Progress of the conceptual design of the European DEMO Breeding Blanket, Tritium Extraction and Coolant Purification Systems

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Outline

- Introduction
- HCPB design
- WCLL design
- HCPB BB shielding performance studies
- Water activation
- TER HCPB design
- TER WCLL design
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    - o GLC technology
- Tritium transport analysis
- Tritium permeation experiments
- Helium and water CPS pre-conceptual design
- Conclusion

Introduction

- The Helium Cooled Pebble Bed (HCPB) and the Water Cooled Lithium Lead (WCLL) concepts are the two TBM concepts to be tested in ITER and are being developed as possible candidates to become driver Breeding Blanket (BB) for the EU DEMO.

- Some technical features of the BB (the type of coolant and breeder, the technology used for the tritium extraction/control and for the coolant purification) impact not only the design of the BB system but also the design of the interfacing systems and, as a consequence, of the overall tokamak layout.

- Design and integration studies have been carried out in a holistic way (thinking about the big picture) in order to verify that architectures being developed are consistent and the major issues are addressed and tackled.

- Two main design and integration cross fields have been identified:

  - **Radiation protection** in the blanket and adjacent systems;

  - Definition of the **Tritium management systems** (extraction, inventories and releases) → selection of the technology and definition of working point

HCPB design

Active areas of research:

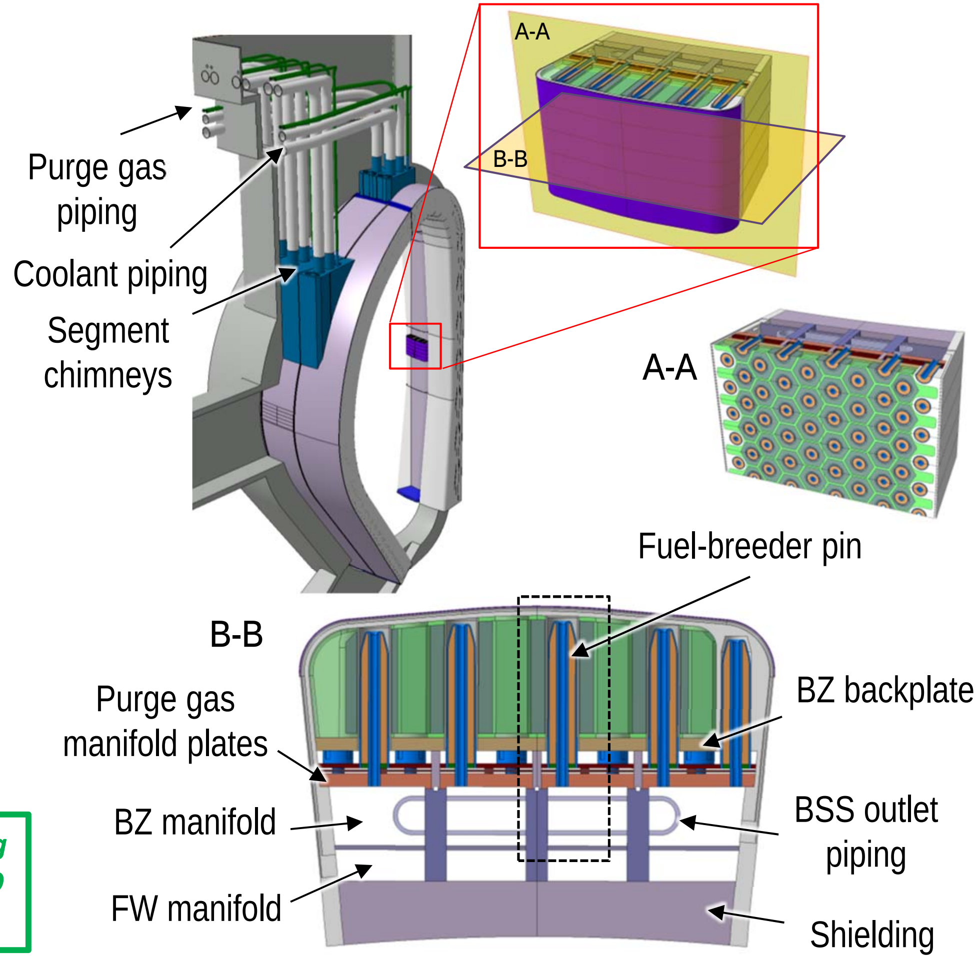
- TBR margin (1.20) and possibly room for dedicated VV shielding;
- Improve removal of high heat flux in FW and BZ with turbulence promoters;
- Focus on holistic design:
  - BoP-PHTS: simplification of internals to reduce Δp: $P_{electr} \approx 90$ MW;
  - RAMI and costs: focus on reliability and cost improvement;
  - Safety: functional materials with low T inventory and resilient against accidents;
  - TER and CPS: studies on alternative purge gas chemistry.

Key issues still need to be solved:

- Integral manufacturing demonstrators;
- Need for integral, large scale experiments on thermal-hydraulics and thermo-mechanics;
- Cost reduction of functional materials, recycling of $Be_{12}Ti$.

F. A. Hernández et al., *Consolidated Design of the HCPB Breeding Blanket for the pre-Conceptual Design Activities of the EU DEMO and Harmonization with the ITER HCPB TBM Program* (POSTER)

- Fuel-breeder pin hexagonal assembly
  - Li_4SiO_4 + 35mol% Li_2TiO_3 ceramic breeder (CB) pebble bed
  - $Be_{12}Ti$ prismatic blocks
- He coolant (inlet 300°C, outlet 520°C, 8 MPa).
- Purge gas (0.2 MPa): He + 0.1% wt. H_2 (H_2O alternative)



WCLL design

Active areas of research:

- Integration of water and PbLi pipes in Upper and Lower Ports;
- Optimization of FW and BZ cooling → enhanced TBR (target > 1.15);
- PbLi flow modelling under magnetic field;
- EXP and numerical studies of H_2O/PbLi reaction;
- R&D on permeation barriers: Al2O3 coating;
- Water coolant chemistry R&D.

Key issues still need to be solved:

- Water drainage procedure;
- Integral manufacturing demonstrators;
- Need for integral, large scale experiments on H_2O and PbLi technologies.

