FusionEPtalks: Invited Talk
Online, 30 May, 2022

EUROfusion

Helium Cooled Pebble Bed Breeding Blanket for the European DEMO

Guangming Zhou, Francisco A. Hernández

Karlsruhe Institute of Technology

Breeding Blanket Project in EUROfusion

Outline

1. Why Breeding Blanket?
2. What is a HCPB?
3. EU-DMEO Top-Level Requirements
4. The current HCPB Breeding Blanket
5. Challenges
6. Conclusions

Role of tritium in D-T fusion power plants

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

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

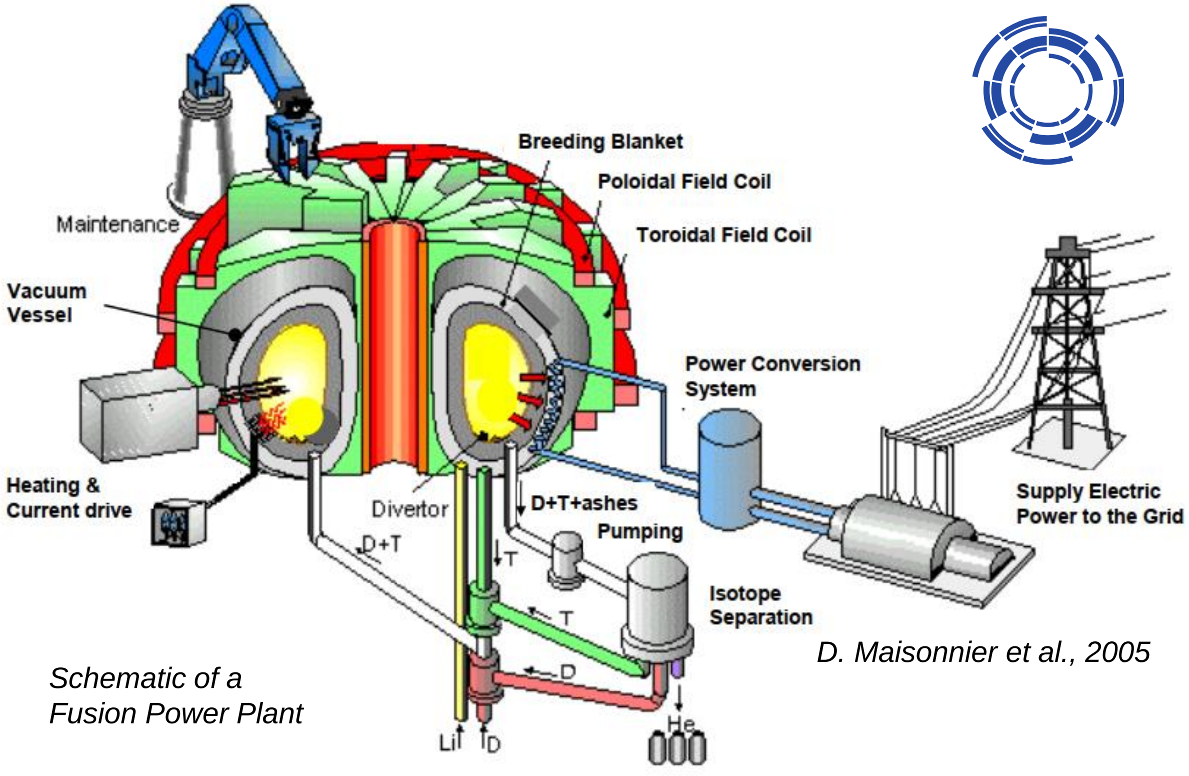
1 GW fusion (thermal) power device:
~56 kg *T* per full power year (fpy).

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

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

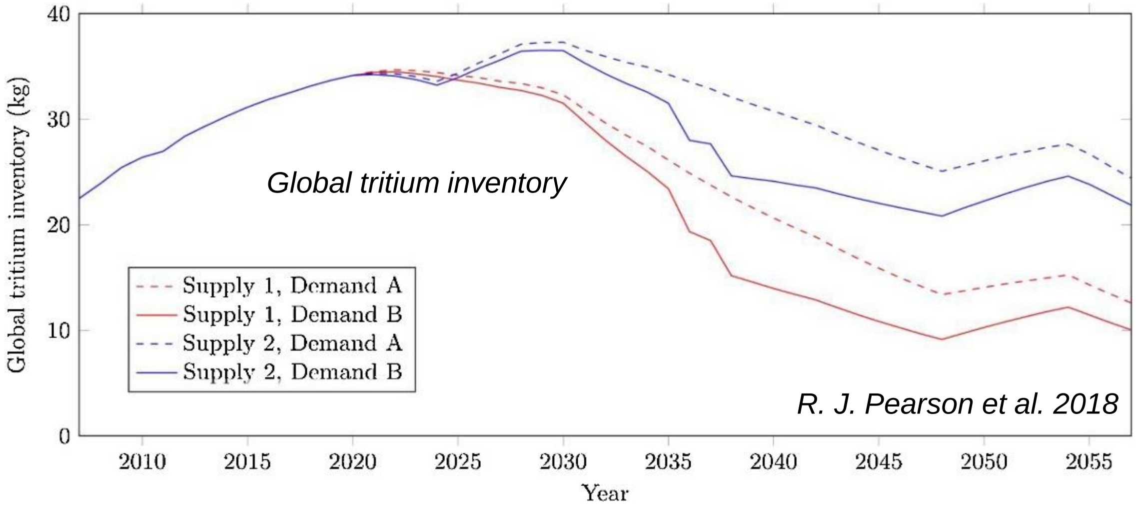
$$ n + {}^{2}_{1}D \rightarrow {}^{3}_{1}T + \gamma $$

