Invited Talk
FuseNet Master Event
Online, 5-6 October, 2021

FuseNet Master Event 5 and 6 October

EUROfusion

DEMO Breeding Blanket Concepts in EURO*fusion*
Work Package Breeding Blanket (WPBB)

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Outline

1. What is a Breeding Blanket? Why Breeding Blanket?
2. What is a HCPB? And a WCLL? Why those as candidates?
3. Common Architectural Features and Top-Level Requirements
4. The HCPB Solid Breeding Blanket
5. The WCLL Liquid Metal Breeding Blanket
6. Challenges
7. Conclusions

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Breeding Blanket: a key system in any D-T fusion electricity-producing devices.

$$^{3}_{1}T + ^{2}_{1}D \rightarrow ^{4}_{2}He + n + 17.6\ \text{MeV}$$

Tritium (*T*) has a half-life of 12.3 years. ***T*** decays at a rate of 5.5%/yr.

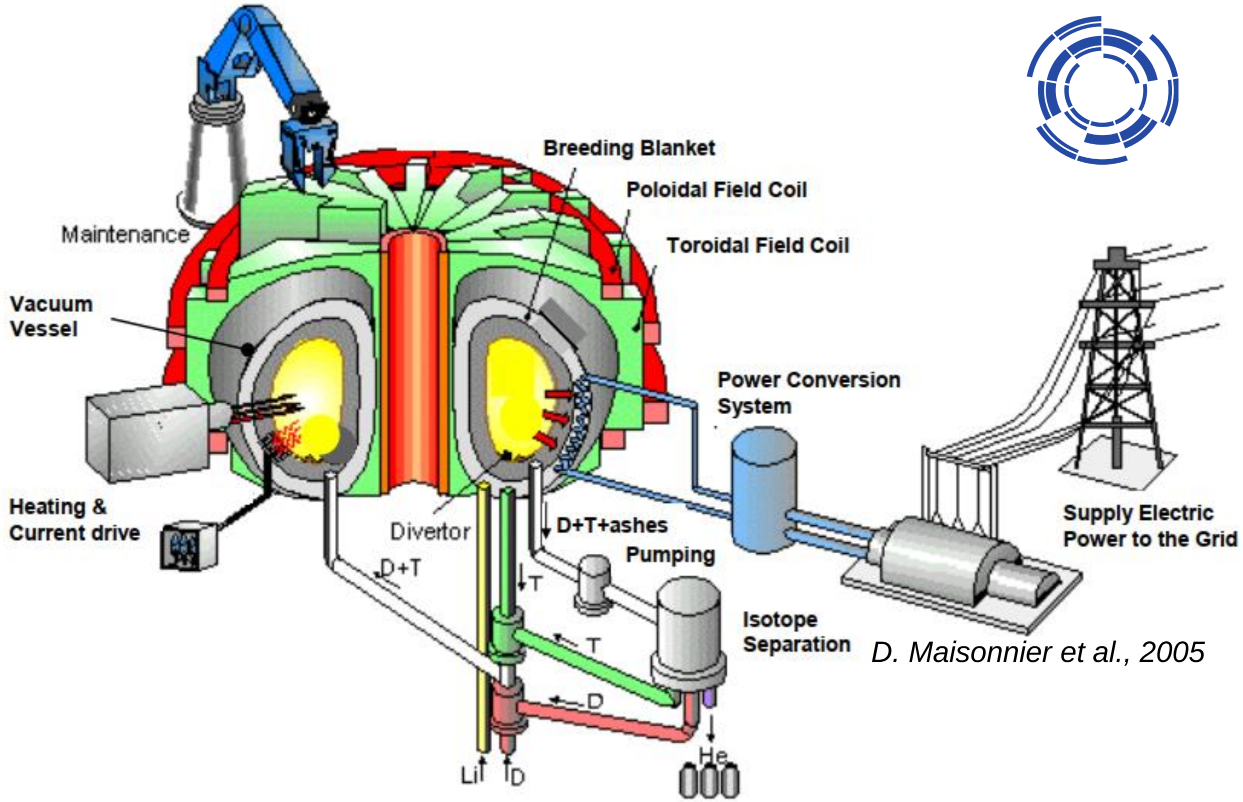
1 GW fusion (thermal) power device:
56 kg *T* per full power year (fpy).

2 GW EU-DEMO fusion power: 112 kg ***T*** per fpy

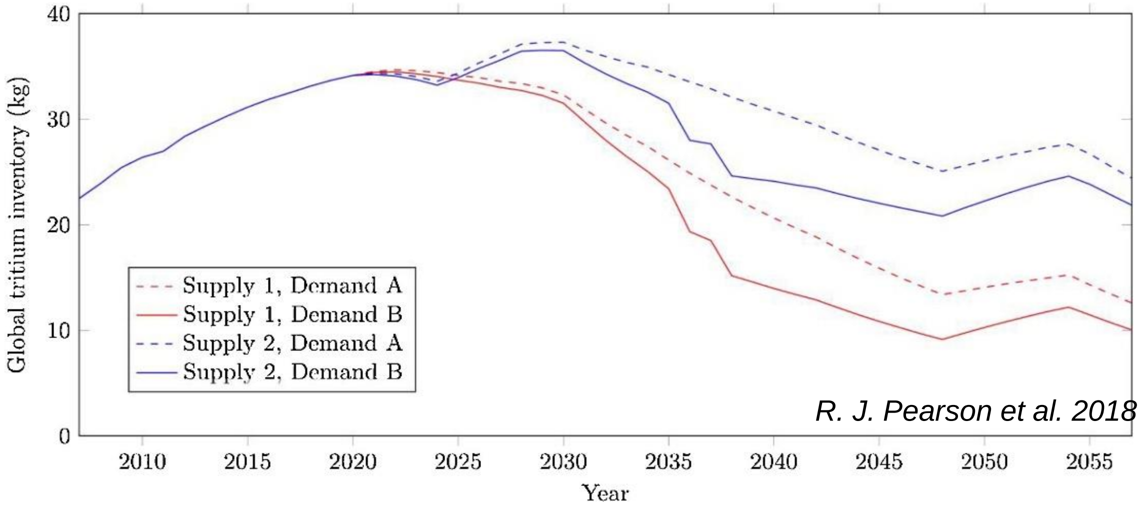
Global availabe *T* inventory: Heavy Water (D_2O) Reactors (CANDU)

$$n + ^{2}_{1}D \rightarrow ^{3}_{1}T + \gamma$$

Need to produce ***T***, in order to economically viable.



D. Maisonnier et al., 2005



R. J. Pearson et al. 2018

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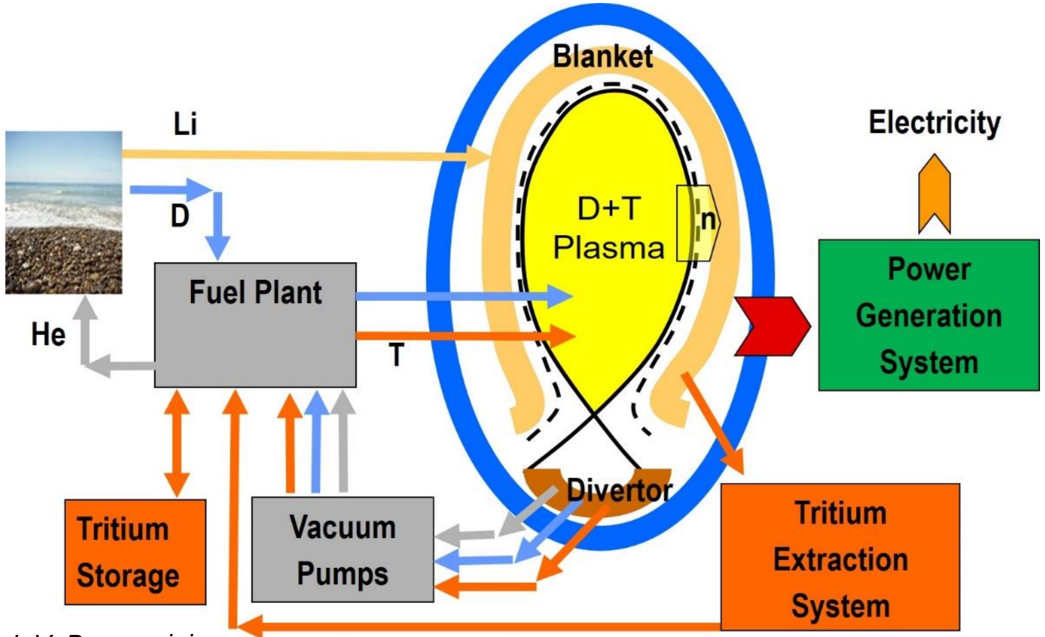
Why Breeding Blanket?

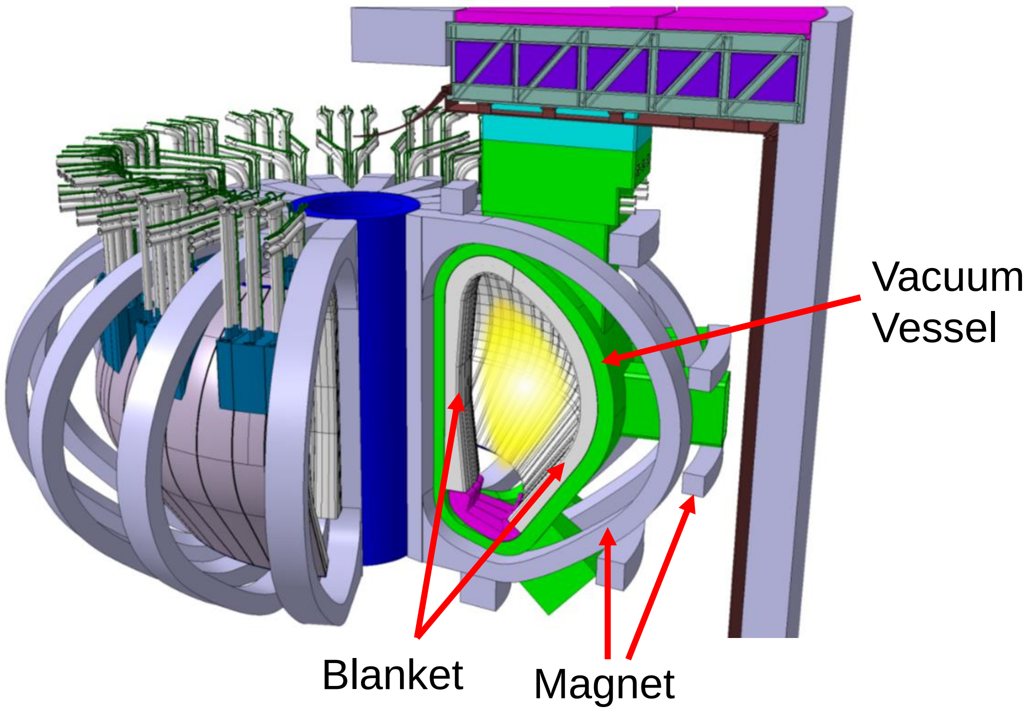
- **Main functions of the blanket:**
  - tritium breeding => tritium self-sufficiency
  - heat removal => electricity production
  - shielding => protect magnets from neutrons

$$^{6}_{3}Li + n \rightarrow \, ^{4}_{2}He + T$$

$$^{3}_{1}T + \, ^{2}_{1}D \rightarrow \, ^{4}_{2}He + n + 17.6\ \mathrm{MeV}$$



Credit: L.V. Boccaccini



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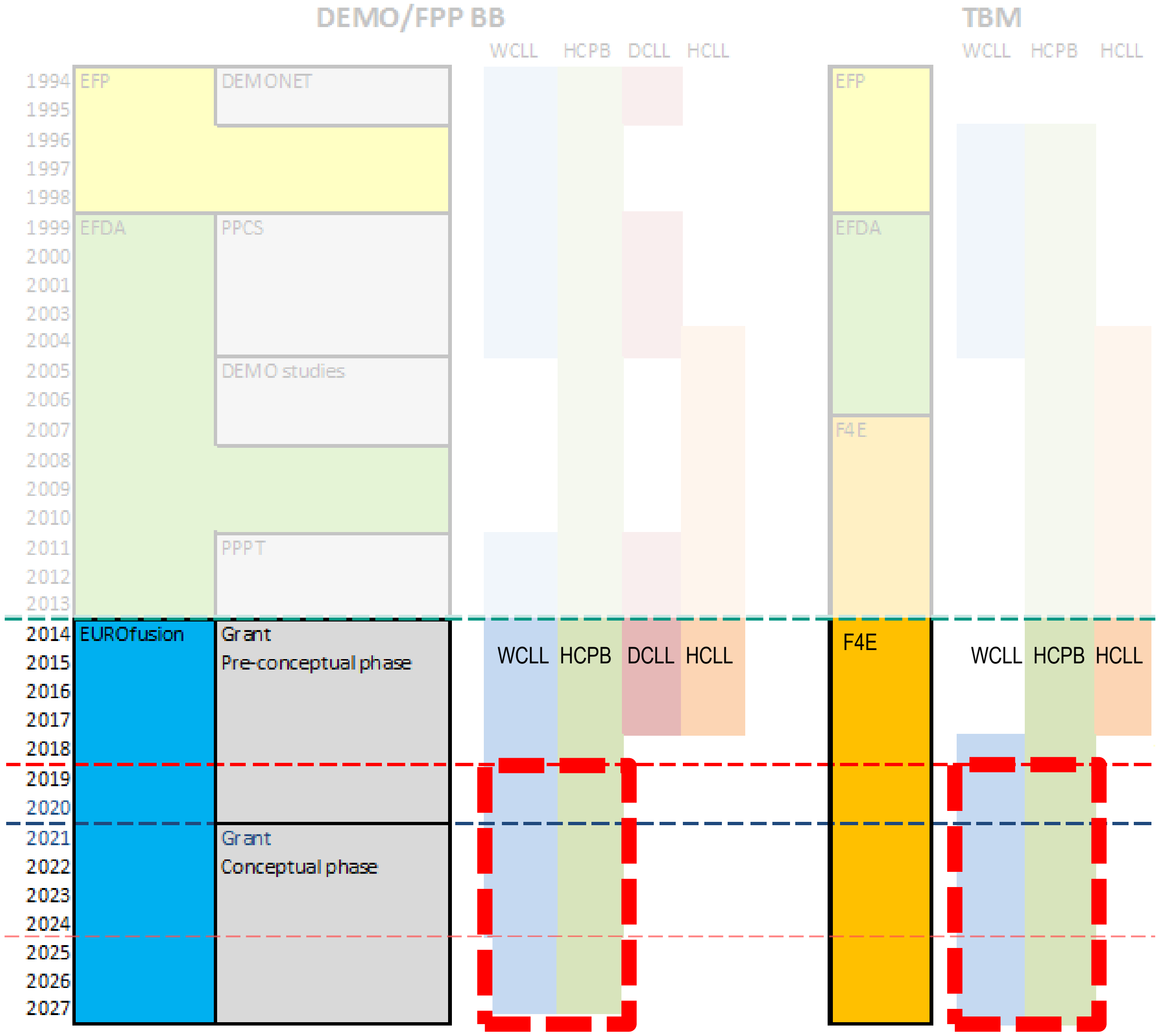
Brief History of the EU BB Programme