Presented @ ISNFT-14

F. Edemetti et al., P1-075

I. Catanzaro et al., P1-067

A. Tassone et al., P1-122

M. Eboli et al., P2-038

S. Khani, P2-049

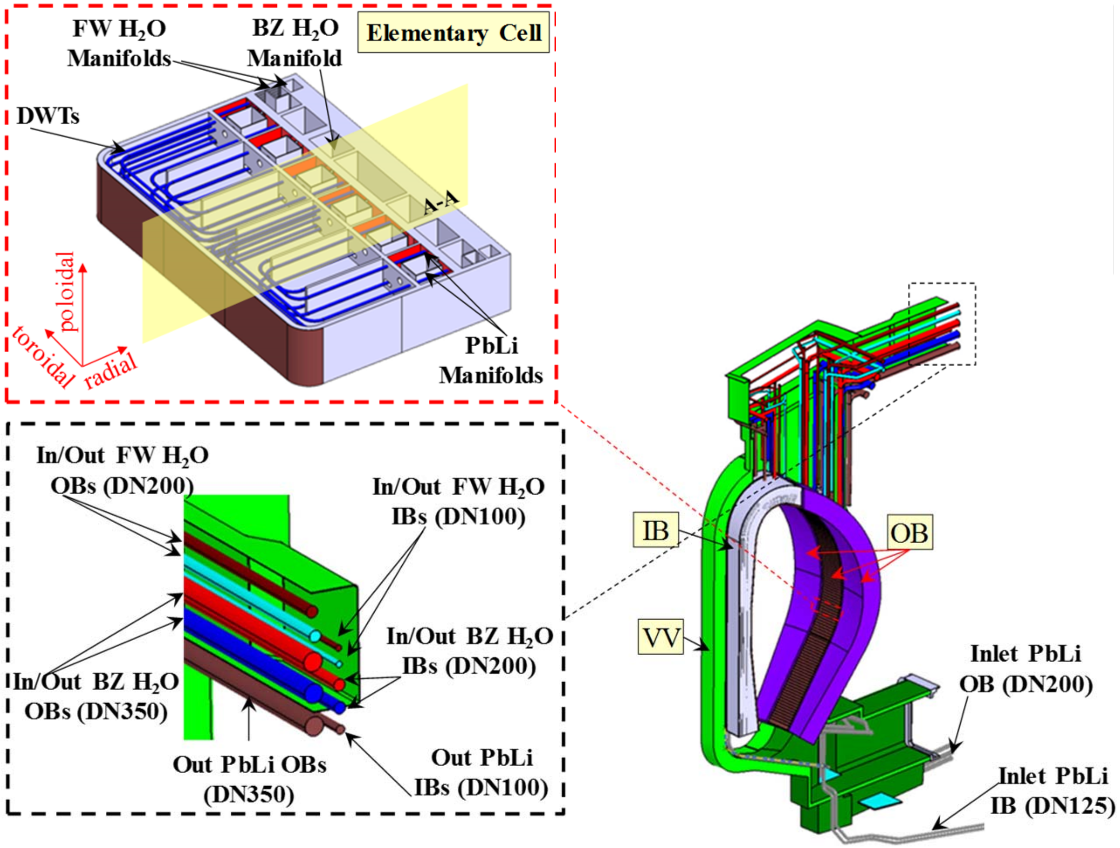
F. Galleni, P2-044

F. Moro et al., P1-031

I. Mocato, P1-101

P. Chiovaro, P1-071

- PbLi as breeder, n-multiplier and T carrier.
- Water coolant at PWR conditions: 295 – 328 °C @ 15.5 MPa.
- Two independent loops: FW and BZ. BZ cooling system relies on Double-Wall Tubes (DWT).



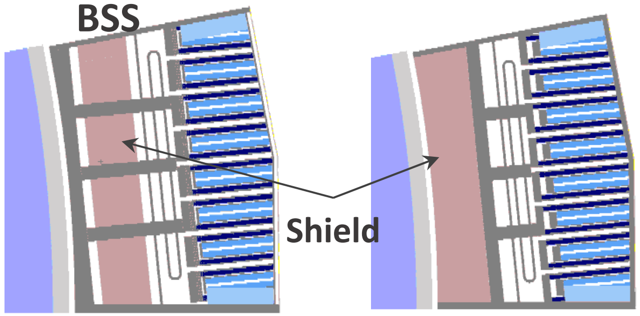
A. Del Nevo et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fus Eng Des (2019), article in press, https://doi.org/10.1016/j.fusengdes.2019.03.040

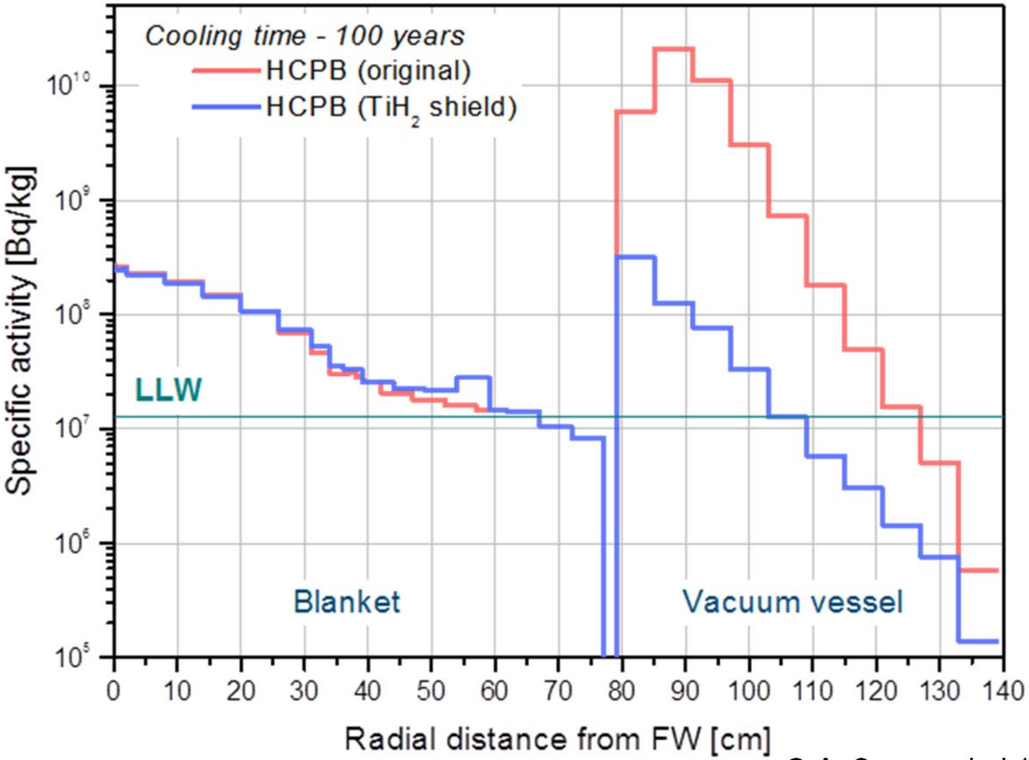
HCPB BB shielding performance studies

- Assessment of shielding options for the HCPB blanket to reduce VV long term activation.
- The following nuclear responses have been assessed:
  - *Effect on DPA accumulation in the VV;*
  - *VV Activation.*
- Two shield integration options: inside the manifolds and on the back of the BSS.

P. Pereslavtev et al., Analyses of the shielding options for HCPB DEMO blanket (POSTER)

DPA/FPY	$ZrH_{1.6}$	TiH_2	WB
Inside	0.015	0.014	0.019
Outside	0.010	0.008	0.012





Achievements:

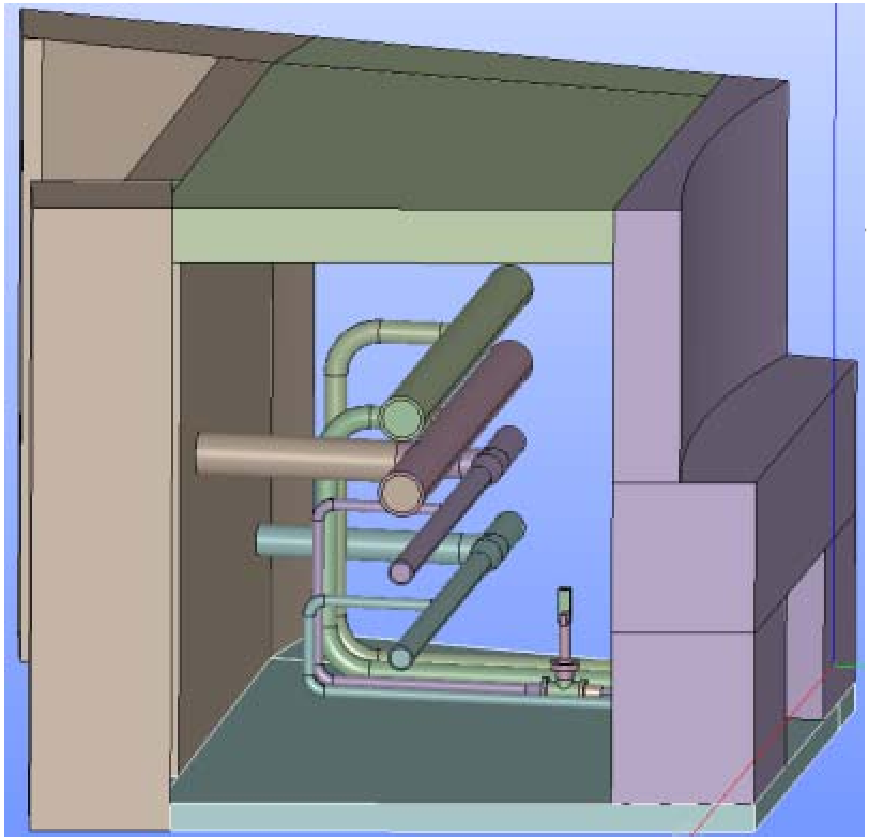
- DPA accumulation in the VV inner shell:
  - *In the HCPB original – 0.14 dpa/FPY;*
  - *In the HCPB with TiH_2 shield decreased up ~15 times with a 18 cm shield.*
- With 18 cm TiH_2 shield reduction of VV activation by a factor of ~10;

