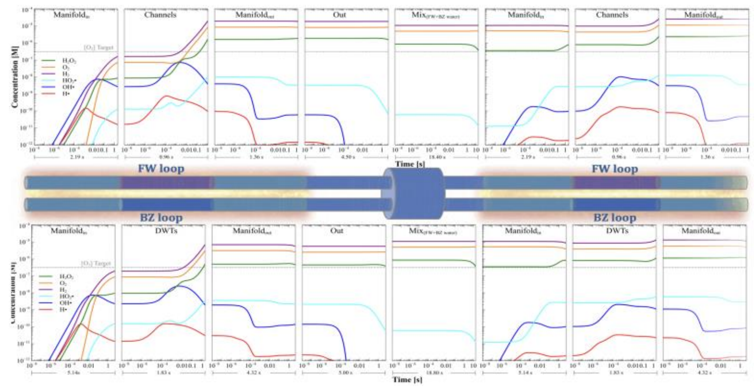
- Alternative assembly technology for the Double Wall Tube (DWT) / Back Plate (BP) junction other than GTAW welding process → **expansion methods**

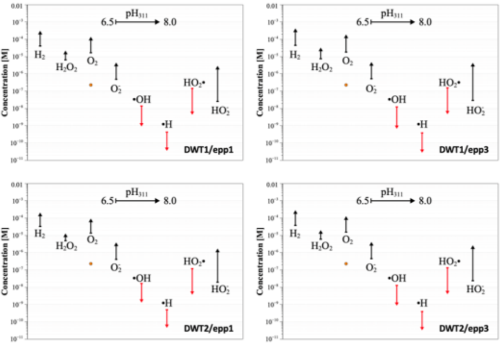




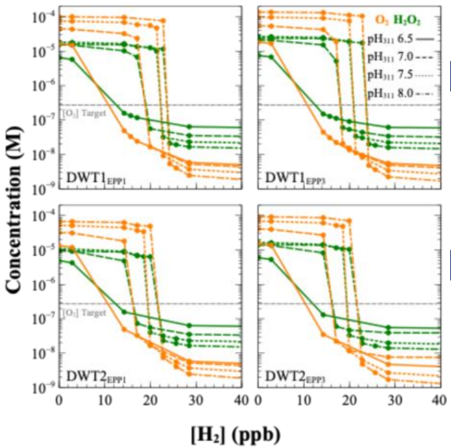


Other activities: water chemistry



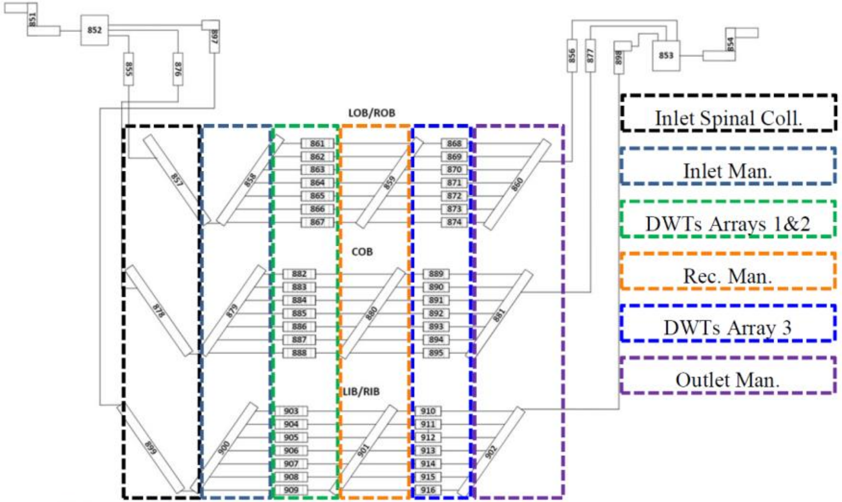


No hydrogen addition

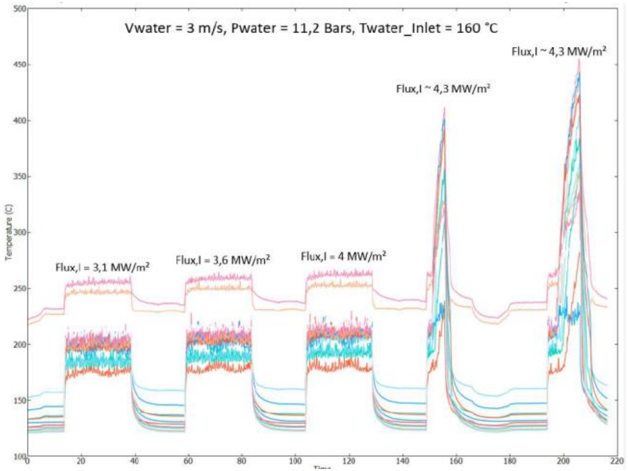


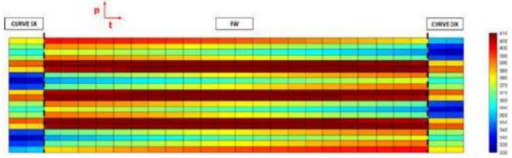
- The importance of pH control emerges as crucial to minimizing the influence of iron ions and, consequently, hydrolysis
- It is necessary to keep the ‘impurity’ level as low as possible, especially the $[Fe^{3+}]$, to avoid any interference with the mechanism of water recombination
- H_2 effectively suppresses oxidants when its concentration exceeds the threshold hydrogen concentration (THC)
- THC increases with pH, requiring higher hydrogen levels in alkaline conditions.