- EU: BB development of solid and liquid BBs since 80s.
- **90s:** key studies (DEMONET 1995-1998) and PPCS 1999-2004) to define EU BB concepts for DEMO and TBM.
- **2003:** HCLL replaced WCLL. New architecture for HCPB and HCLL, both selected for ITER TBM.
- **2007:** F4E takes responsibility for the TBM program in ITER.
- **2011:** EFDA PPPT
- **2014:** EUROFusion PPPT begins, broad framework for EU DEMO BB development proposed.
- **2018:** EUROfusion – F4E BB program realignment: HCPB and WCLL as EU DEMO BB options
- **2024:** Blanket selection for DEMO
- **2027:** Conceptual phase concluded

Abbreviations:

HCPB – Helium Cooled Pebble Bed
WCLL – Water Cooled Lithium Lead
HCLL – Helium Cooled Lithium Lead
DCLL – Dual Coolant Lithium Lead
F4E – Fusion for Energy
PPPT – Power Plant Physics and Technology

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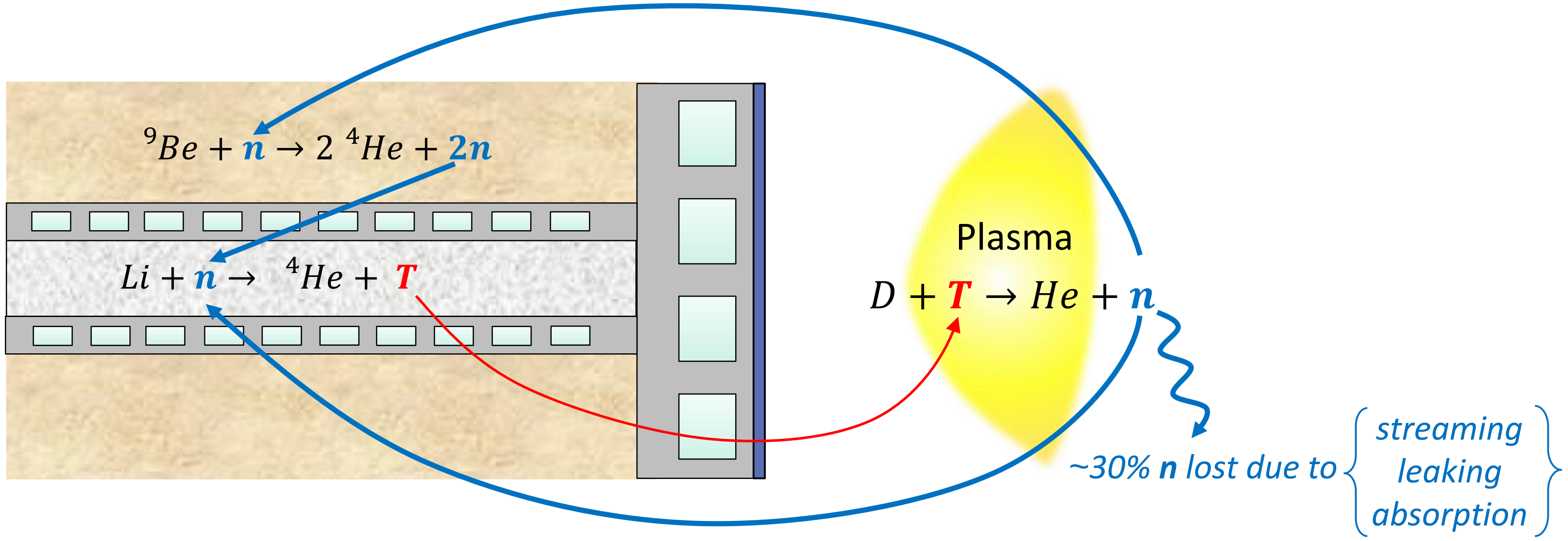
2. What is a HCPB (Solid Breeder)?

- ***Helium Cooled Pebble Bed Breeding Blanket*** (HCPB BB)



- Tritium Breeding Function

  $^{6}Li + \boldsymbol{n} \rightarrow\ ^{4}He + \boldsymbol{T}$

  *Li compound (Li ceramics) as **T** breeder*

- Neutron multiplier (NM) function:

  $^{9}Be + \boldsymbol{n} \rightarrow 2\ ^{4}He + \boldsymbol{2n}$

  *Be/Beryllides as **n** multiplier*

- Structural material: Reduced Activation Ferritic Martensitic (RAFM) steel, Eurofer-97

- Heat extraction: Helium (HTR-like)

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2. Why the HCPB as candidate BB for DEMO?

- Tritium Breeding Function

  $^{6}_{3}Li + \boldsymbol{n} \rightarrow {}^{4}_{2}He + \boldsymbol{T}$

  ↳ *Li compound (Li ceramics) as* $\boldsymbol{T}$ *breeder*

  - High Li density: compactness, low ^{6}Li enrichment
  - Avoid MHD, reactivity, corrosion, **i.e. no coatings**
  - **Simpler, proven separation of T from purge gas**
  - **Simpler, proven T extraction from breeder**

- Structural material: RAFM Eurofer-97 steel
  - High temperature operation (≈550°C)
  - **Good thermal conductivity (2x SS316)**
  - **Capability for high irradiation damage**

- Neutron multiplier (NM) function:

  $^{9}_{4}Be + \boldsymbol{n} \rightarrow 2{}^{4}_{2}He + \boldsymbol{2n}$

  ↳ *Be/Be-alloy as* $\boldsymbol{n}$ *multiplier*

  - Dual function: multiplier and moderator
  - Allows best setting NMM-to-breeder ratio
  - **Best** $\boldsymbol{T}$ **breeding in compact space**

- Heat extraction: Helium gas
  - **Neutronically transparent, no activation**
  - **1-phase** (high temperature operation)
  - **Chemically inert, no chemistry needed**
  - **Best compatibility with Eurofer-97 and functional materials**
  - **Nuclear experience in High Temperature Gas Reactors (HTGR: HTR-PM demonstration power plant)**

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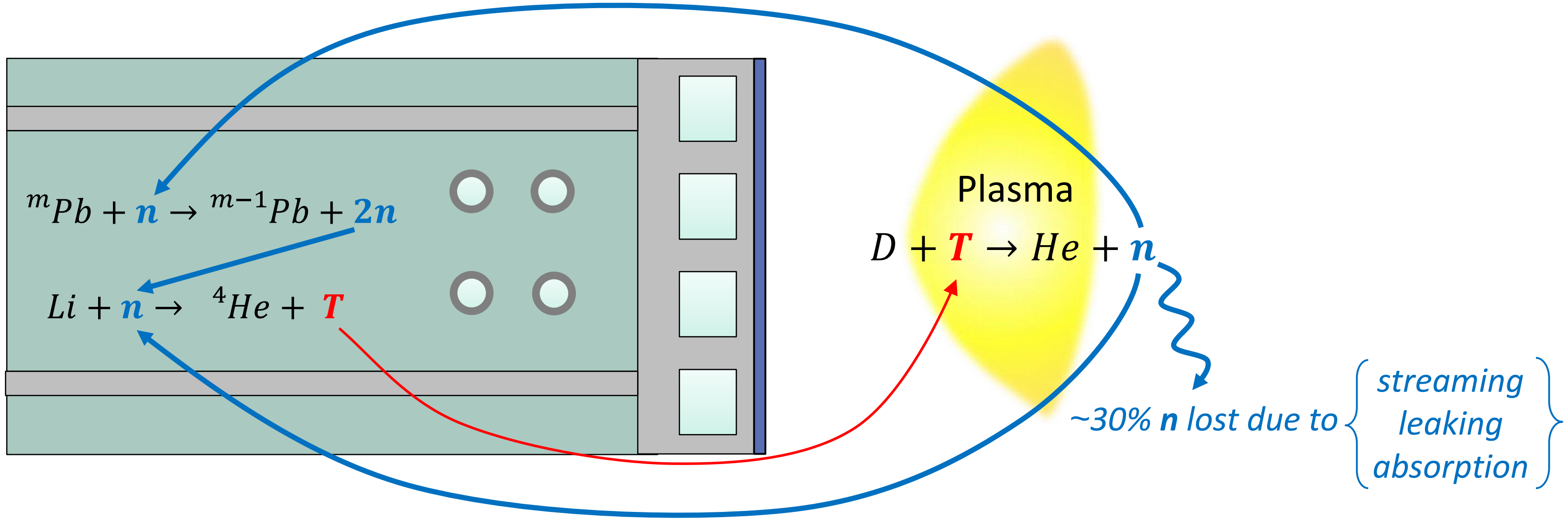
2. What is a WCLL (Liquid Metal Breeder)?

- ***Water Cooled Lead Lithium Breeding Blanket*** (WCLL BB)



- Tritium Breeding Function

$$Li + \boldsymbol{n} \rightarrow {}^{4}He + \boldsymbol{T}$$

- Neutron multiplier (NM) function

$$^{m}Pb + \boldsymbol{n} \rightarrow {}^{m-1}Pb + \boldsymbol{2n}$$

Li – Pb alloy (15.7%Li-84.3%Pb eutectic)
as $\boldsymbol{T}$ *breeder and* $\boldsymbol{n}$ *multiplier*

- Structural material: Reduced Activation Ferritic Martensitic (RAFM) steel, Eurofer-97
- Heat extraction: Water (PWR-like)

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2. Why the WCLL as candidate BB for DEMO?

- Tritium Breeding Function

$$Li + \mathbf{n} \rightarrow {}^{4}He + \mathbf{T}$$

- Neutron multiplier (NM) function

$$ {}^{m}Pb + \mathbf{n} \rightarrow {}^{m-1}Pb + \mathbf{2n}$$

Li – Pb alloy (15.7%Li-84.3%Pb eutectic)
as $\mathbf{T}$ breeder and $\mathbf{n}$ multiplier

- $\mathbf{T}$ breeder and $\mathbf{n}$ multiplier combined as a single material
- **Eutectic alloy, liquid phase**
- Satisfactory $\mathbf{T}$ breeding performance
- **Low $\mathbf{T}$ solubility, online $\mathbf{T}$ extraction**
- **Reasonable heat transfer performances**

- Structural material: RAFM Eurofer-97 steel
  - High temperature operation (≈550°C)
  - **Good thermal conductivity (2x SS316)**
  - **Capability for high irradiation damage**

- Heat extraction: Water (PWR)
  - Cheap and largely available
  - **Excellent heat transfer features**
  - Excellent thermalizing neutrons (good for shielding, not so good for NMM)
  - **Widely used in fission industry**

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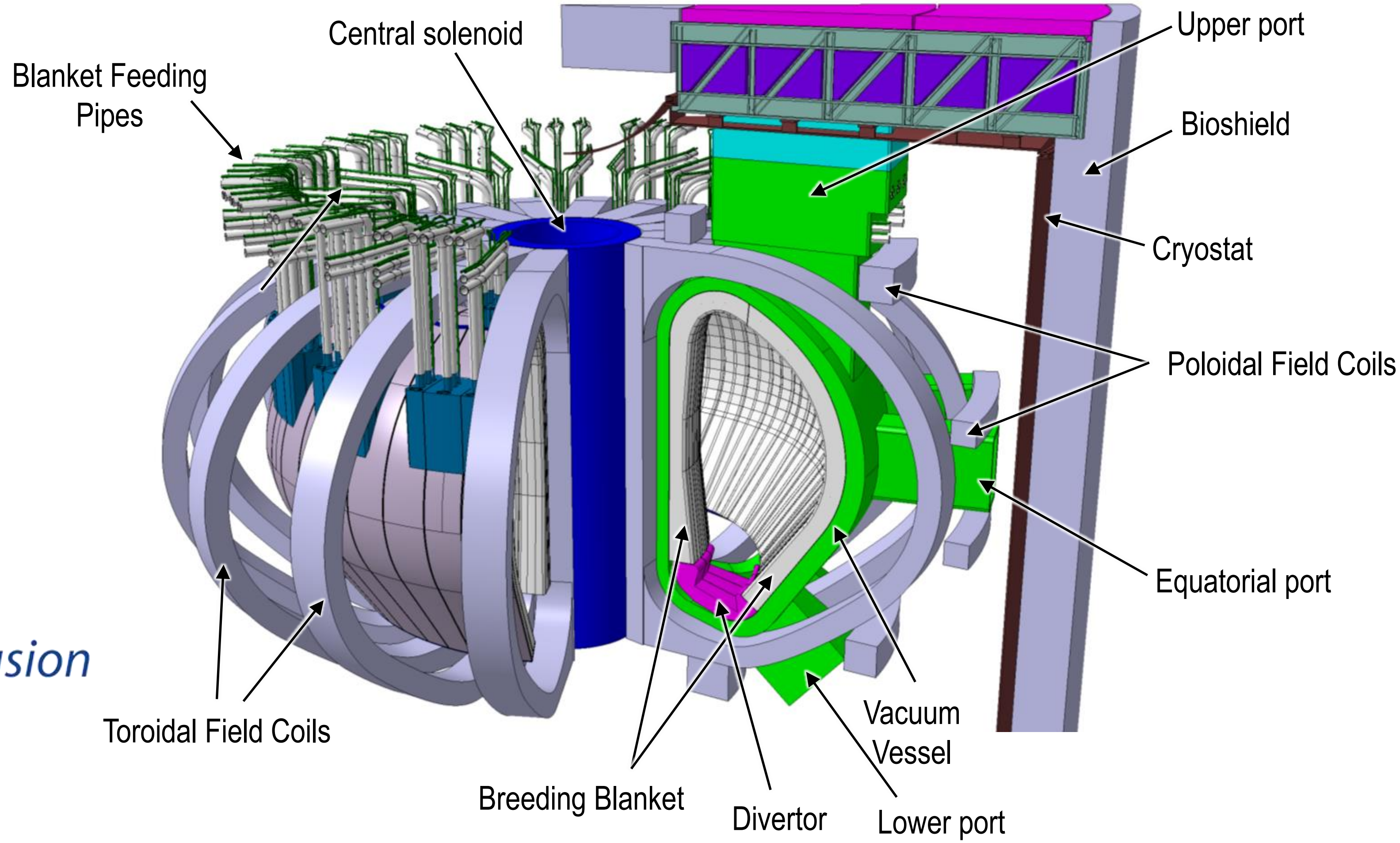
Outline