Issues to be still addressed:

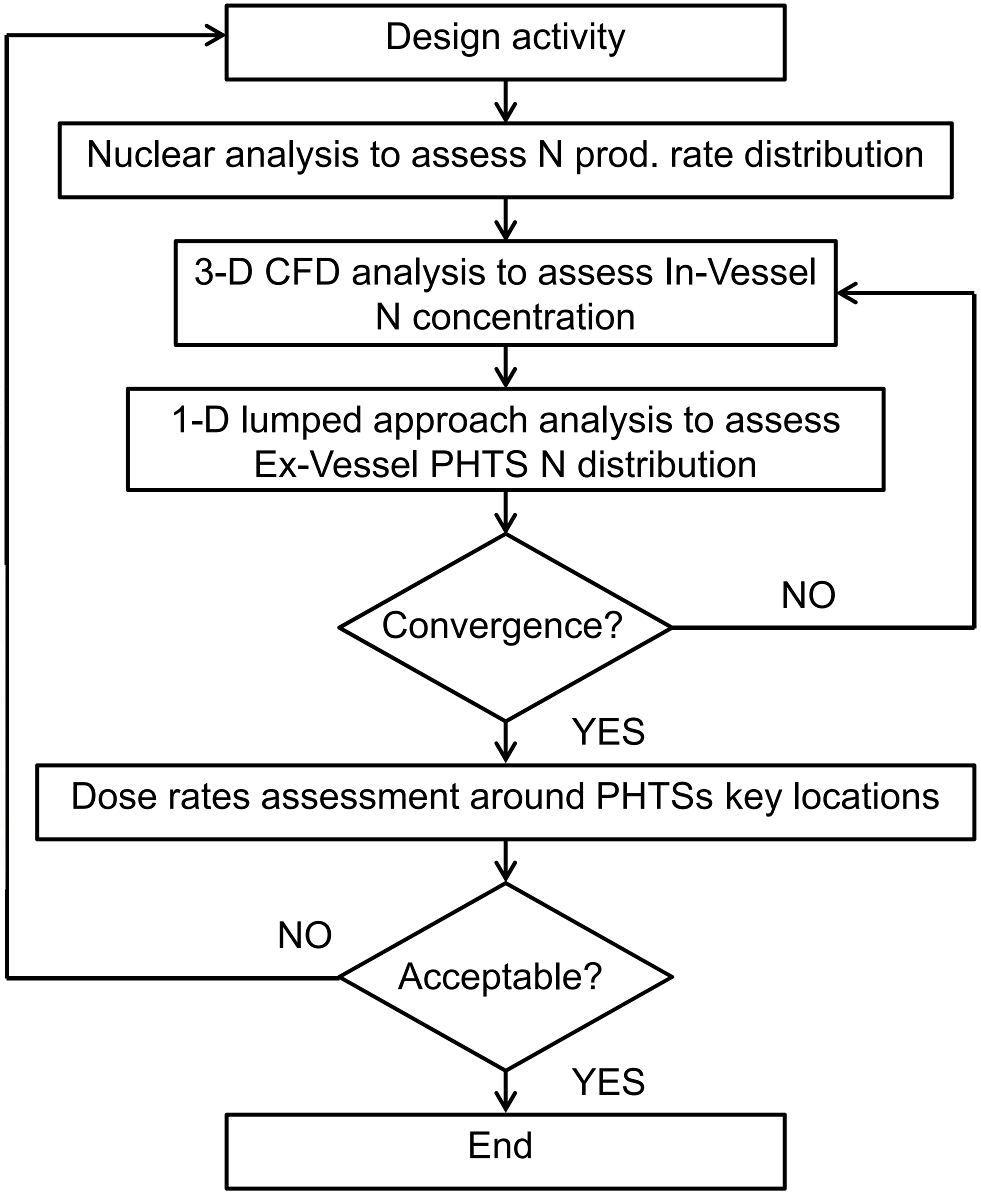
- Integration feasibility (TH/TM);
- Impact on cost of the HCPB BB.

Water activation

I. Moscato et al., ***Assessment of the Dose Rates due to Water Activation on an Isolation Valve of the DEMO WCLL Breeding Blanket Primary Heat Transfer System*** **(POSTER)**