Need to produce ***T***



Schematic of a Fusion Power Plant

D. Maisonnier et al., 2005



R. J. Pearson et al. 2018

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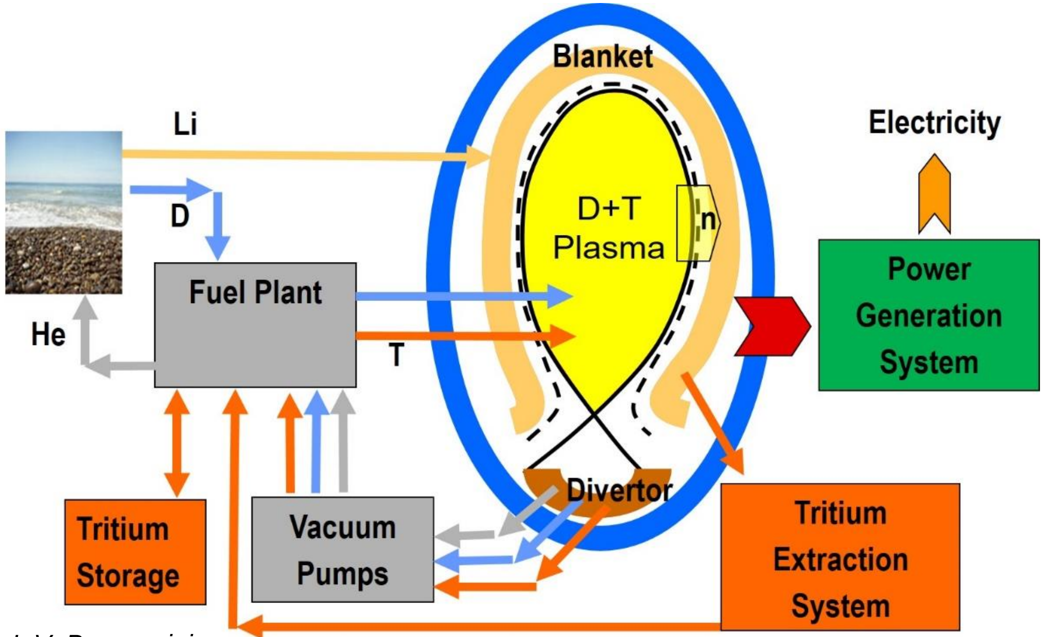
Why Breeding Blanket (BB)?

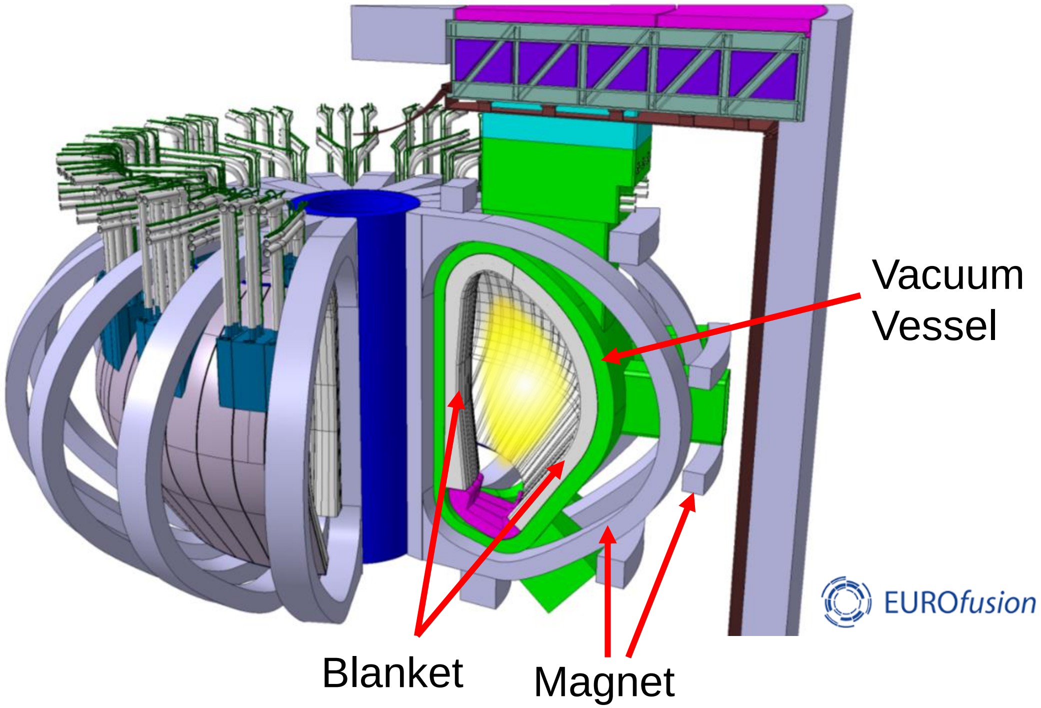
- **Main functions of the blanket:**
  - tritium breeding => tritium self-sufficiency
  - heat removal => electricity production
  - shielding => protect magnets from neutrons