3. Common Architectural Features: Blanket Segmentation

- EU DEMO Tokamak Baseline 2017 (latest reference, R_0=9m, A=3.1, P_{fus}≈2GW)



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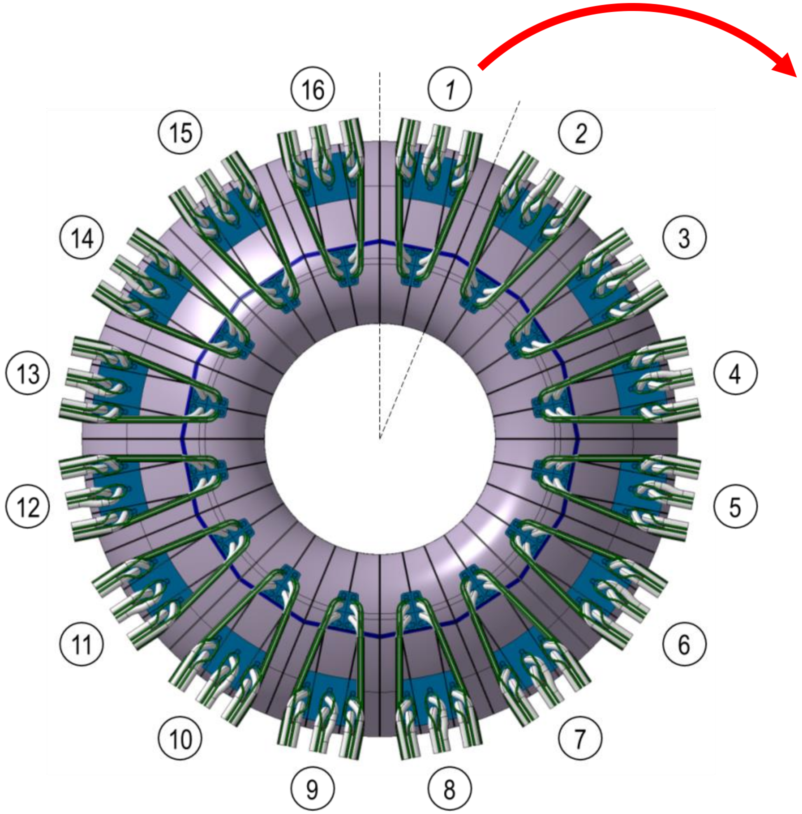
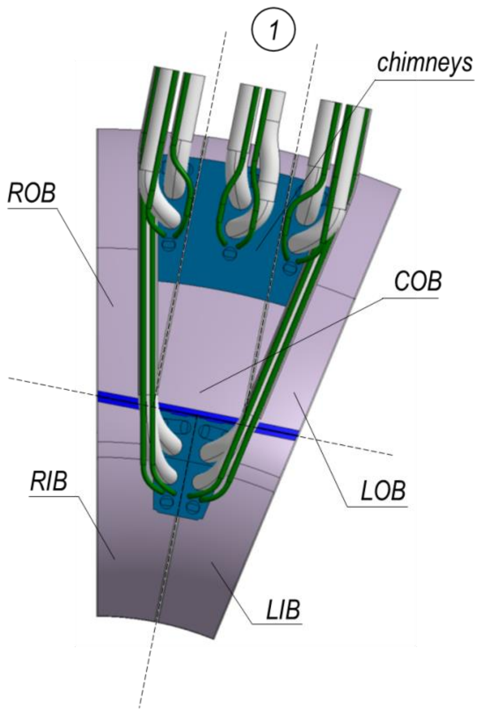
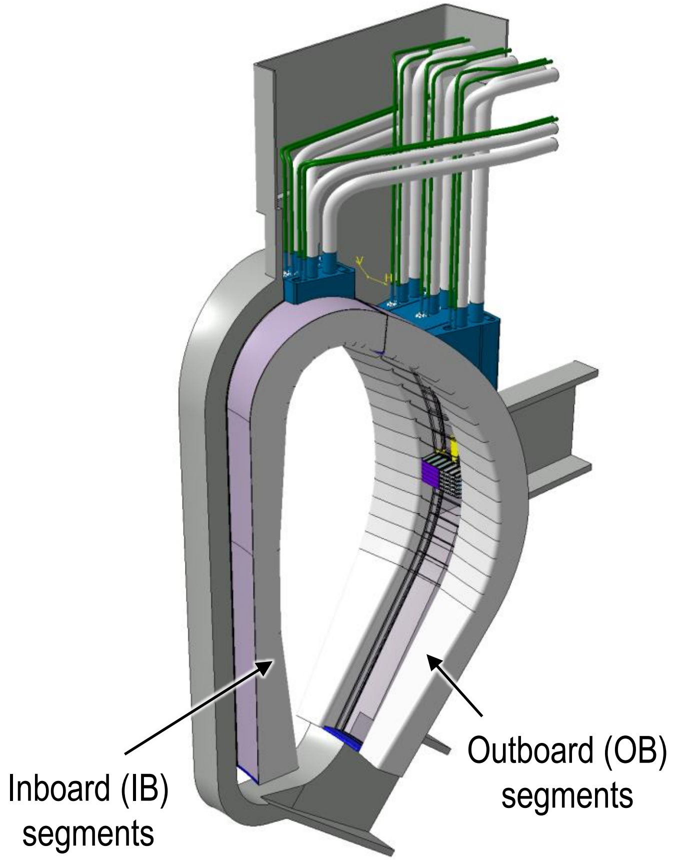
3. Common Architectural Features: Blanket Segmentation

- EU DEMO Tokamak Baseline 2017 (latest reference, R_0=9m, A=3.1, P_{fus}≈2GW)
  - Tokamak divided in **SECTORS** (16 sectors as of BL2017)
  - Breeding Blanket SECTORS divided in Blanket **SEGMENTS**
  - Blanket SEGMENTS divided in **INBOARD** and **OUTBOARD SEGMENTS**
  - Per SECTOR: 2x INBOARD SEGMENTS and 3x OUTBOARD SEGMENTS







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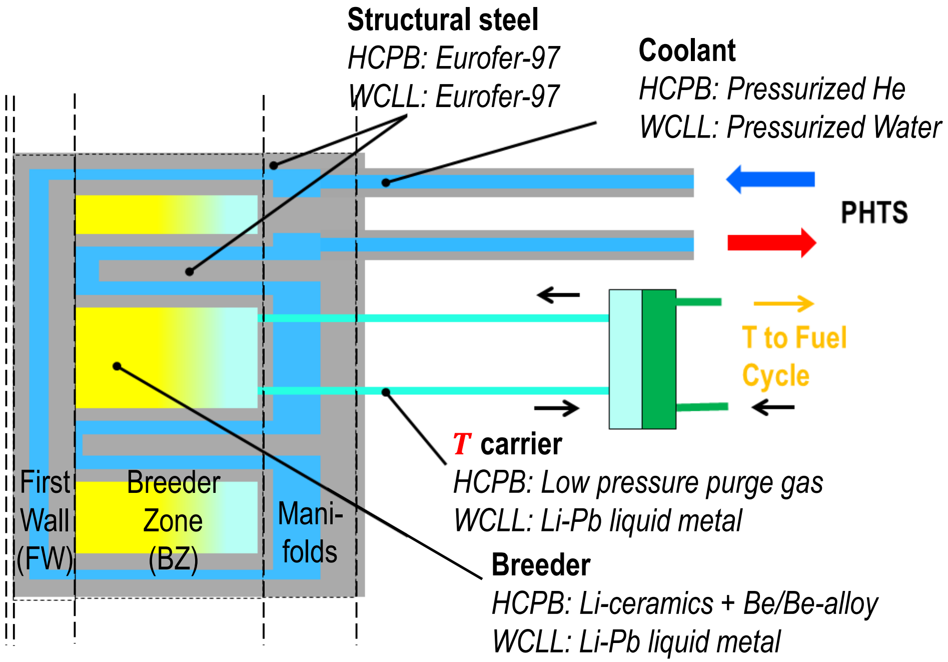
3. Common Architectural Features: Separate Breeding / Cooling Functions

- Many architectural solutions exist.
- Near term BB architecture for the EU DEMO => **Breeder and coolant are contained into two completely separate circuits with separate functions**
  - **The coolant loop function**: It removes heat and allows to transport it from the Primary Heat Transfer System (PHTS) to the Power Conversion System (PCS)
  - **The breeder loop function**: It produces ***T*** and allows to transport it (with a ***T*** carrier) outside the vacuum vessel. ***T*** is then be removed (from the carrier) and recovered (as molecular form) and delivered to the Fuel Cycle



Credit: L.V. Boccaccini

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3. Common Top-Level Requirements

- **Reactor Availability** > 30%
- **Tritium Breeding Ratio (TBR):** $TBR_{required} \geq 1.05$, $TBR_{design} \geq 1.15$ (w/o BB loss of coverage)
- **Neutron shielding:**
  - Nuclear heating in TFC < 50 W/m³, vacuum vessel (VV) damage < 0.2dpa/fpy, He production in steel structures to be rewelded < 1appm/fpy, SDDR in accessible regions <100µSv/hr
- **Temperature design limits:**
  - Li-ceramics: ≈ 400°C (***T***-release) – 920°C (pebbles sintering)
  - Be-alloy: ≈ 500°C (***T***-release) – 900°C (max. tested under irradiation)
  - Pb-Li: > 235°C (avoid freezing) – 500°C (at Eurofer-97 interfaces, corrosion)
  - Eurofer-97: 350°C (DBTT*) – 550°C (S_{creep})
- **Thermo-mechanics and design**
  - Fulfilment of criteria in selected nuclear codes and standards (ASME, RCC-MRx, JSME…)
  - Selected code: RCC-MRx 2018 (DEMO specific code under development, SDC-DC)
    - Stress limits under P-type (excessive deformation, plastic collapse, creep) and S-type damage (ratcheting, fatigue, creep-fatigue) modes, fast fracture mode if embrittlement occurs
    - Component design, materials, manufacturing and joining qualification after code rules

*DBTT – Ductile Brittle Transition Temperature

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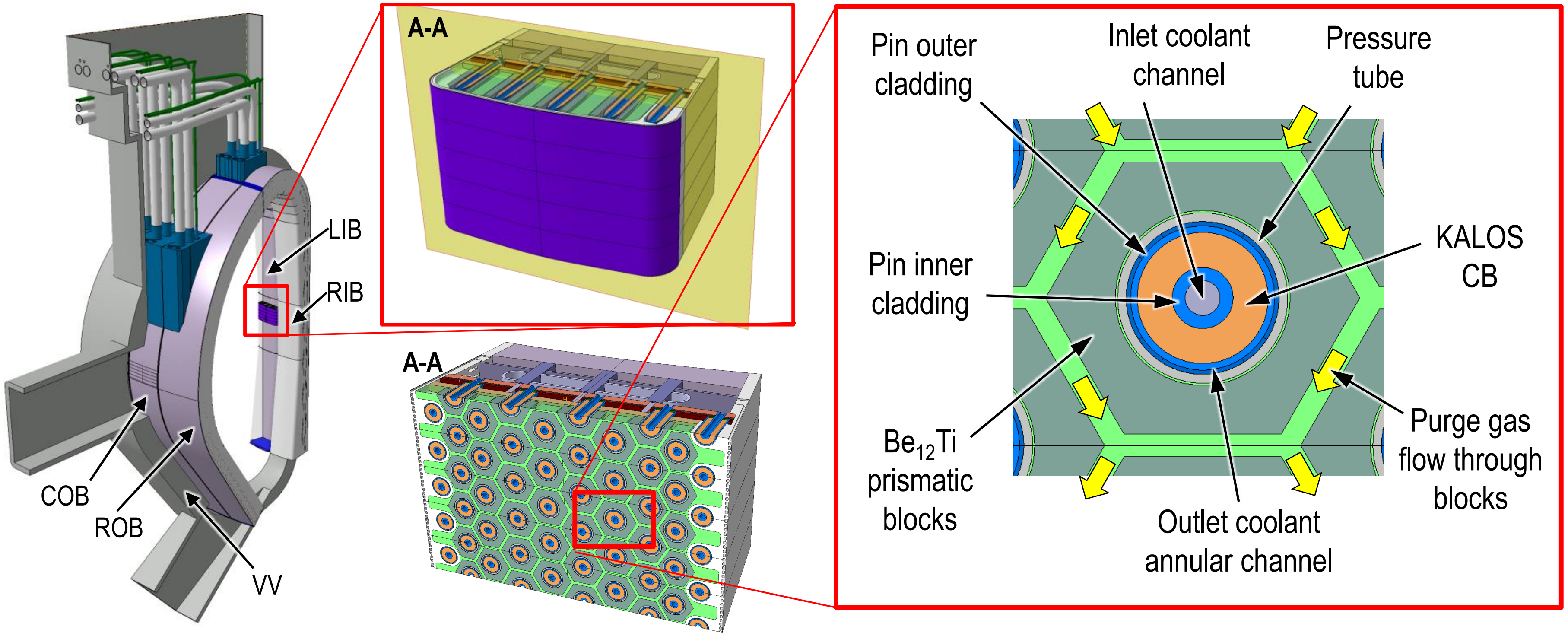
4. The HCPB BB: General Description

- HCPB „fuel-breeder pin“ design (BL2017)



- Arrangement of fuel-breeder pins containing ***T*** breeder material
- Pins inserted into hexagonal prismatic blocks of neutron multiplier
- Structural steel: Eurofer-97