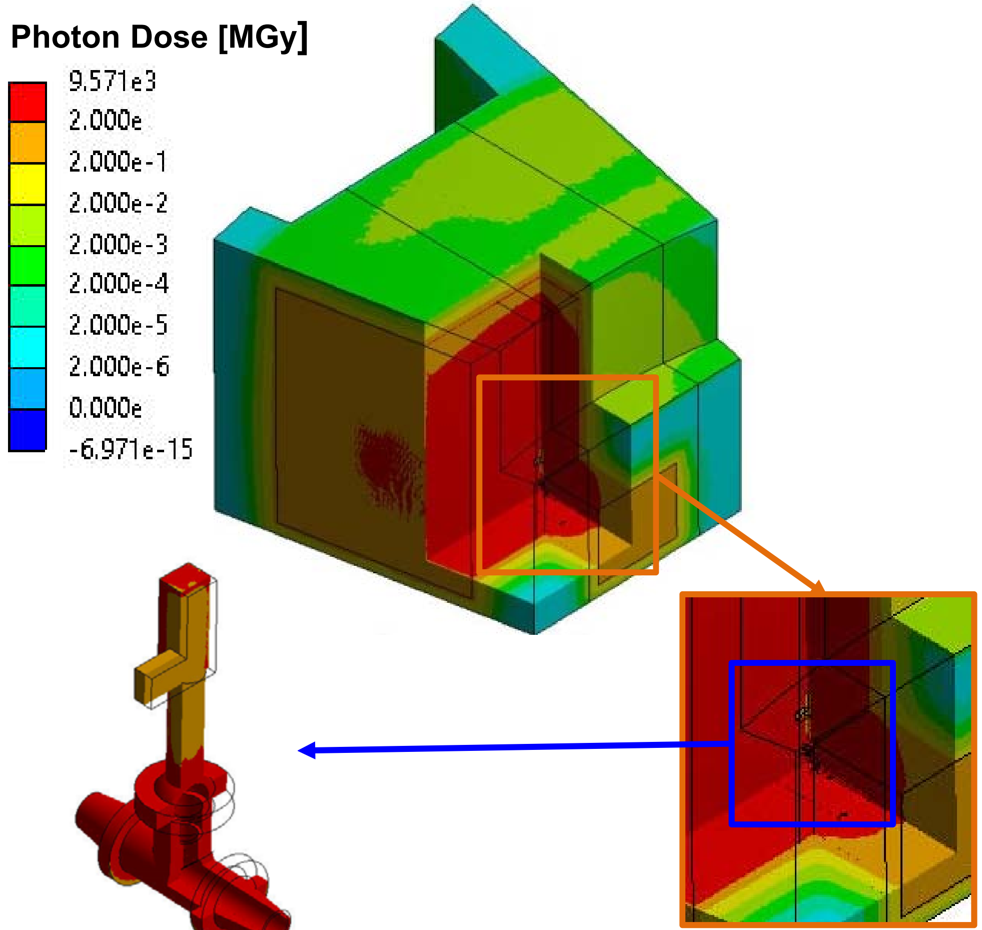


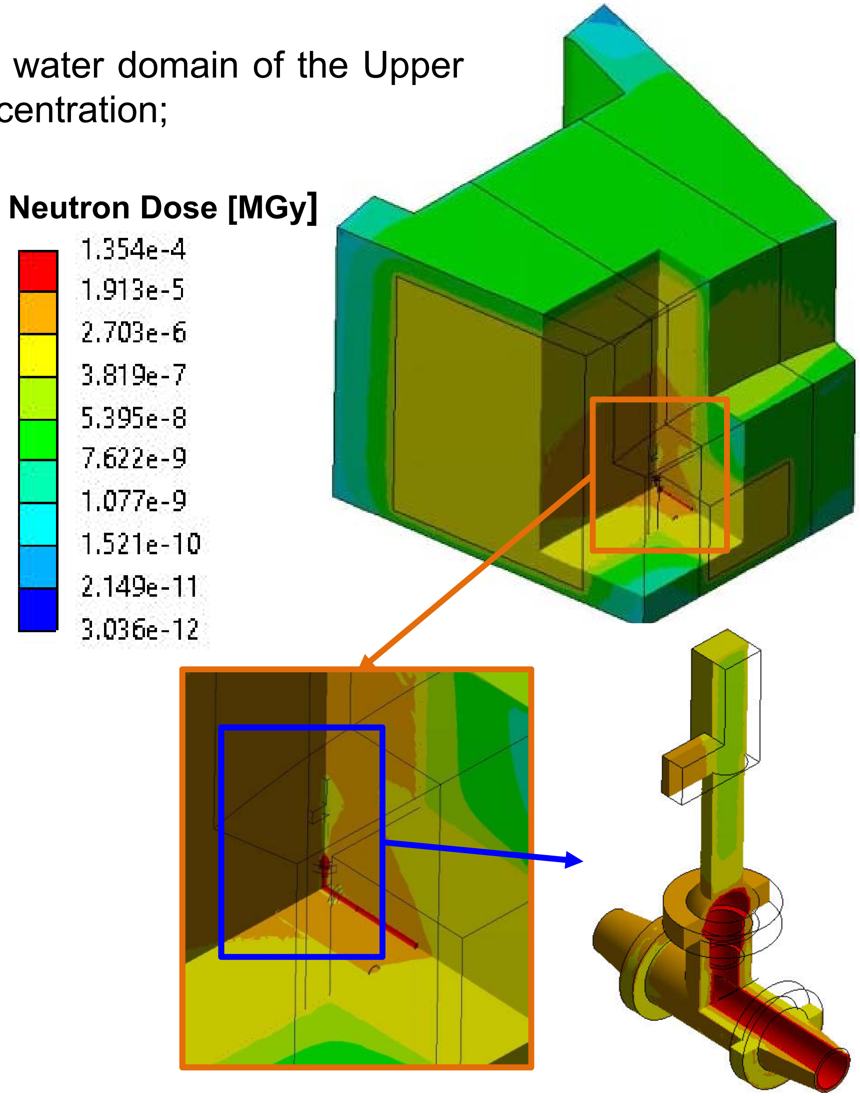
P. Chiovaro et al., ***Investigation of the DEMO WCLL Breeding Blanket Cooling Water Activation*** **(POSTER)**



Water activation

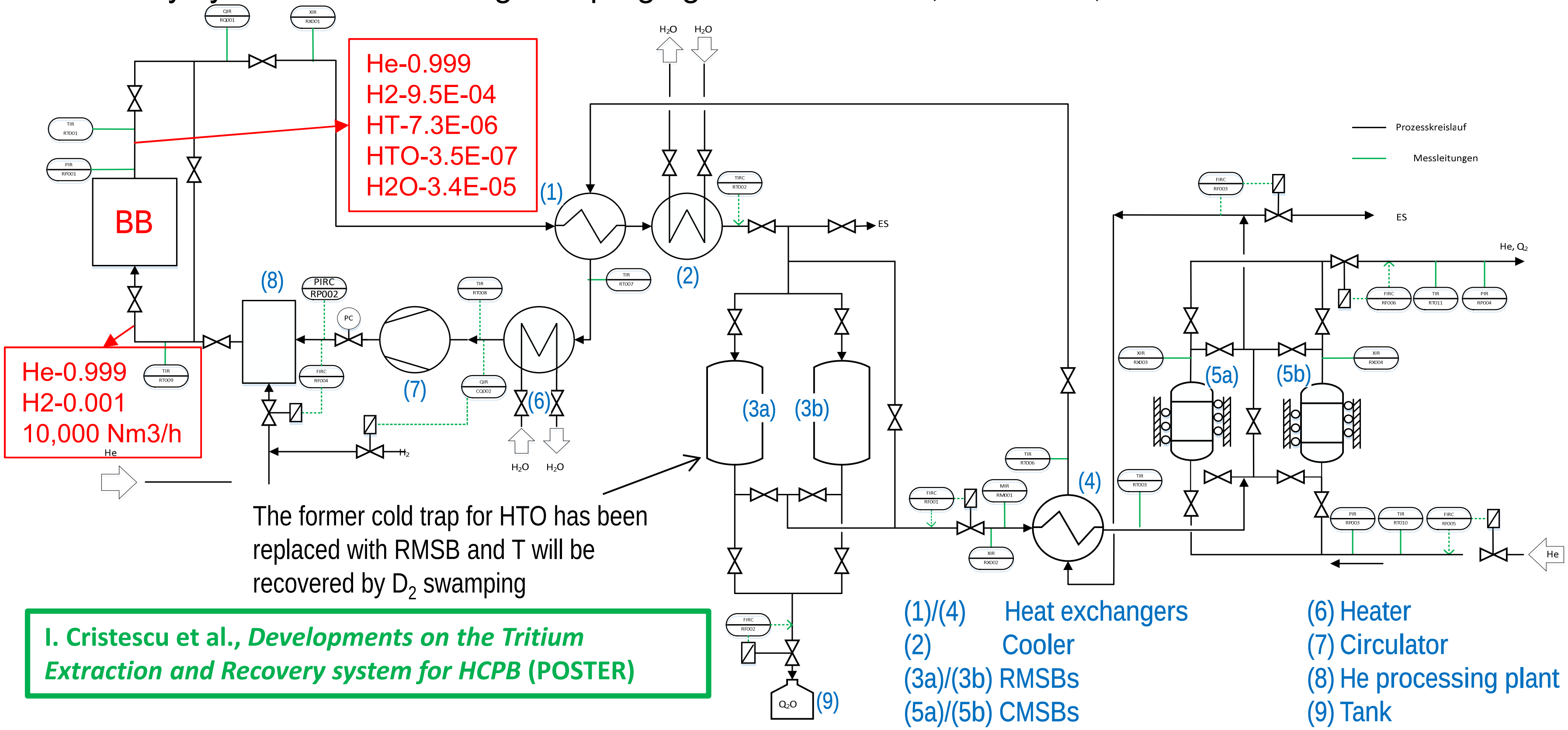
- Assessment of the dose in FW and BZ cooling circuit due to γ and *neutron* radiation from ^{16}N and ^{17}N has been carried out;
- The γ and *neutron* source has been implemented in the water domain of the Upper Pipe Chase considering the inventory of ^{16}N and ^{17}N concentration;
- A period of 7 FPY has been considered.





TER HCPB design

- The HCPB TER technology is based on HTO trapping (@ 20° C) on reactive molecular sieve beds (RMSB) followed by cryo-absorption (CMSB @ 77 K);
- Large amount of liquid nitrogen (~ 400 - 500 kg/h);
- Bulky system due to the large He purge gas flowrate ~ 10,000 Nm³/h;



- Possibility to use purge gas containing steam to mitigate the T permeation in the BB coolant is currently investigated.