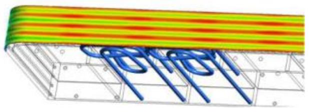
Other activities: SYS-TH and CHF experiments

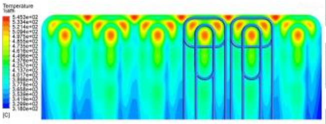


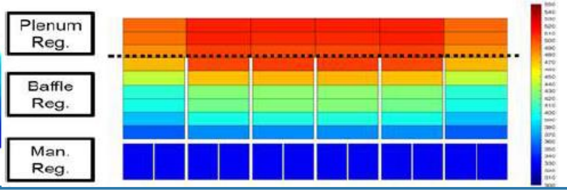
HTC & CHF experiments for FW “rectangular”channels

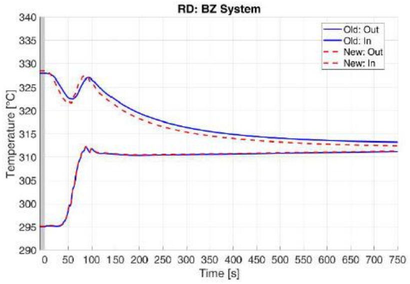


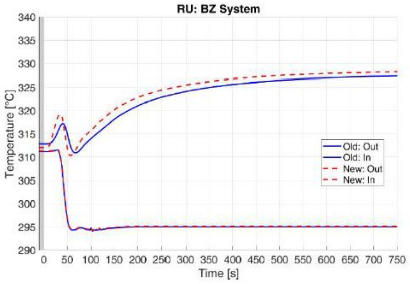




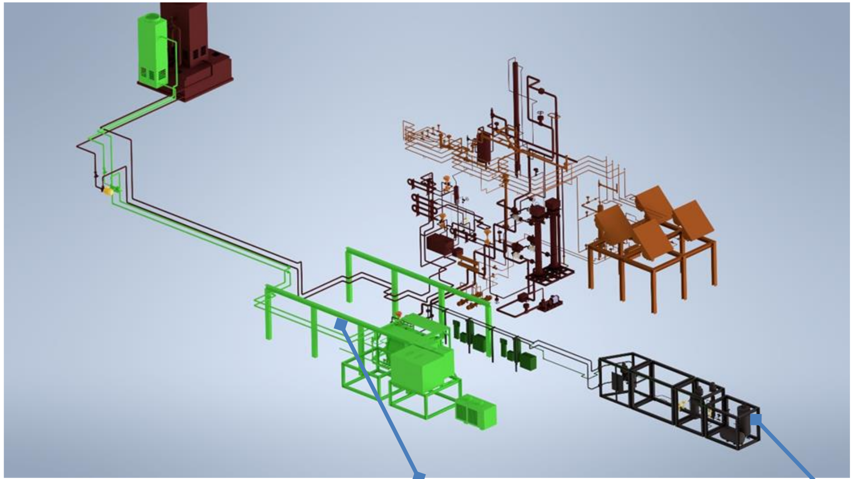




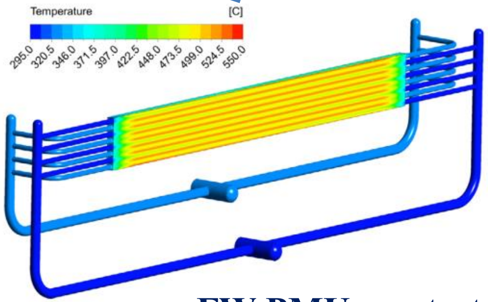




Other activities: experiments – W-HYDRA platform

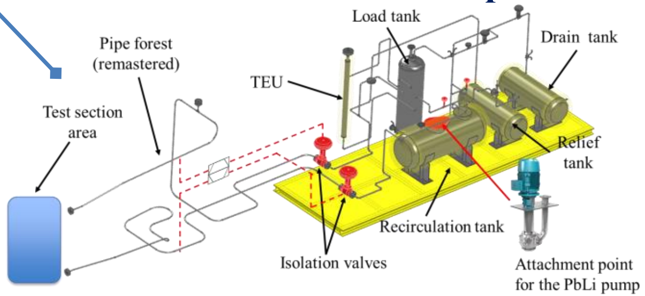


- ❑ Water Loop (WL): high pressure (15.5 MPa) water loop with the capability of hosting different test sections
- ❑ LIFUS5/Mod4: PbLi loop reproducing that foreseen for the ITER WCLL-TBM. It is integrated with the WL to investigate the PbLi/water interaction at TBM scale



FW PMU pre-test analyses

PbLi-water interaction experiments



Conclusions and future perspectives

- The design of the WCLL BB concept has been continuously updated during last years to improve its performances and to outdo existing criticalities
- The adoption of helicoidal DWTs and the new BZ manifold layout have allowed the improvements of several figures of merit to be reached
- The neutronic and tritium transport analyses show encouraging results for the performance of the WCLL BB concept
- Once the different sensitivities are finalised, global analyses will be re-run to assess the general behaviour of the WCLL BB in the new DEMO LAR configuration to improve geometry and layout optimization
- Due to the advanced design stage reached by the WCLL BB concept, it is now mandatory to test the manufacturing and assembly of the different breeding units and segment to verify the reliability of this BB concept
- It will be of pivotal importance the construction and commissioning of experimental facilities (e.g. WHYDRA, MAPLE, HADES) for the testing and qualification of selected prototypical mock-ups, as well as continuing the code development and validation activities.

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Thank you for the attention

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