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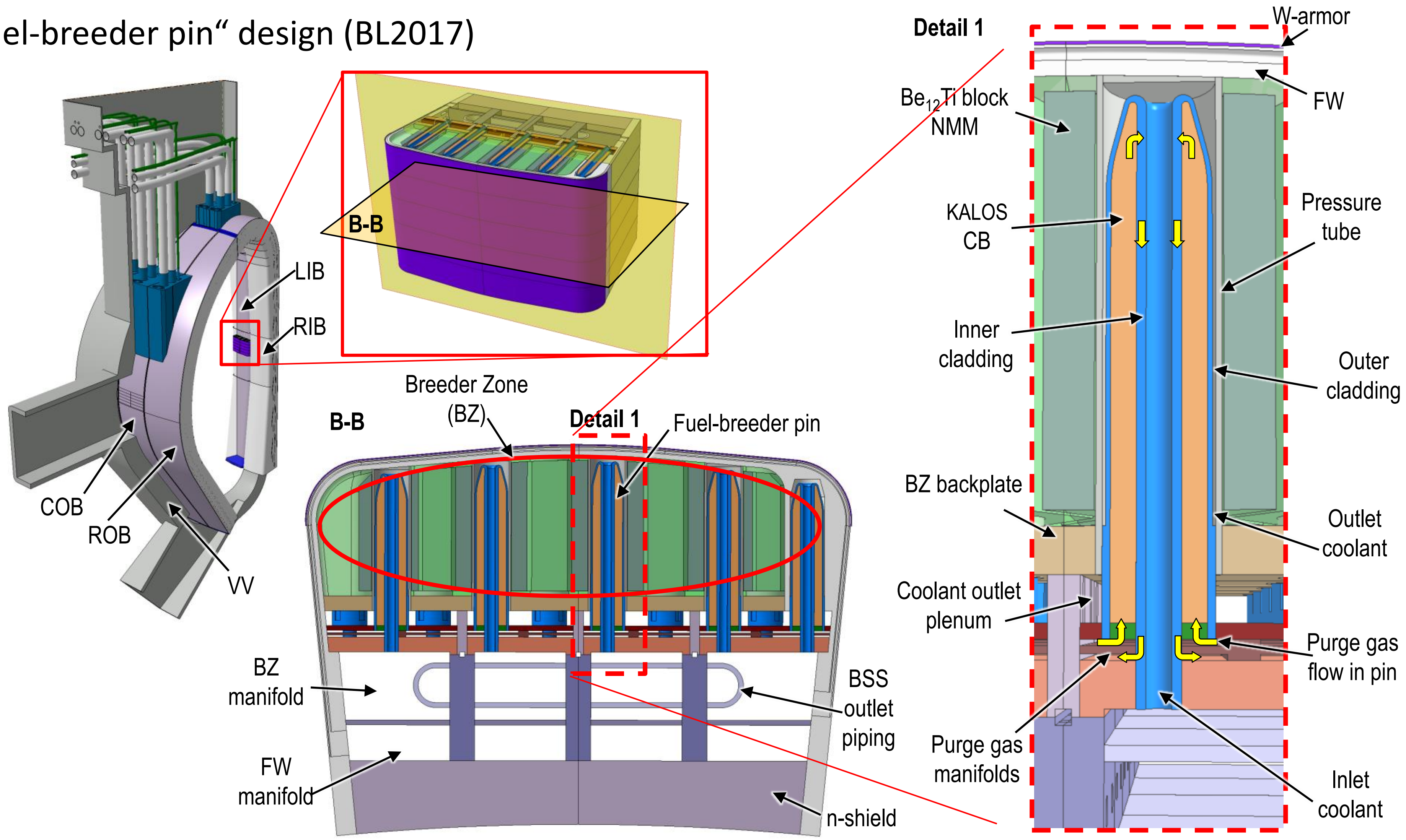
- HCPB „fuel-breeder pin“ design (BL2017)



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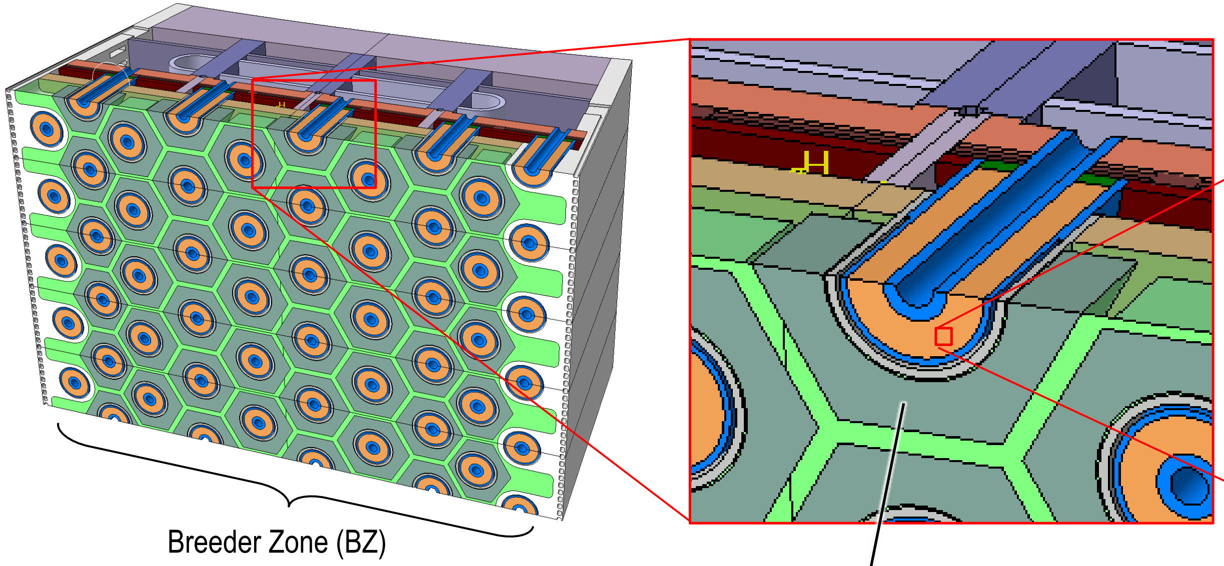
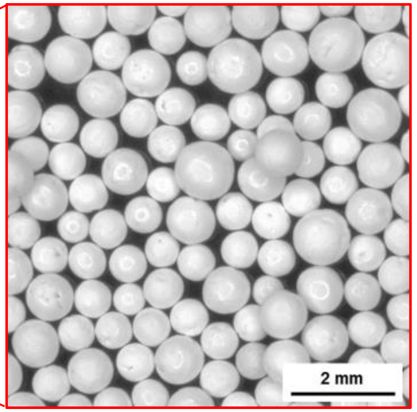
4. The HCPB BB: General Description

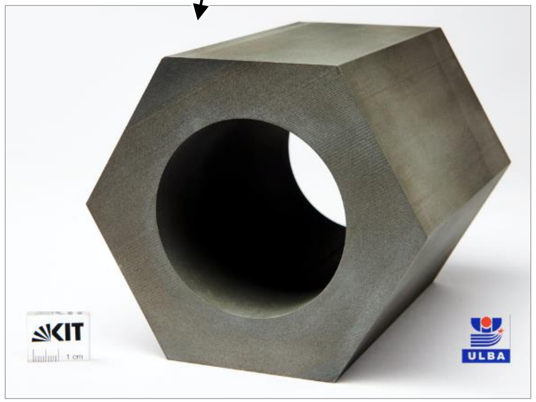
- Functional materials



- ***T*** breeder: Li ceramics (Li_4SiO_4 + 35%mol Li_2TiO_3), ^6Li 60% enriched, in form of pebbles



- Neutron multiplier: Be intermetallics ($Be_{12}Ti$) in form of hexagonal prismatic blocks



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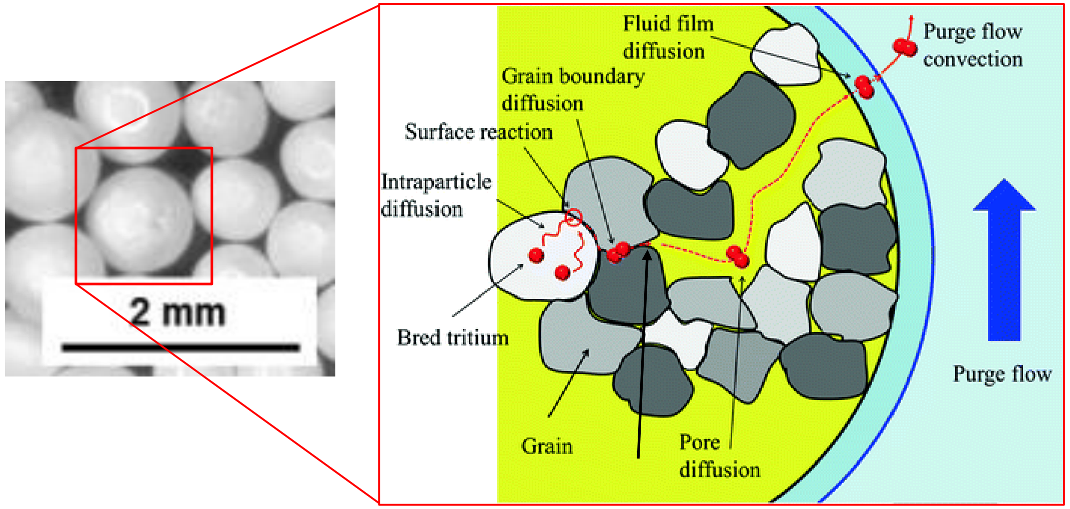
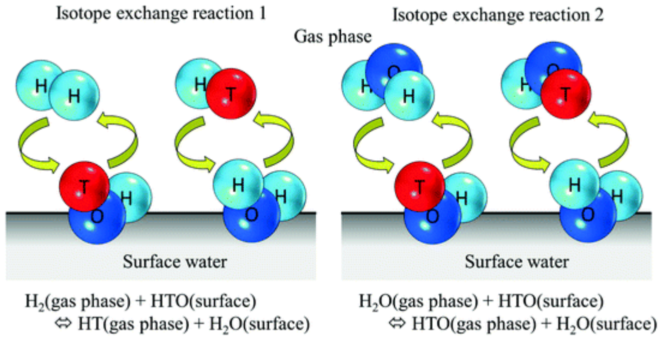
4. The HCPB BB: General Description

- ***T*** breeding and extraction: Purge gas function
  - ***T*** is formed in the Li ceramics (pebbles) and <u>it is extracted at the BB</u> in form of H***T***O, H***T***
  - A purge gas flow through the pebble beds collects H***T***O, H***T*** and transports it out of the BB
  - Purge gas chemistry: carrier (He) + doping agent (H_2/H_2O) to favour isotopic exchange reactions
  - ***T*** transport mechanisms at pebble bed level:



1. Intergranular diffusion through grain bulk
2. Surface reactions (isotopic exchange)



3. Grain-boundary diffusion to a pore
4. Surface adsorption / desorption into the pore
5. Pore diffusion to pebble boundaries
6. Release to purge gas flow and convection

  - Use of Li ceramic pebbles: Minimize temperature gradients in ceramics and the ***T*** residence time

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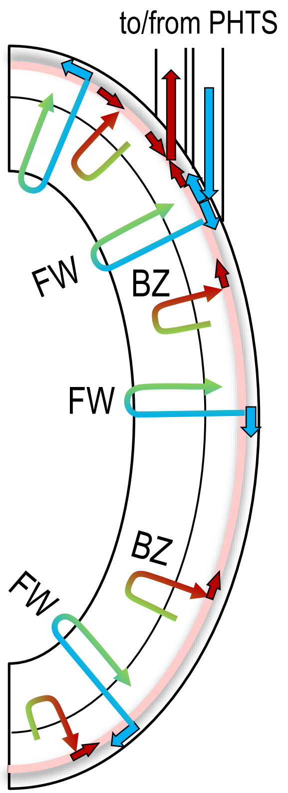
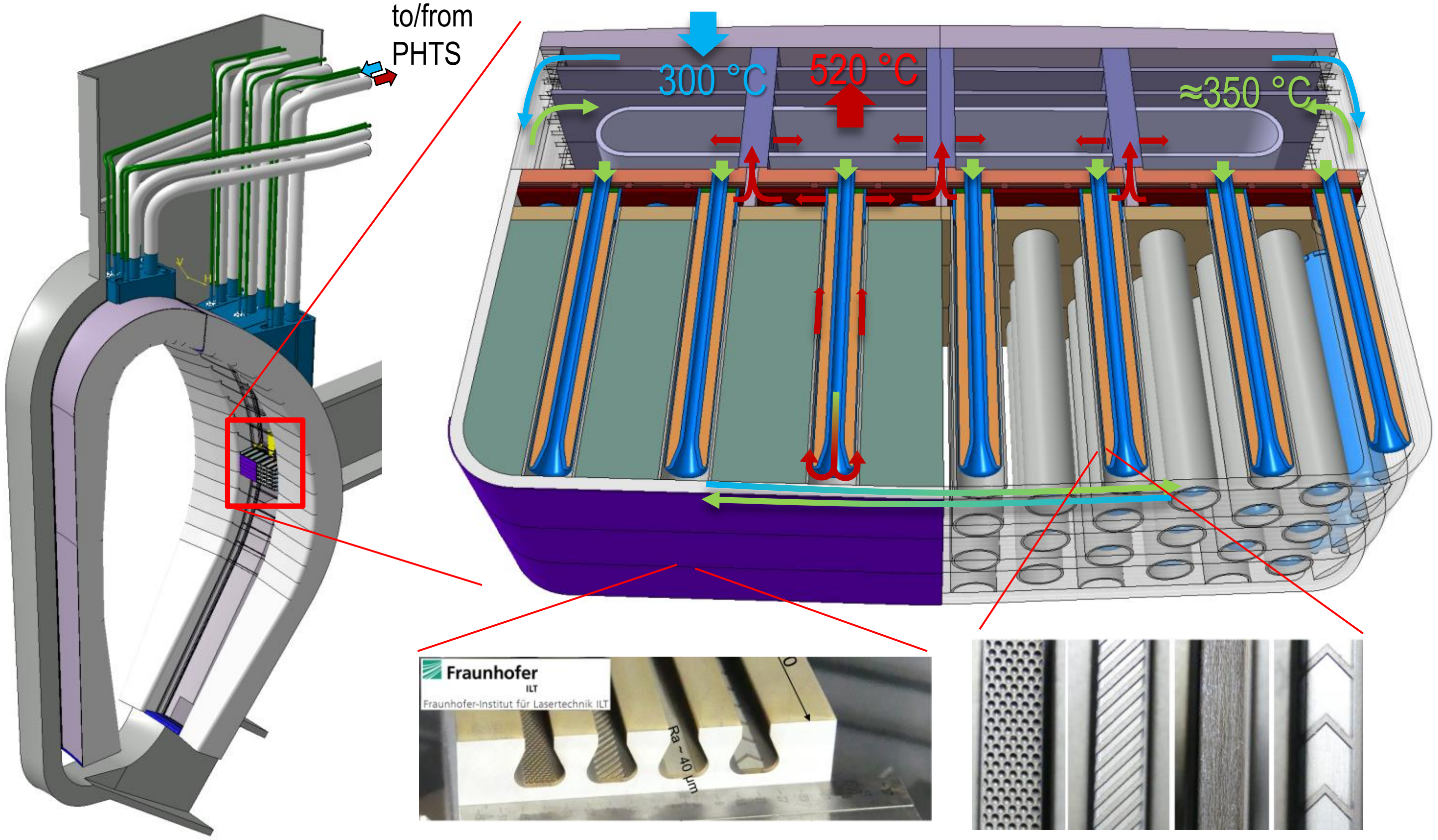
4. The HCPB BB: Coolant Scheme