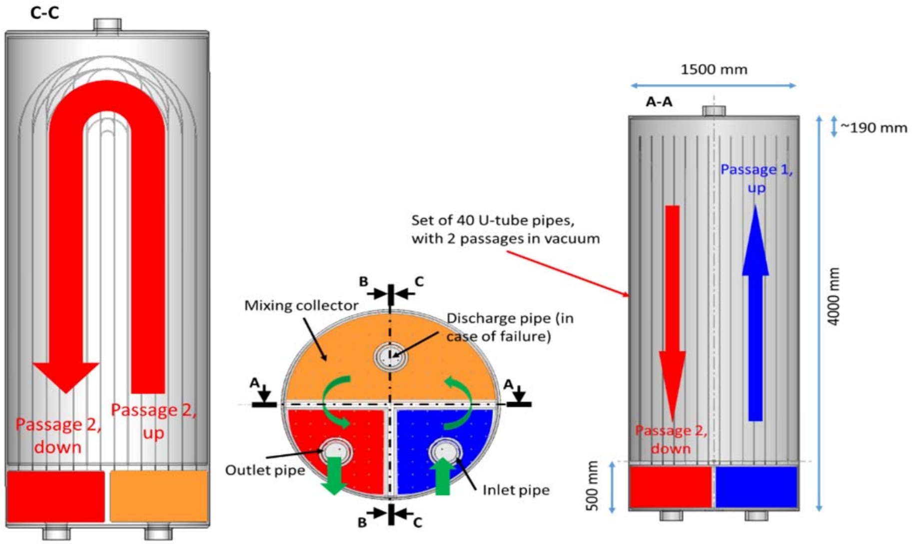
TER WCLL design – PAV technology

Design Parameters for WCLL BB TER	
Pb-16Li mass flow rate [kg/s]	~956
N. Pb-16Li Loops (IB+OB)	6
Pb-16Li mass flow rate IB/Pb-16Li loop [kg/s]	55
Pb-16Li mass flow rate OB/Pb-16Li loop [kg/s]	264
TER Pb-16Li inlet Temperature [°C]	**330-500**
TER efficiency [%]	**80-90**

- Permeator Against Vacuum (PAV) is the selected technology for the WCLL TER;
- Gas Liquid Contactor (GLC) is the back-up solution;
- PAV is based on tritium permeation through a membrane in contact with Pb-16Li/vacuum.
- Two PAV design:
  - Vanadium membrane to be qualified in CLIPPER facility (CIEMAT);
  - Niobium membrane to be qualified in TRIEX-II facility (ENEA).

Design Parameters ENEA PAV mock-up	Value
PbLi velocity	0.5 m/s
PbLi mass flow rate	250 kg/s
PbLi temperature	330°C
Pressure Drops	<0.3 MPa
Vessel Diamater	4 m
Height tank	7 m

Niobium PAV for TRIEX-II

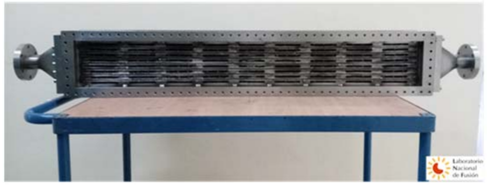
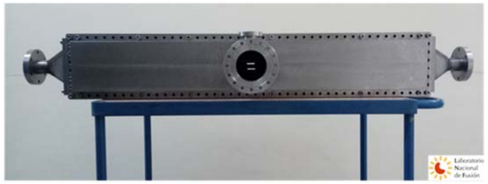


TER WCLL design – PAV technology

- **CLIPPER** (CIEMAT) aims to demostrate the feasibility of PAV in different scenarios (test section: 300 - 500 ºC / 0.1 - 1 m/s)
- **TRITON**: first PAV prototype (V membranes) was assembled and first tests performed:
  - Two new approaches for complex manufacturing process : EB welding (satisfactory preliminary tests) / use of special gaskets.

O3-1.2, D. Rapisarda et al., *Tritium extraction from PbLi: Technologies and* Progresses (TALK)

V PAV for CLIPPER

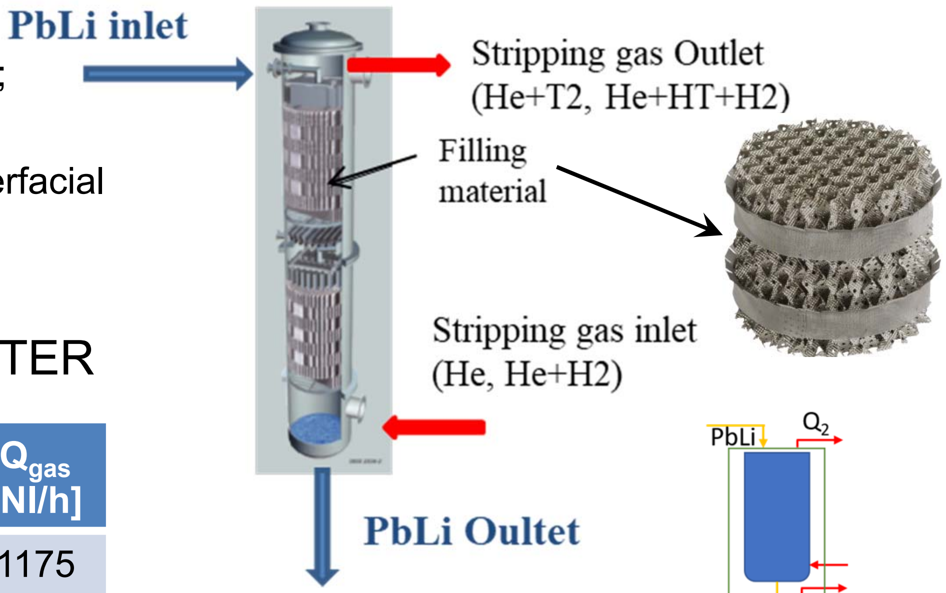
Planned activities

- First PbLi injection → Oct 2019
- First experiments → Jan-2020
- **First phase:** demonstrate the technique at most favorable scenario (high H partial pressure, temperature, reduced mass flow rate);
- **Second phase**: test matrix operation focused on WCLL conditions.

TER WCLL design – GLC technology

The Gas/Liquid Contactor technology

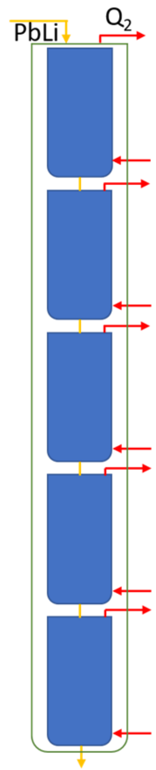
- Diffusion interchange between gas and liquid phase;
- Vertical columns filled with a packing → large interfacial surface, count.r-current and co-current flow;



Design Parameters for WCLL BB TER

b	h (5 units) [cm]	D [cm]	Q_{gas} [Nl/h]
IB 50 kg/s PbLi	153,8	150	1175
	86,5	200	1175
OB 250 kg/s PbLi	793	150	5877
	432,5	200	5877

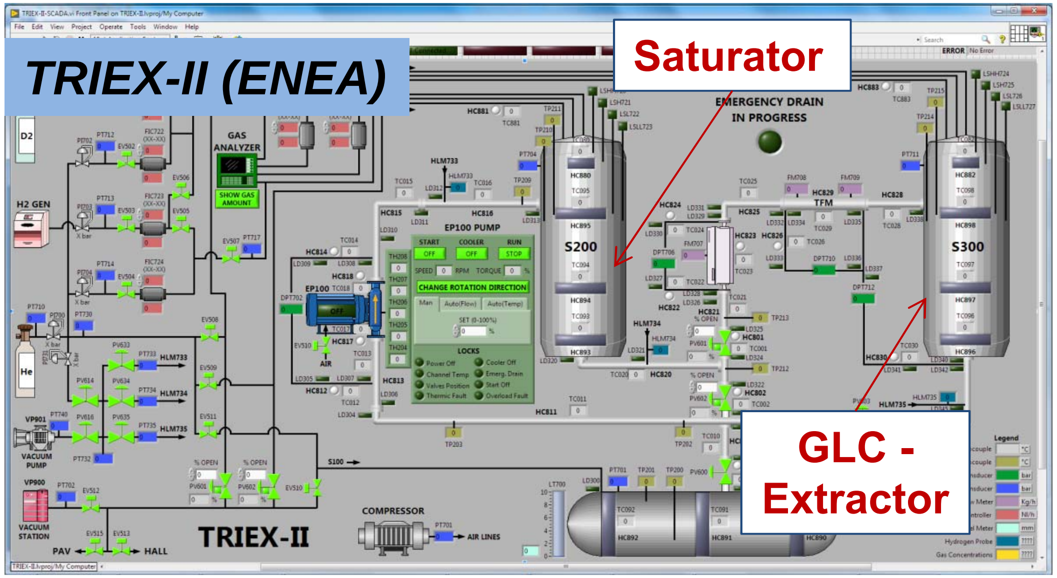
GLC for TRIEX-II

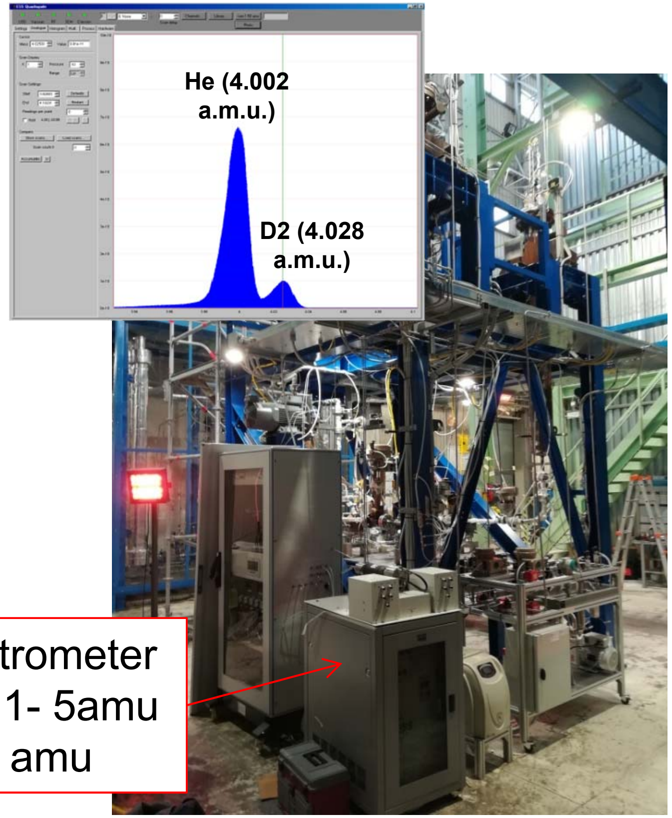


- 5 units foreseen for each PbLi circuit → modules arranged in series (OB total height module 5 m);
- Large size of GLCs → compromise can be achieved (shorter height, larger diameter);

TER WCLL design – GLC technology

- GLC mock-up was qualified in TRIEX-II loop in 2019 showing a tritium extraction efficiency up to 44% (He and He + H_2 used as stripping gas).





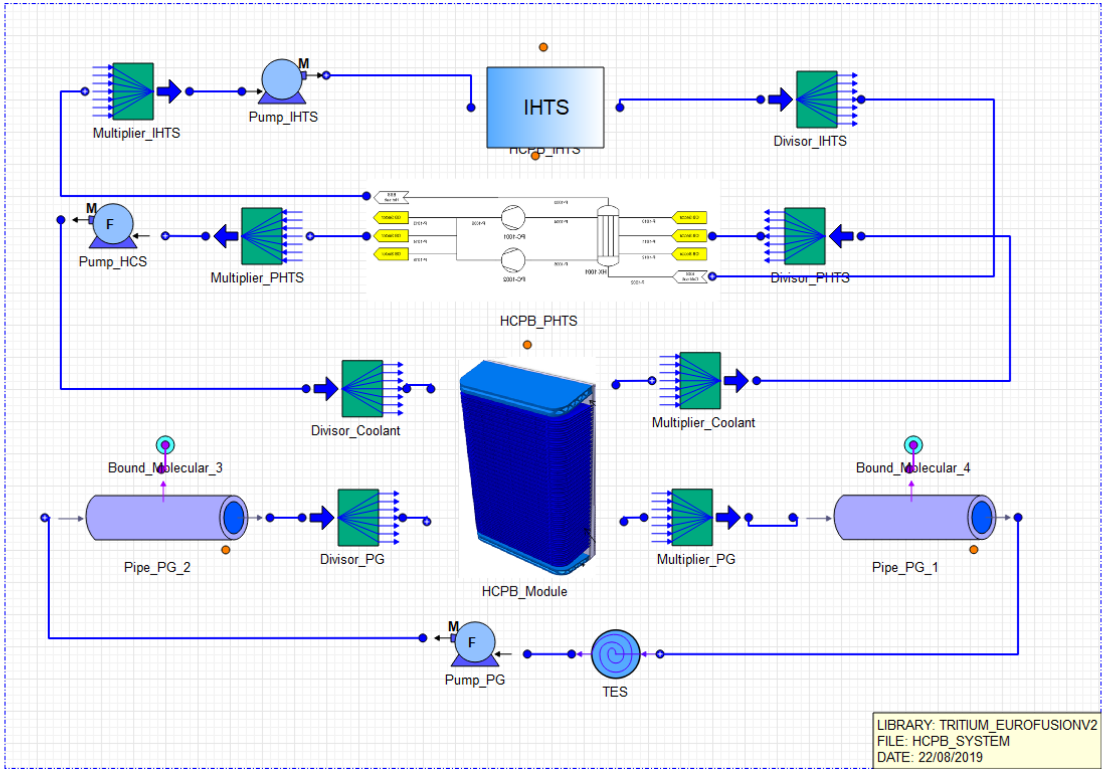
Parameters	Value
Design Pressure	1.0MPa
Design Temperature	530°C
PbLi Mass flow rate	0.1-8kg
H2 concentration in PbLi	0 - 3.000 Pa
D2 concentration in PbLi	0-3.000 Pa
Stripping gas	Helium

Mass spectrometer resolution: 1- 5amu and 1- 200 amu

M. Utili et al., *Characterisation of Tritium Extraction Unit from Liquid Pb-16Li alloy of WCLL-TBM in TRIEX-II facility* (POSTER)

Tritium transport analysis

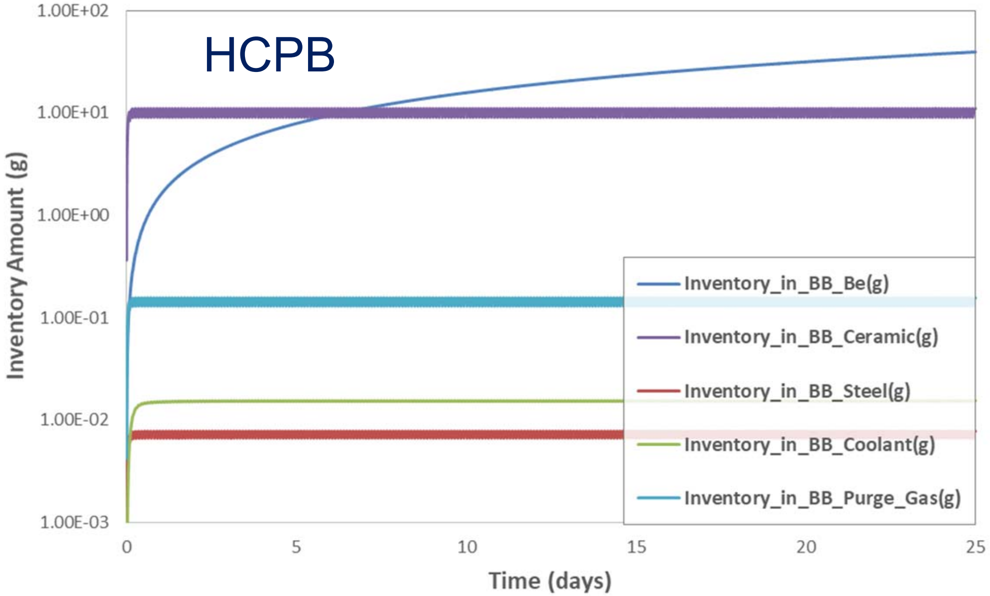
- The HCPB/WCLL models have been developed using the object oriented software EcosimPro;
- The HCPB/WCLL systems are modelled using a process flow diagram;
- Each component computes a certain amount of dynamical equations.
- Current HCPB and WCLL models integrate the ancillary systems:
  - PHTS;
  - IHTS;
  - TER;
  - CPS.