- Coolant thermo-hydraulic parameters:
  - He 80 bar, T_{in} = 300°C (limited by $\boldsymbol{n}$-induced DBTT shift), T_{out} = 520°C (limited by steel S_{creep})
  - FW and BZ connected in series
  - Need for heat transfer augmentation structures in FW and fuel pins





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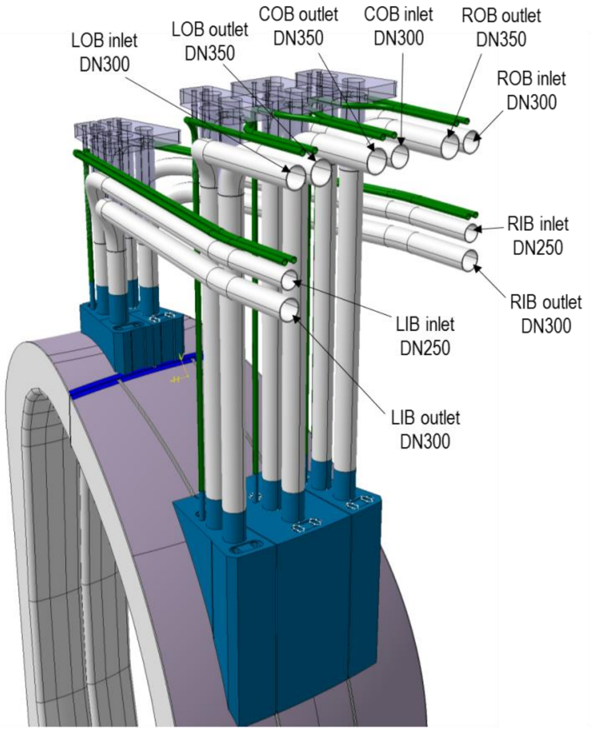
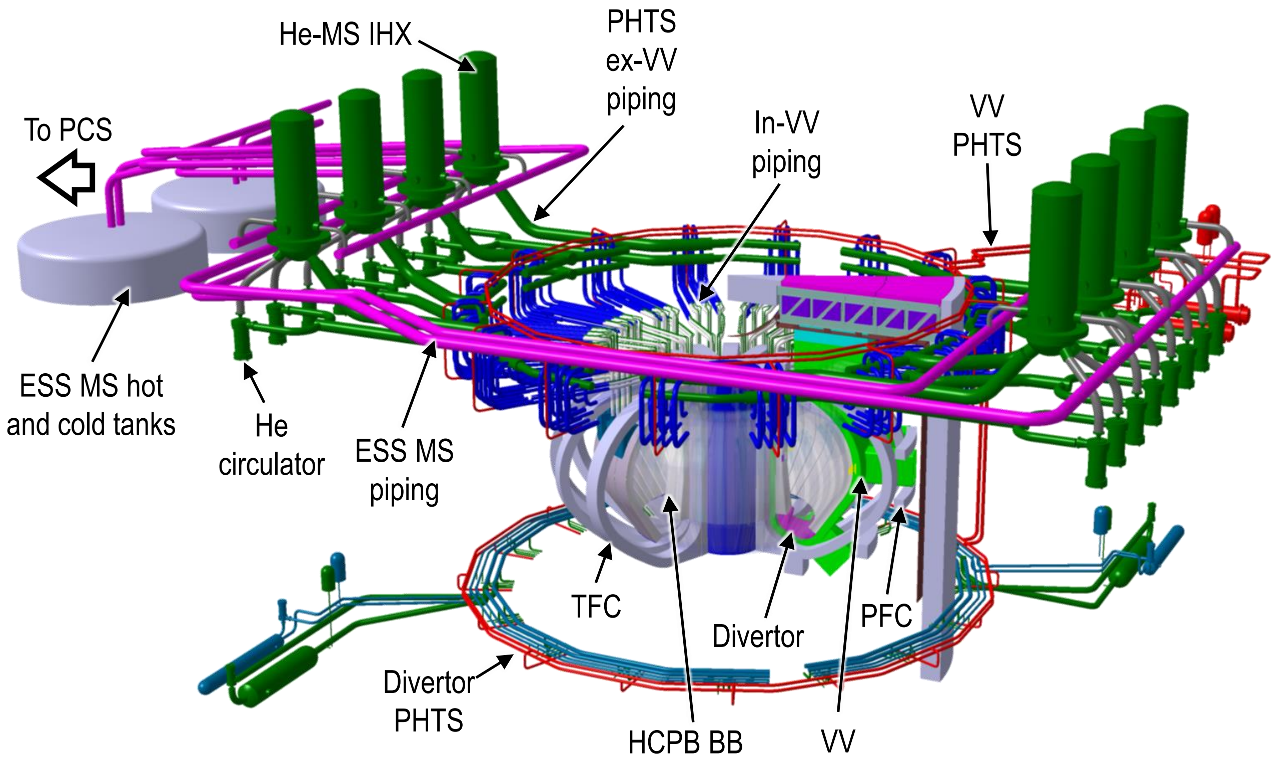
4. The HCPB BB: Coolant Scheme, BoP Interface

- One of key BB interfaces: Balance of Plant (BoP) = Σ { Primary Heat Transfer System (PHTS); Intermediate Heat Transfer System (IHTS); Power Conversion System (PCS) }





- IHTS incorporates an Energy Storage System (ESS, CSP-like molten salt system)
- PHTS = 8 cooling loops, 1 loop = 1 IHX (He – molten salt) + 2 He circulators
- High BoP TRL ⇔ $P_{1circ,el}$ <6MW ⇔ Δp_{PHTS} <3 bar (for P_{fus}≈2GW); Δp_{inVV}≈0.8 bar; Δp_{exVV}≈1.9 bar; Δp_{PHTS}≈2.7 bar => **$P_{1circ,el}$ ≈5.6 MW**

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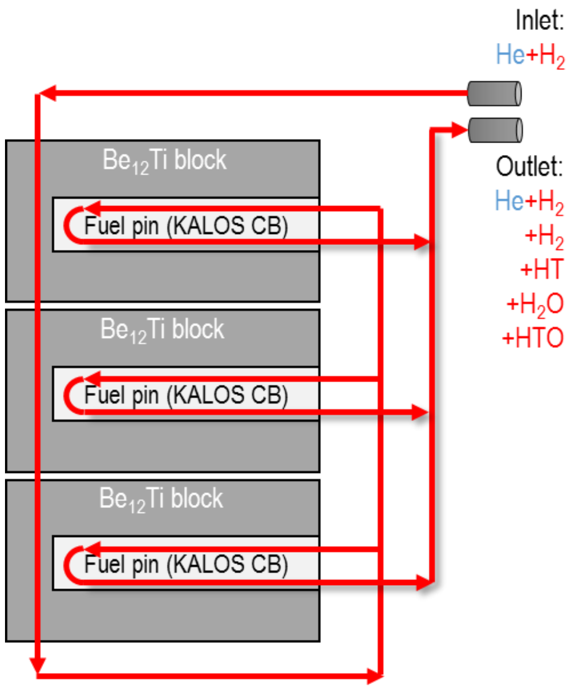
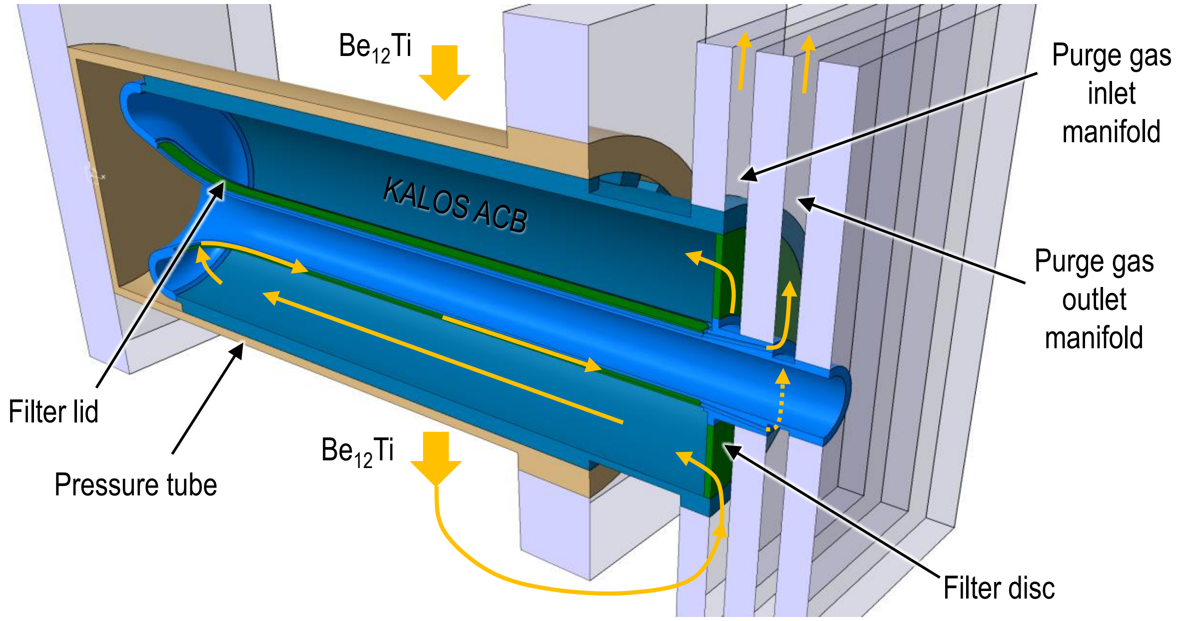
4. The HCPB BB: Purge Gas Scheme

- Purge gas parameters:
  - Carrier: He gas (inert, ideal material compatibility)
  - Doping agent: ≈200 Pa (0.1%vol) H_2 (to facilitate isotopic exchange)
  - Loop: $Be_{12}Ti$ first (it also produces ***T***, yet only 1% from total), then Li-ceramics

$$^{9}Be + \boldsymbol{n} \rightarrow \, ^{7}Li + \boldsymbol{T}$$





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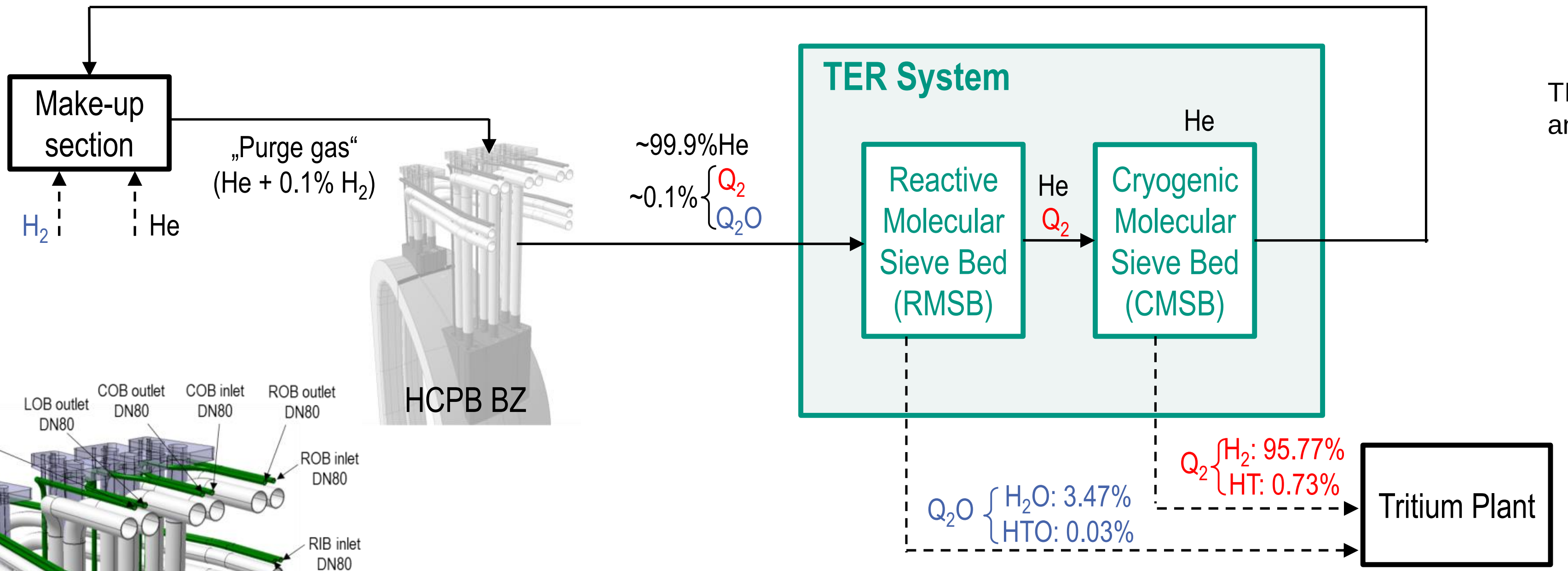
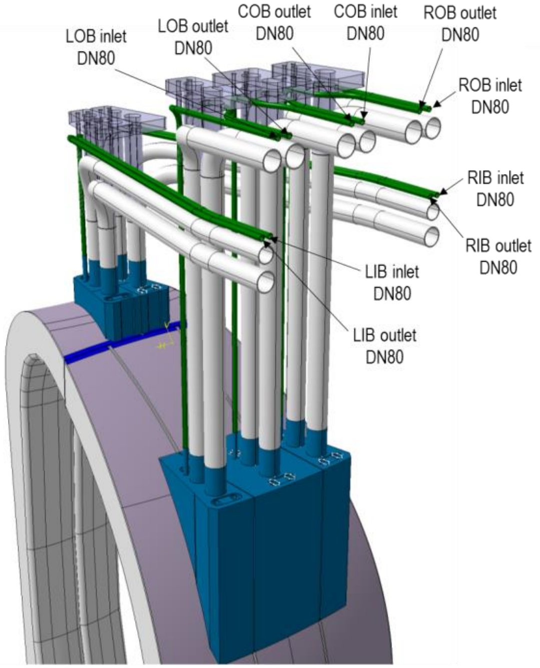
4. The HCPB BB: Purge Gas Scheme, TER Interface