Issues to be still addressed:

- He leakage from the PHTS;
- T permeation from plasma through the FW.
- Correct implementation of co-permeation.

Tritium transport analysis

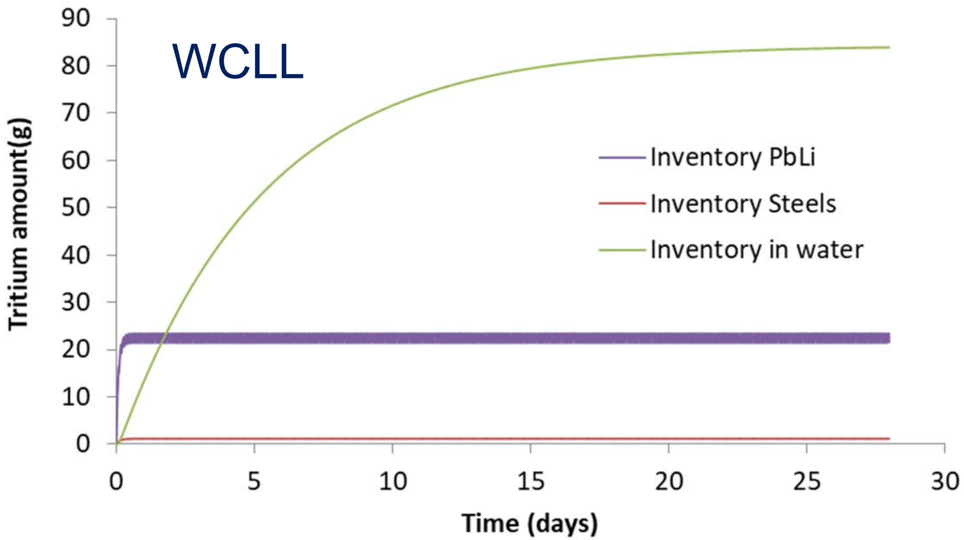


Input for HCPB	Value
Tritium generation rate, g/d	~ 320
Purge gas G, kg/s	~ 0.5
H_2 in purge gas, % wt.	0.1
TES efficiency, %	80
H_2 addition in coolant, % vol.	0.1
CPS efficiency, %	95
CPS bypass, %	0.083

HCPB Permeation Rate (in 25 days)	Value
From Purge Gas to Coolant, g/d	1.12
From PHTS to Environment, g/d	0.002
From Purge Gas to Environment, g/d	0.006

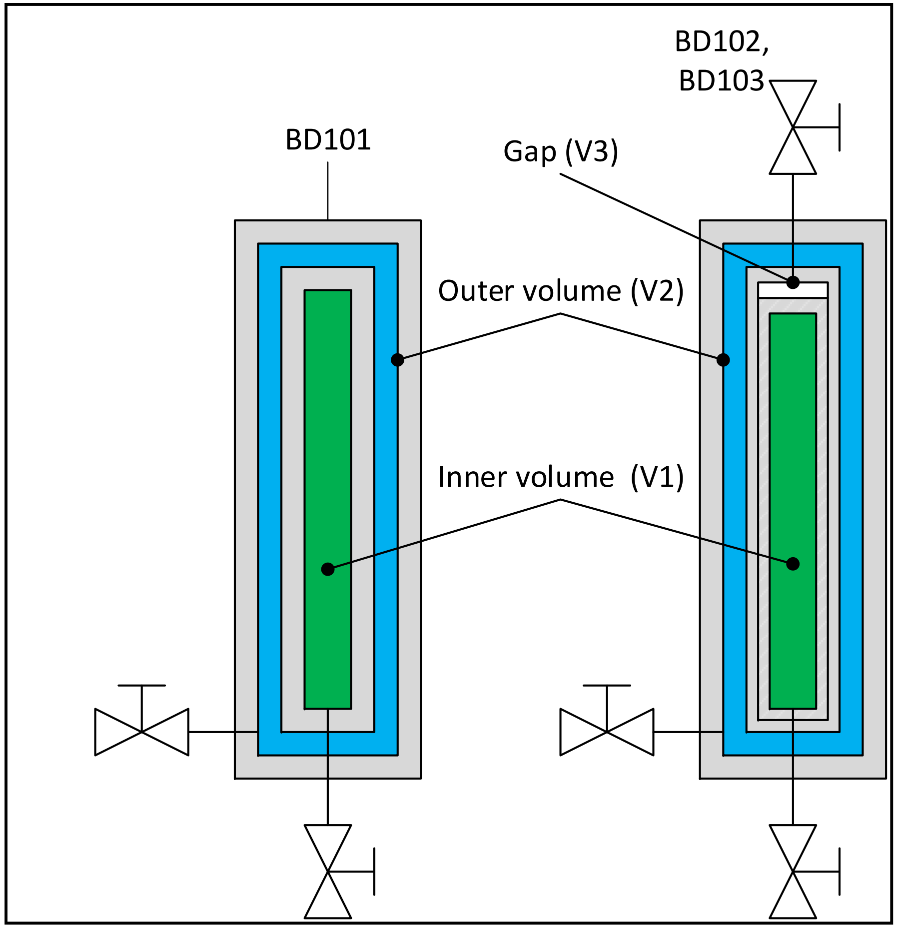
Input for WCLL	Value
Tritium generation rate, g/d	~ 320
TES efficiency, %	80
H_2 amount in coolant, ppm	8
CPS efficiency, %	90
CPS bypass, %	0.01

- Tritium permeation rate into coolant between ~16-38 g/d depending on CPS mass flow rate and assumptions on anti-permeation barriers;
- The isotopic exchange reaction between HT and H_2O trap most of the permeated tritium as HTO.



Tritium permeation experiments

- Experiments have been designed to calibrate the key WCLL and HCPB permeation parameters (e.g. Sievert's constant) into the modelling tool (e.g. EcosimPro);



Experiments relevant for the WCLL

- *Permeation from BZ to coolant:*
  - **NO PbLi**. He with a T partial pressure as expected in WCLL breeder is applied (V1);
  - Water at ~ 350 ° C (V2).
- *Permeation through SG:*
  - Tritiated water at ~ 350 ° C (V1). Assessment of dissociation and atomic permeation;
  - NO tritiated Water at ~ 350 ° C (V2).

Experiments relevant for the HCPB

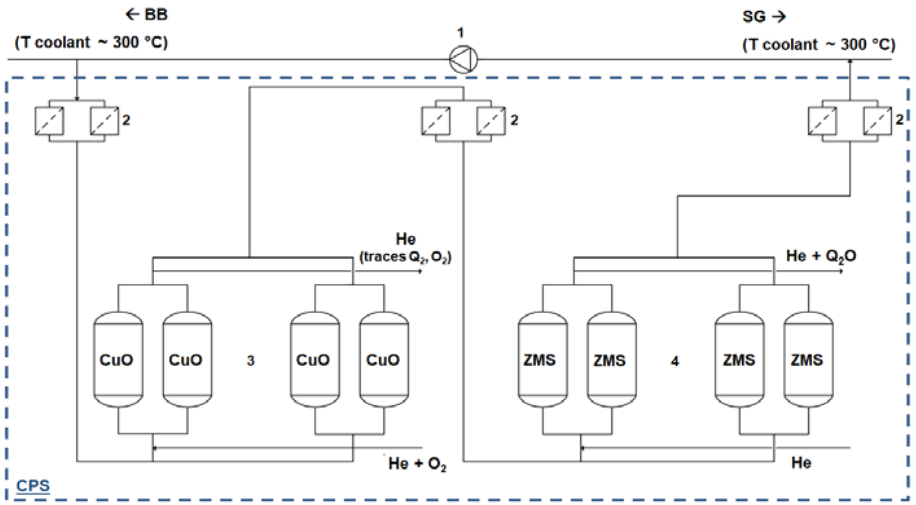
- *Permeation from BZ to coolant:*
  - He with T (V1);
  - He with hydrogen/deuterium at various partial pressure (V2).