TER – Tritium Extraction and Recovery



- Selected TER technology: cryogenic approach (higher TRL), however batch process (large T inventories, safety issue) and energy and LN2 consumption
- Alternative TER technology: CMSB replaced by getter beds, less TRL but will be tested in ITER, allows online T removal, less energy intensive (no LN2 consumption)
- Key issue: Permeating Q_2 species => T permeation problem
- Reference chemistry: He + 0.1%H_2 (+ %H_2O against T permeation under study)

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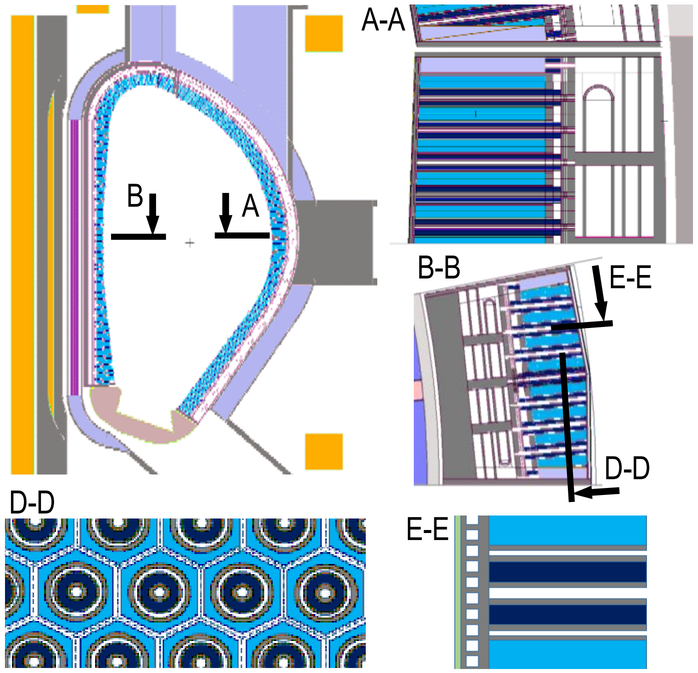
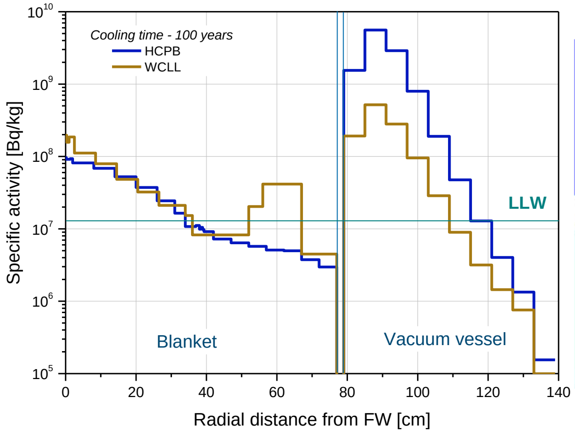
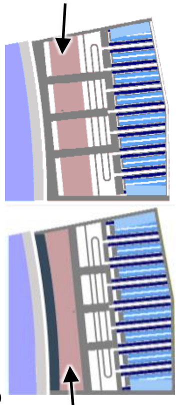
4. The HCPB BB: Performance Figures

- Fully heterogeneous MCNP model
- Tritium Breeding:
  - ^{6}Li 60%: $TBR_{design} \approx 1.20$, ^{6}Li 40%: $TBR_{design} \approx 1.16$
- Neutron shielding:
  - $dpa_{VV} \approx 0.130$dpa/fpy
  - Best shielding materials: TiH_2, $ZrH_{1.6}$, $YH_{1.75}$, WC, B_4C





Internal shield



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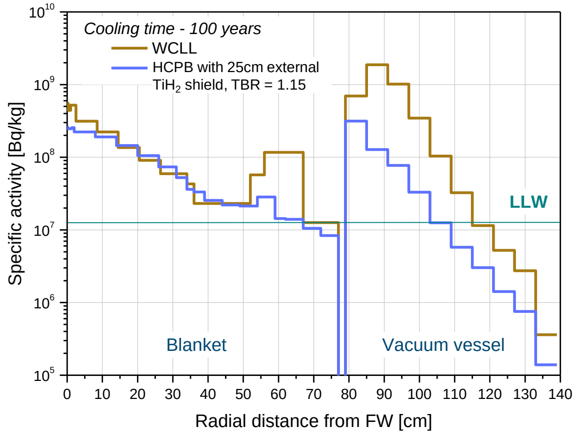

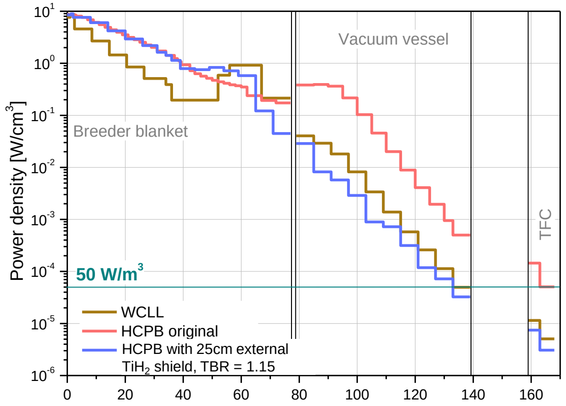

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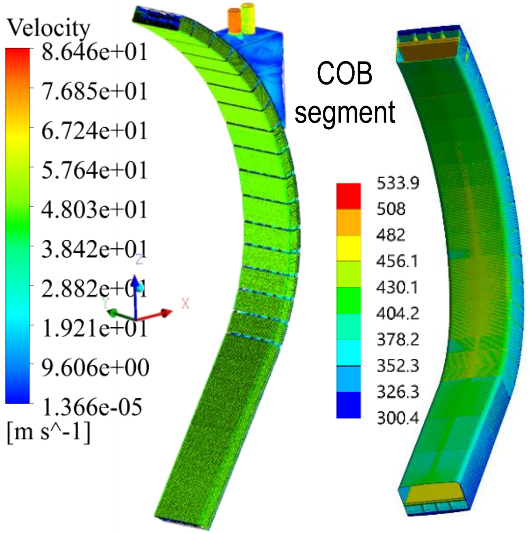
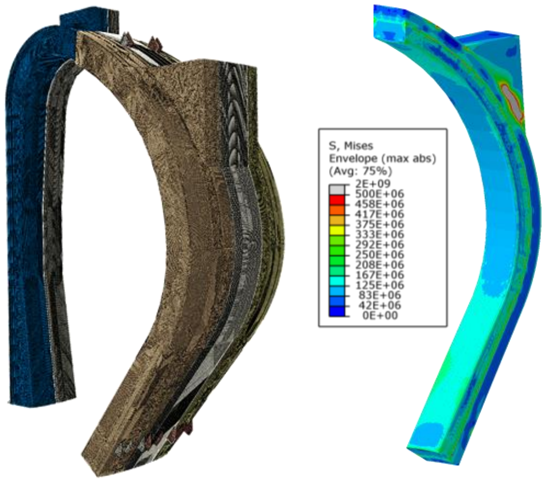
4. The HCPB BB: Performance Figures

- Global FEM & CFD TH analyses



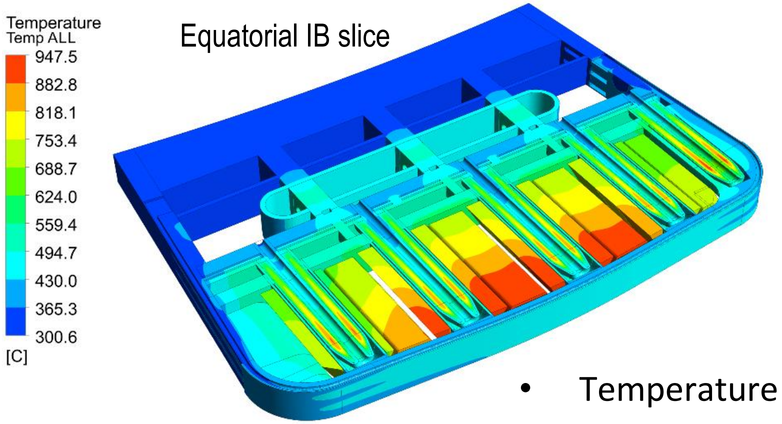
- Consistency of TH design
- Input for further TM analyses
- Total BB pressure drops (0.8 bar!)
- Benchmark/ calibration of TH models (RELAP5)

- Global FEM TM analyses



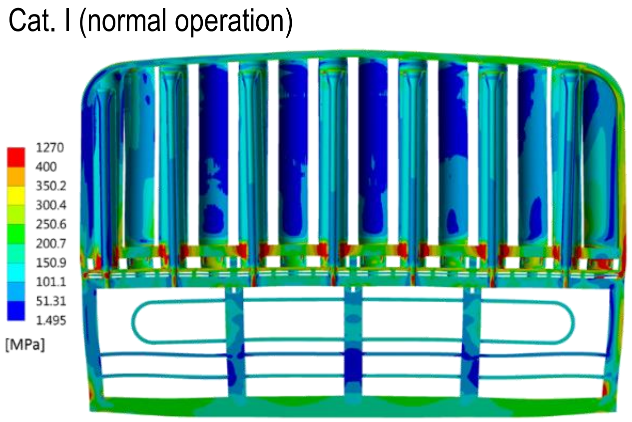
- Evaluation of off-normal cases (e.g. plasma disruption)
- Global assessment and compliance with RCC-MRx (French nuclear code)

- Detailed local CFD TH analyses



- Temperature limits compliance
- Input for further TM analyses

- Detailed local TM analyses



- Evaluation of normal and off-normal (e.g. in-box LOCA) operation
- Compliance with RCC-MRx code

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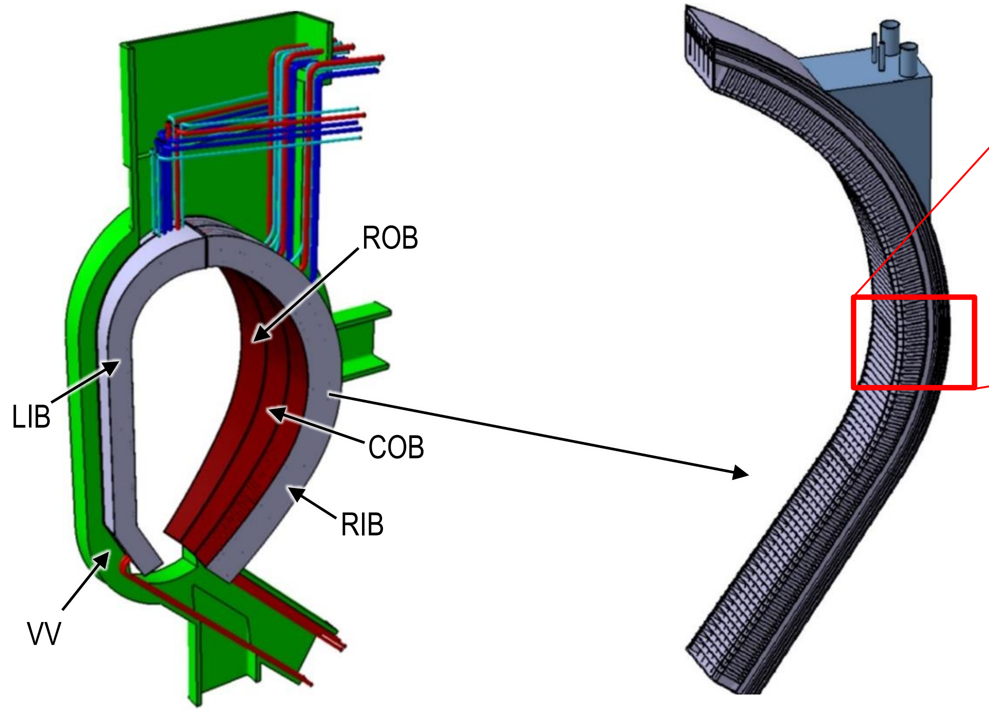
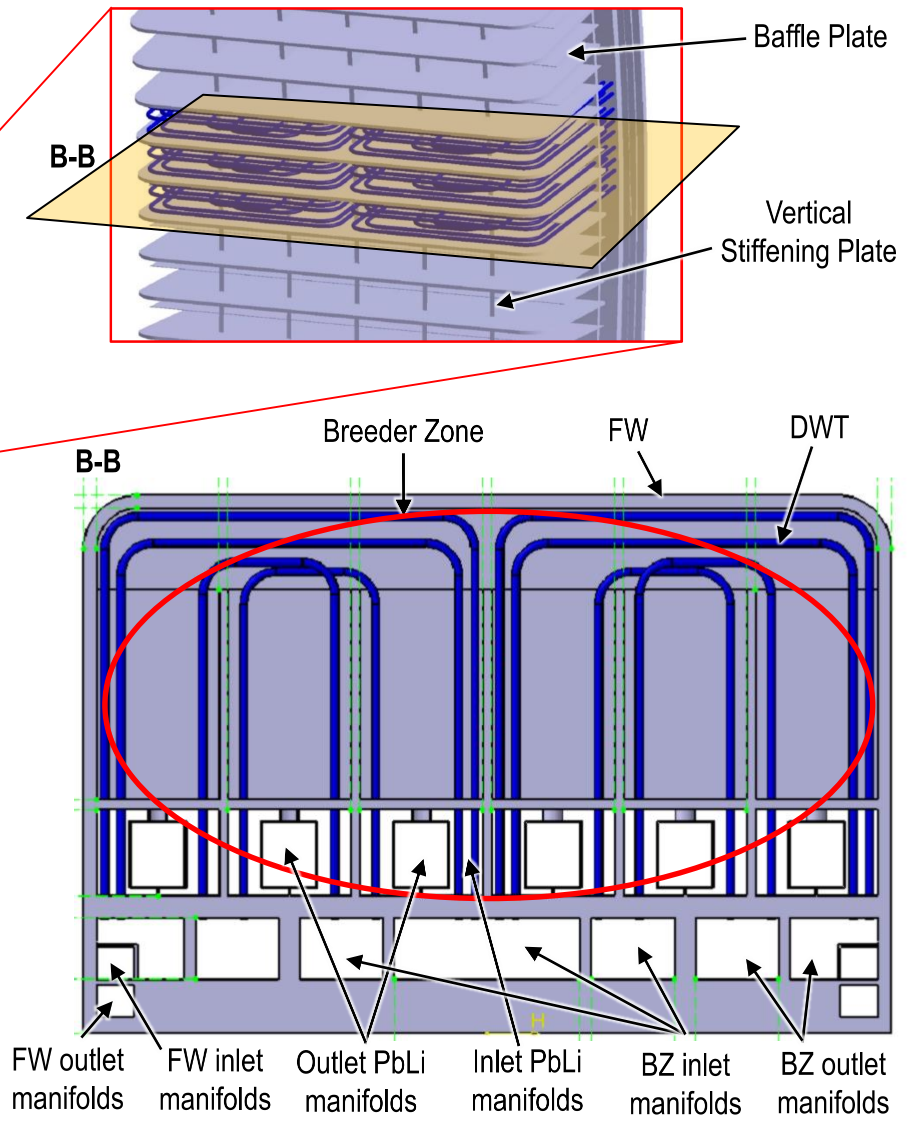
5. The WCLL BB: General Description

- WCLL design (BL2017)





DWT – Double Wall Tube

- Arrangement of vertical stiffening plates, baffle plates and DWT which cool structures and functional material
- Functional material: liquid metal Pb-Li eutectic alloy, ^{6}Li 90% enriched
- Structural steel: Eurofer-97

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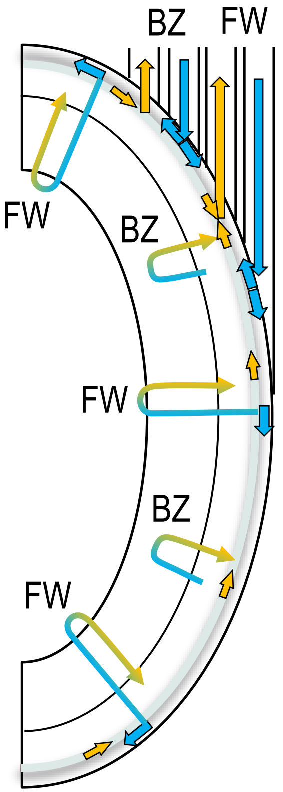
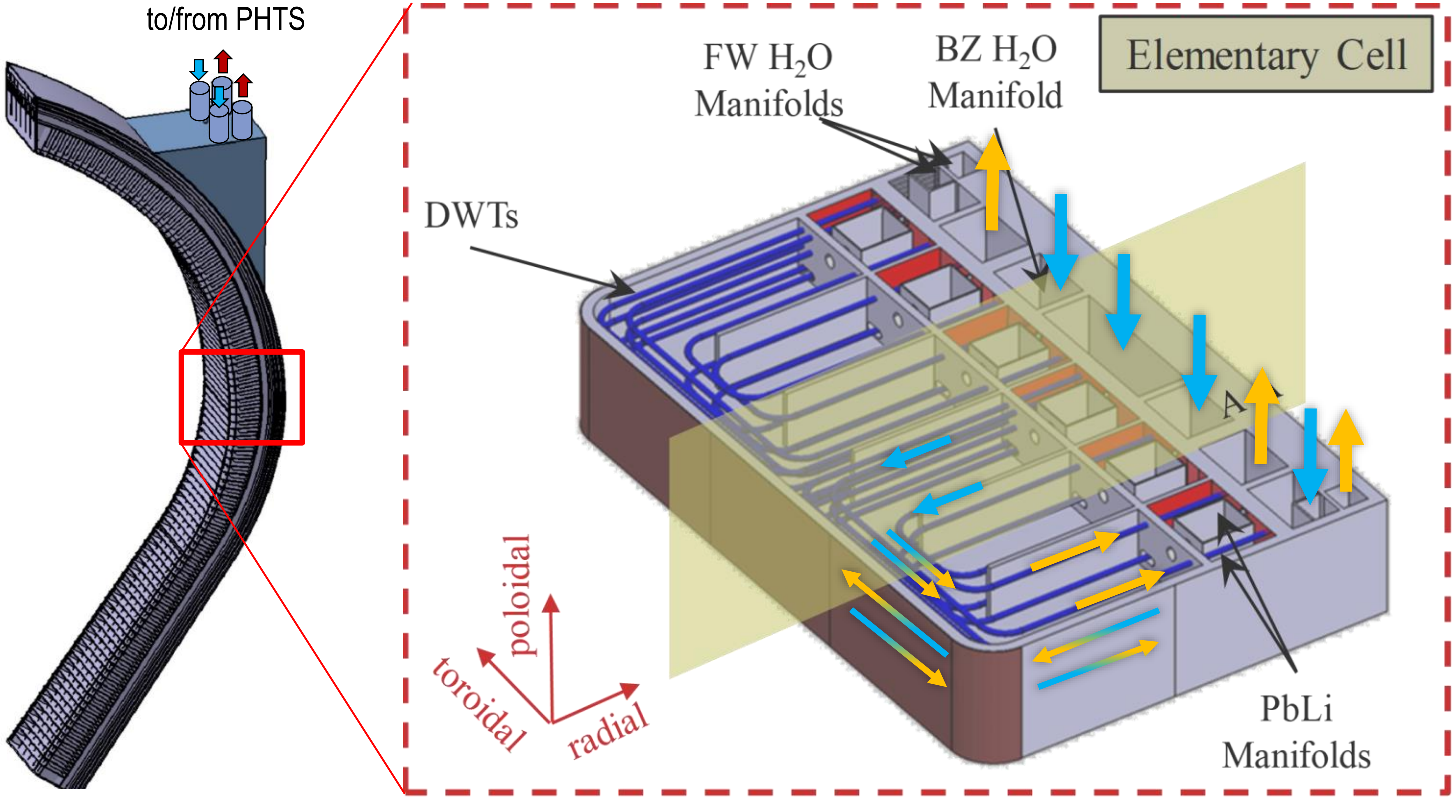
5. The WCLL BB: Coolant Scheme

- Coolant thermo-hydraulic parameters:
  - Water 155 bar, T_{in} = 295°C, T_{out} = 328°C, PWR-like conditions
  - FW and BZ cooling loops in parallel, separated (design choice, impact in PHTS architecture)





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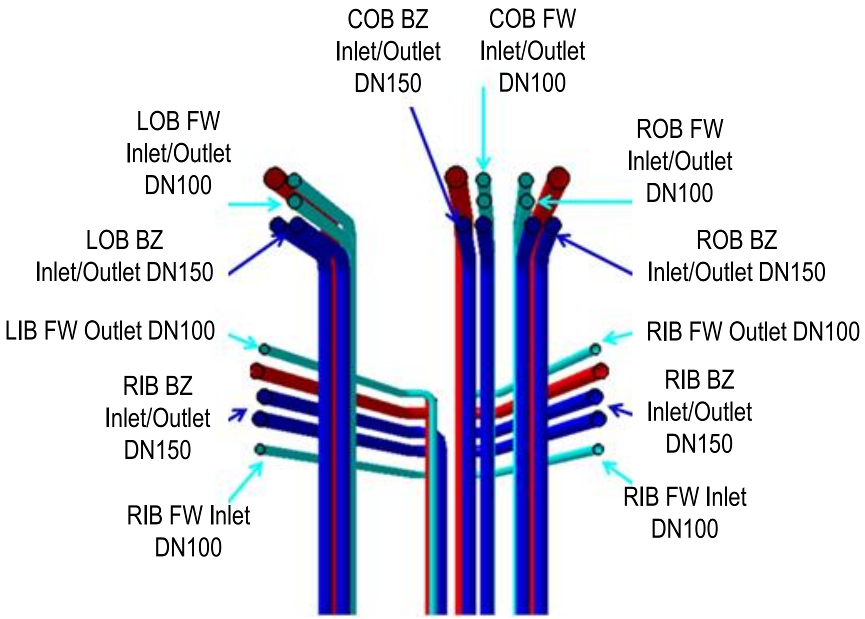
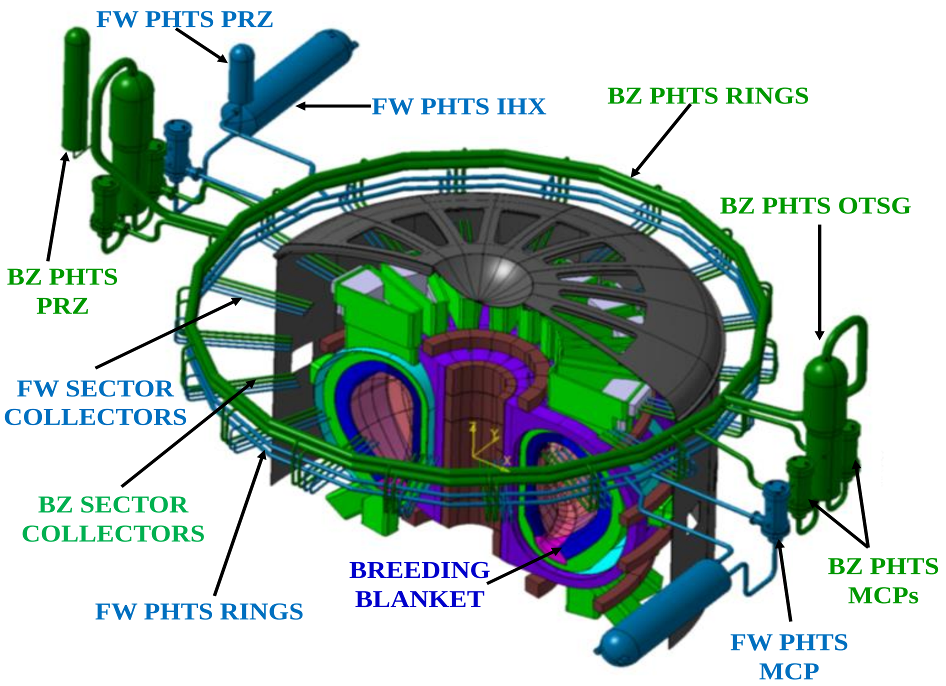
5. The WCLL BB: Coolant Scheme, PHTS Interface

- One of key BB interfaces: Balance of Plant (BoP) = Σ{ Primary Heat Transfer System (PHTS), Intermediate Heat Transfer System (IHTS), Power Conversion System (PCS) }





- Two parallel loops (both PWR-like), in order to minimize ***T*** and coolant inventory:
  - 1 BZ PHTS loop, connected to PCS via once-through steam generators (OTSG): 2 OTSG, 4 pumps
  - 2 FW PHTS loops, connected to the IHTS (ESS) to bridge pulsed operation: 1 OTSG & pump/loop
- High BoP TRL, PWR-like technology

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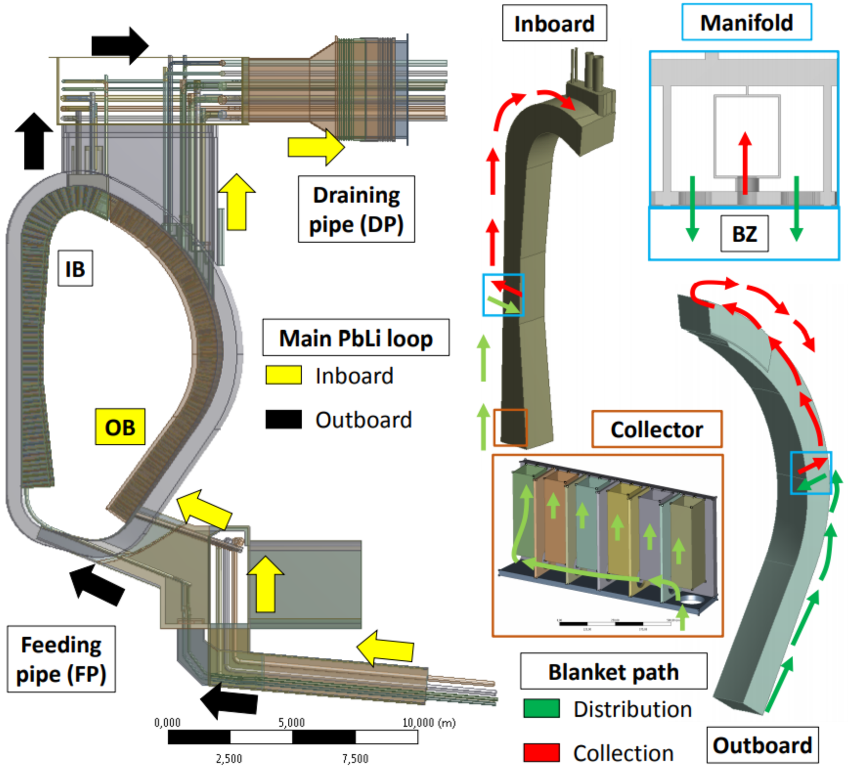
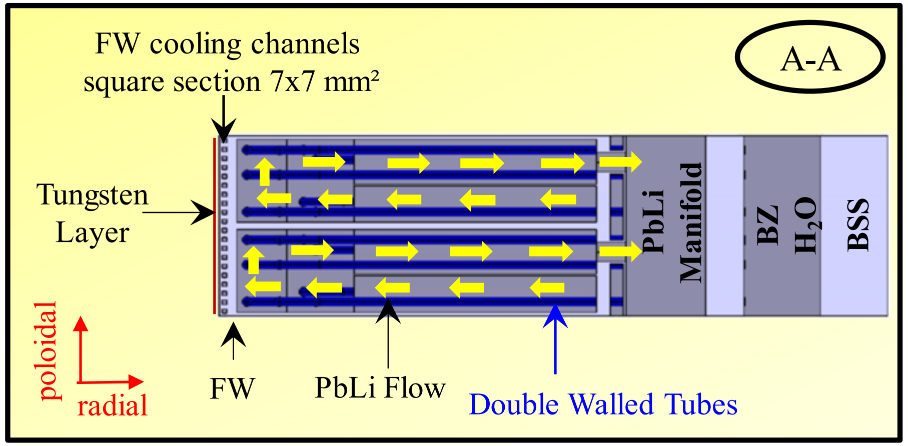
5. The WCLL BB: Pb-Li Scheme