- Results are relevant also for the EU TBM program.

O3-2.4, A. Ying et al., *Recent Advances in Tritium Modeling and Impacts on Tritium Management for Outer Fuel Cycle* (TALK)

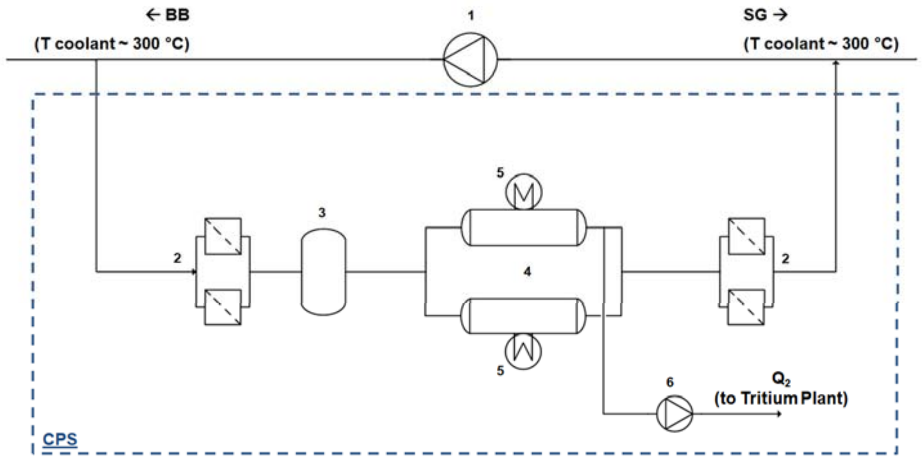
Helium CPS pre-conceptual design

- CPS main function → extract H isotopes from coolant;
- Two processes are currently considered:
  1. Scale-up of the *ITER-based solution* (CuO + ZMS beds);
  2. New approach based on Non-Evaporable Getter, NEG.
- *T permeation rate into Helium* primary coolant is in the order of *$0.1 – 1\ g\ d^{-1}$*;
- Presently No anti-permeation barriers.
- CPS unit *coolant by-pass of $3\ kg\ s^{-1}$*;
- The resulting *HT concentration inside HCS* is between *$4×10^{-3} – 4×10^{-4}$ Pa*;



Legend
1. HCS main compressor unit
2. Filters
3. CuO beds unit
4. Zeolite Molecular Sieve beds unit

1. ITER-based solution (CuO + ZMS beds)



Legend
1. HCS main compressor unit
2. Filters
3. Non regenerable getters
4. NEGs beds
5. Heaters
6. External pump

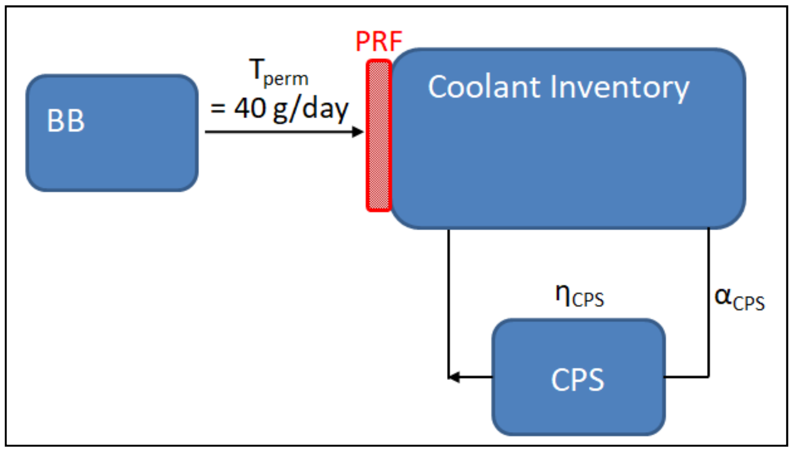
2. New approach (NEG technology)

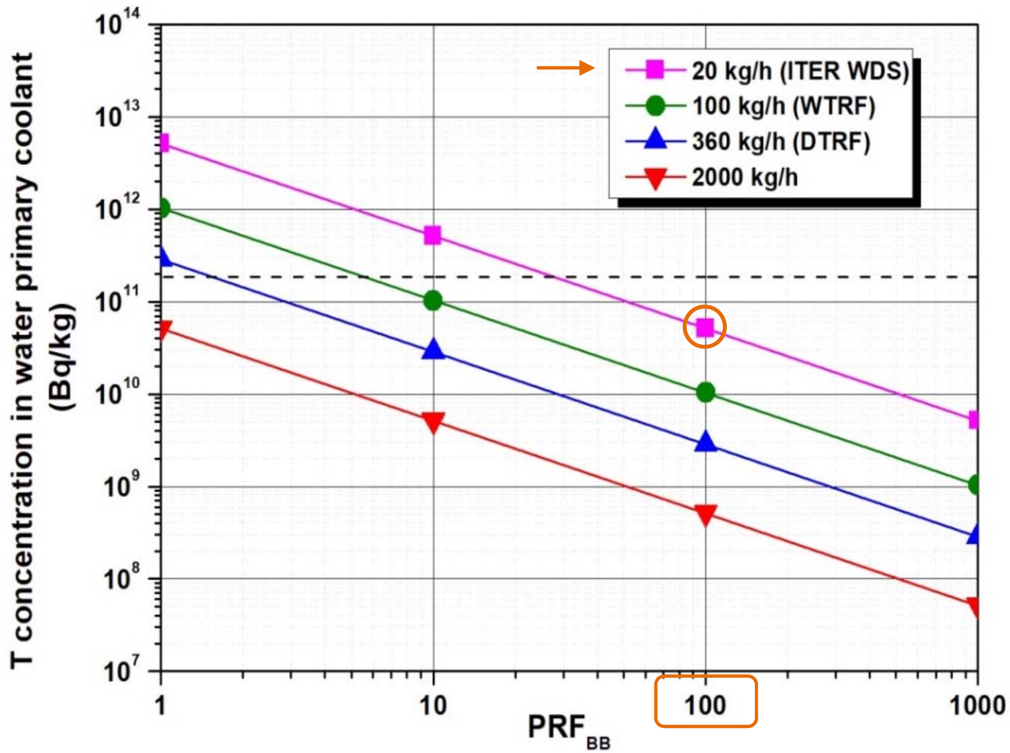
O3-2.5, A. Santucci et al., *The issue of tritium in DEMO coolant and mitigation strategies* (TALK)

Water CPS pre-conceptual design

- *T permeation rate into Water* primary coolant is *about 40 g d^{-1}*;
- Anti-permeation barriers from blanket into primary are required (*PRF_{BB}>100*);
- If a PRF_{BB} ≥100 is applied, the water CPS has to treat a *coolant flow rate of about 20 kg d^{-1}* (i.e. like ITER Water Detritiation System);
- And the resulting *T concentration in water primary coolant is below 1.85×10^{11} Bq kg^{-1}* (limit assumed in CANDU reactors).

Water CPS on-line





O3-2.5, A. Santucci et al., *The issue of tritium in DEMO coolant and mitigation strategies* (TALK)

Summary and Outlooks

Summary

- Significant progresses have been made on the design of the HCPB and WCLL BB segments and of the HCPB and WCLL TERs.
- The impact of the BB systems design on the interfacing DEMO components and system have been studied focusing on the **BB radiation protection** and on the **tritium management system**.
- No showstopper are identified: for different issues (HCPB shielding, WCLL coolant activation, CPS feasibility, TER feasibility) dedicated solutions have been identified and will be further investigated.
- A focused R&D program is running to validate technologies (TER, CPS) and assumptions made in tritium modelling (co-permeation, Sievert constant).

Outlooks

- BB design simplification for improving manufacturability and reliability.
- Selection of the technologies for the Tritium management systems and definition of the working point.
- Qualification of TER and CPS technologies by R&D program.
- Associate to BB segments and TER system design a sound cost estimate, implementing from the conceptual phased cost reduction measures.

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THANKS FOR YOUR ATTENTION

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