- Functional material parameters:
  - Material: PbLi, liquid metal eutectic alloy, 90% ^{6}Li, T_{in}= 330°C, T_{out}= 500°C
  - ***T*** is bred in PbLi, PbLi transports the molecular ***T*** bred in the BZ, however in order to avoid large pressure drops due to MHD, PbLi flows very slowly (mm/s) => ***T*** permeation issue
  - ***T*** is therefore extracted from the functional material (PbLi) outside the BB, in the TER





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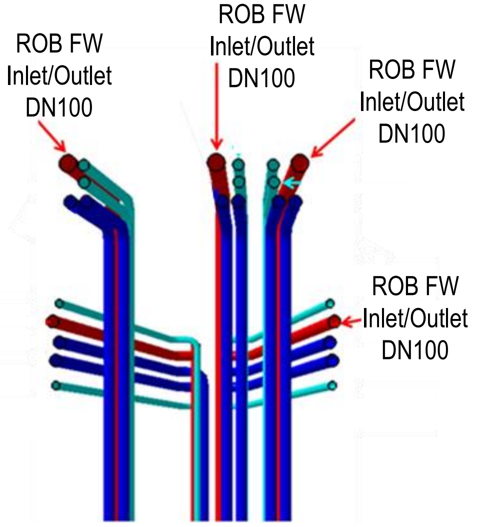
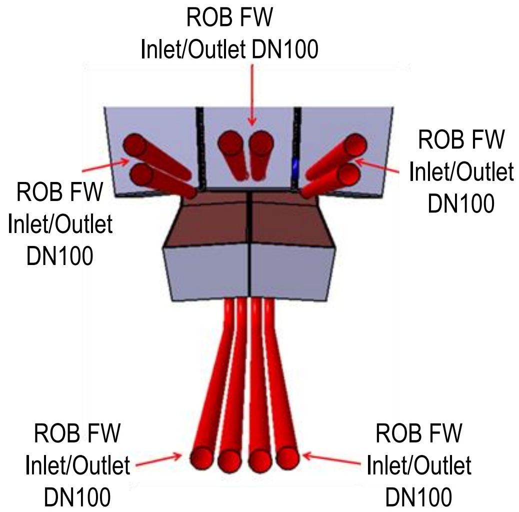
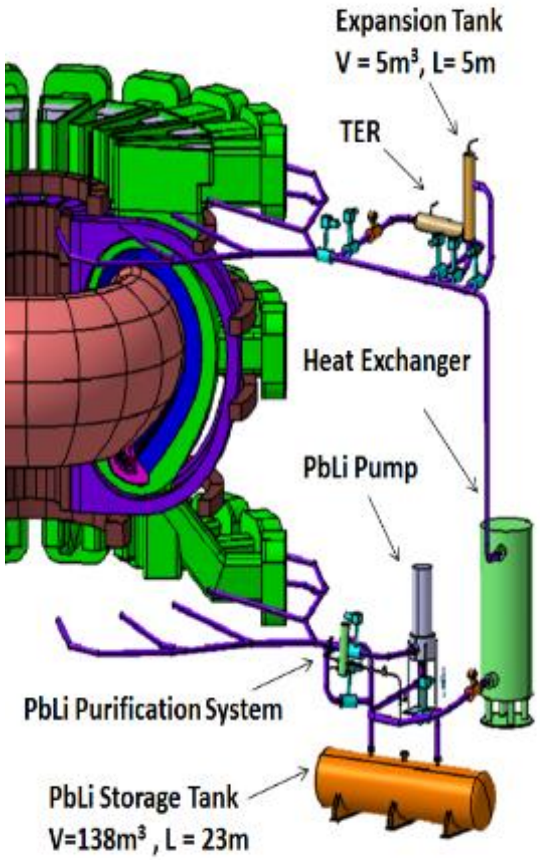
5. The WCLL BB: Pb-Li Scheme, TER Interface







- Selected TER technology: Permeator Against Vacuum (PAV)
  - Continuous operation, high efficiency (but low for low temp. BBs like WCLL) but costly and low TRL
- Two PAV proposals:
  - V membrane (CIEMAT)
  - Nb membrane (ENEA)
- Alternative TER technology: Gas Liquid Contactor (GLC), Liquid Vacuum Contactor (LVC)
  - GLC: Continuous operation, low efficiency, bulky, energy intensive but high TRL
  - LVC: simpler, but low TRL

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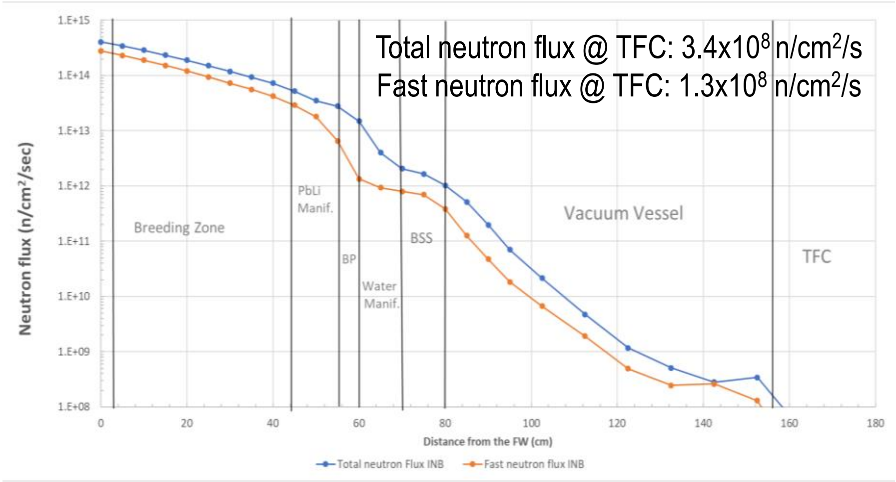
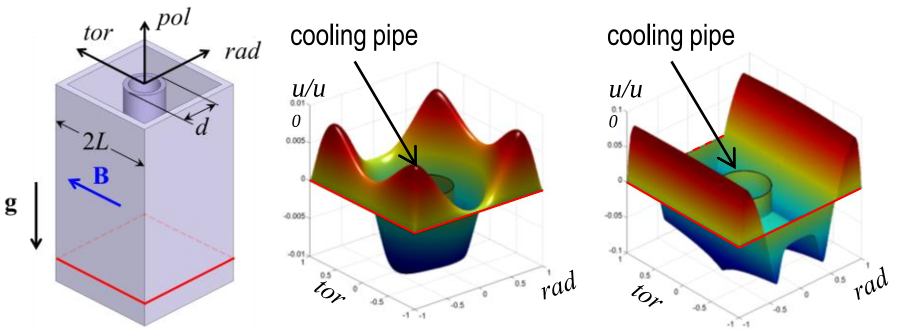
5. The WCLL BB: Performance Figures

- Neutronics:
  - Tritium Breeding:
    - ^{6}Li 90%: $TBR_{design} \approx 1.15$, optimum FW channel geometry changed, heat flux capability↓)
  - Neutron shielding:
    - Best, $dpa_{VV} \approx 0.0130$dpa/fpy



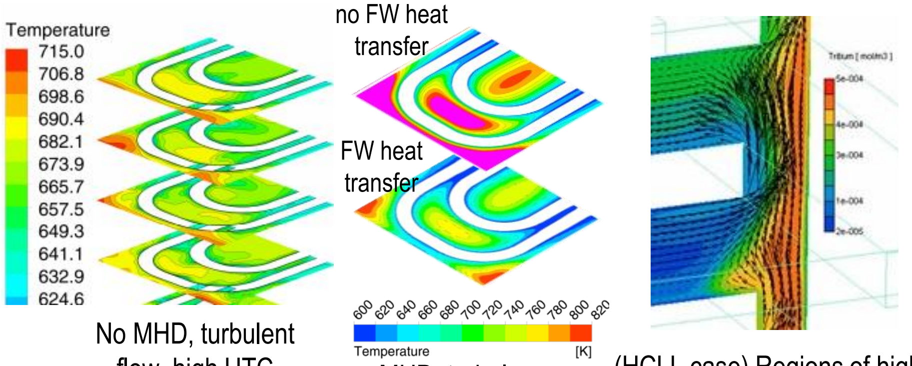
  - Coolant activation and gamma shielding:
    - $^{16}O(n,p)^{16}N$, $^{17}O(n,p)^{17}N$ -> MeV gamma and delayed fast n => PHTS piping shielding

- Magnetohydrodynamics (MHD):
  - Magneto-convective flows in the WCLL DWTs:



***Weak B field Ha*=10** **Strong B field *Ha*=1000**

  - MHD effects in heat transfer and flow
    - MHD hampers HTC: conduction is key
    - MHD produces stagnant regions: ***T*** permeation



No MHD, turbulent flow, high HTC

MHD, turbulence supressed, low HTC

(HCLL case) Regions of high ***T*** concentration (permeation)

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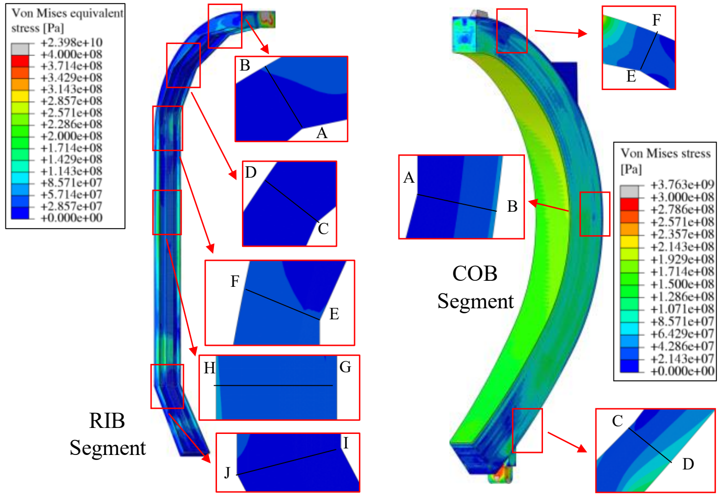
5. The WCLL BB: Performance Figures

- Global FEM TH and TM analyses



- Consistency of TH design
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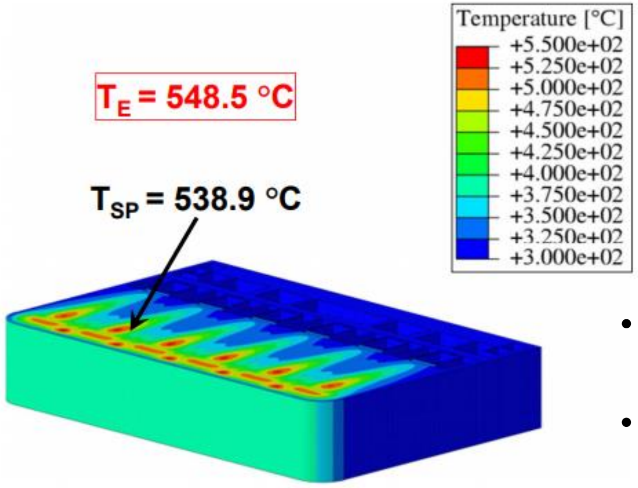
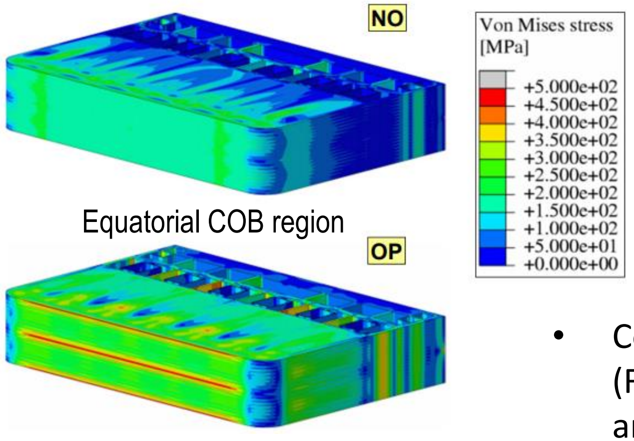
- Benchmark/ calibration of TH models (e.g. RELAP5)
- Evaluation of off-normal cases (e.g. plasma disruption)
- Global assessment and compliance with RCC-MRx (French nuclear code)

- Detailed local FEM TH analyses



- Temperature limits compliance
- Input for further TM analyses

- Local TM analyses



- Compliance with RCC-MRx (French nuclear code), normal and off-normal operation

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6. Challenges

- Reliability, Availability, Inspectability, Maintainability (RAMI)
  - BB structures very large => large number of components that can fail => reliability ↓
- Limited FW heat flux capability
  - About ≈1-1.5MW/m², strongest limiting factor: Eurofer-97
- Low reliability of T modelling (parameter uncertainties, safety issue)
- T permeation into coolant, can lead to safety issue
- Electromagnetic loads, during accidental scenario can be very large (several MN, MNm)
- Strong n-induced DBTT shift at T<350°C (steel embrittlement)
- Manufacturing readiness and costs
- ^{6}Li enrichment level and costs
- Low readiness of the available design Codes and Standards for fusion
  - Implementation of Eurofer-97 into RCC-MRx => multi-decades endeavor, but closing gap
- W-coating technology not yet available for DEMO
  - Some technologies already envisaged, but industrial scale-up to DEMO scale not yet proven

*DBTT – Ductile Brittle Transition Temperature

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Outline

7. Conclusions

- Two BB candidates for the EU DEMO (and ITER‘s TBM): HCPB and WCLL, based on
  - (1) near term characteristics (separate coolant and ***T*** breeding functions)
  - (2) as risk mitigation (2 types of coolants, 2 types of functional materials)
- HCPB main characteristics
  - Solid breeder (Li ceramic pebbles) and multiplier (Be-alloy blocks): high TBR in compact space
  - HTGR-like PHTS (fair TRL), high temperature (higher efficiency, industrial heat)
- WCLL main characteristics
  - PWR-like PHTS (high TRL), large industrial background, best ***n***-shielding, fair TBR
  - PbLi eutectic alloy (no ***n***-damage), online ***T*** breeding adjustment (i.e. ^{6}Li)
- For both (and for any): Pros and Cons => Challenges
  - **Common challenges:** RAMI, steel embrittlement, ***T*** permeation, industrialization and costs
  - **Key HCPB-related challenges**: ***n***-shielding, thermal control and thermo-mechanics of functional materials, production costs, pressure drops, complex PHTS layout and piping…
  - **Key WCLL-related challenges**: ***T*** breeding capability, need for permeation barriers, corrosion and liquid metal embrittlement, water-PbLi reaction, very high pressure operation…

Several open MSc Theses related to HCPB design at KIT.

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KIT-INR Homepage: https://www.inr.kit.edu/english/62.php

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