$$^{6}_{3}Li + n \rightarrow \, ^{4}_{2}He + \, ^{3}_{1}T$$

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



Credit: L.V. Boccaccini



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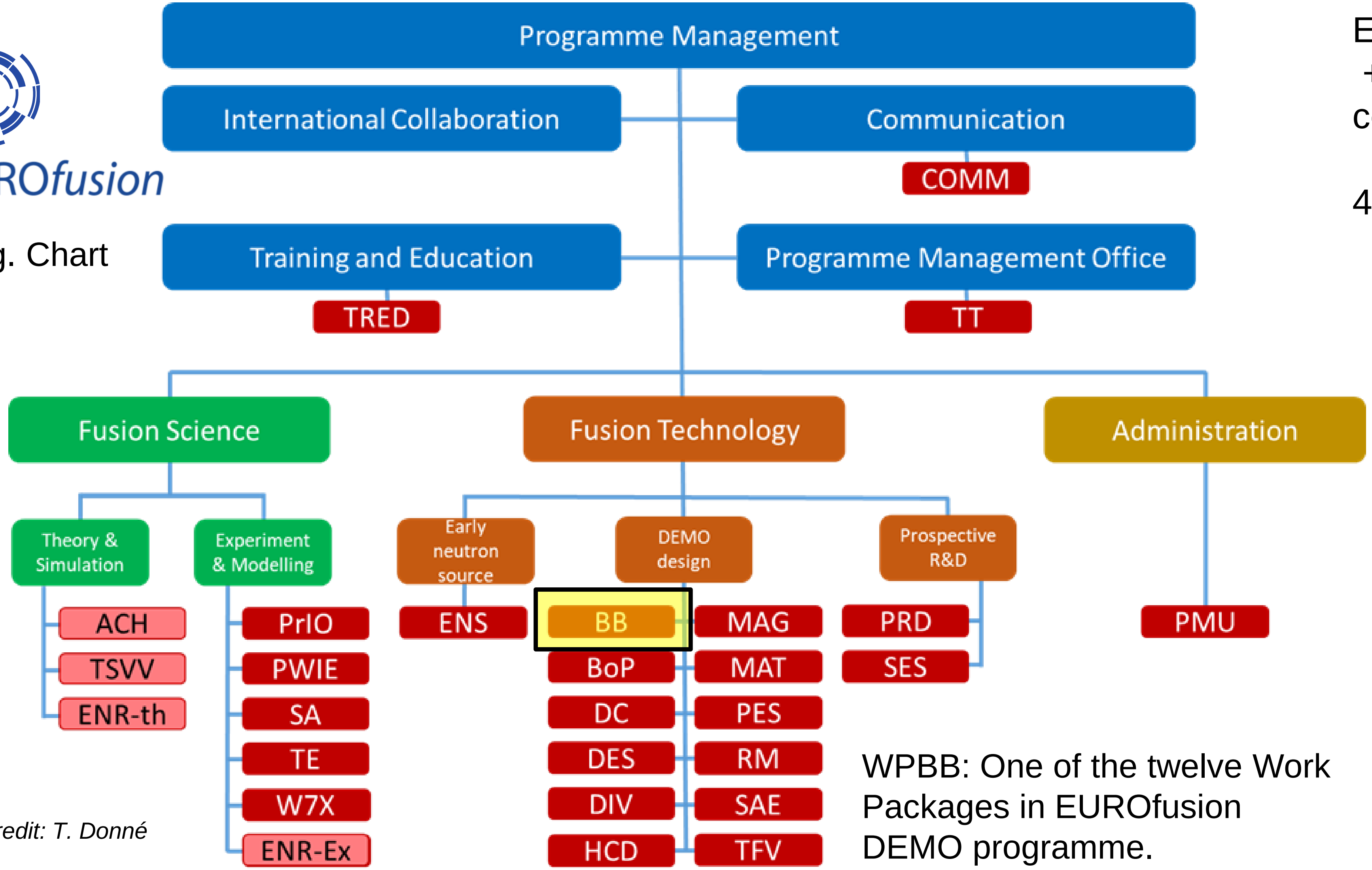
Work Package Breeding Blanket in EURO*fusion*

EURO*fusion*

Org. Chart



Credit: T. Donné

WPBB: One of the twelve Work Packages in EUROfusion DEMO programme.

EUROfusion: 30 research institutes +150 affiliated universities from 28 countries.

4000 scientists and engineers.

EUROfusion coordinates the joint European efforts on developing fusion energy.

Budget:
2014-2020 (7 years)
1.2 billion Euro

2021-2025 (5 years)
1.0 billion Euro

Source: T. Donné

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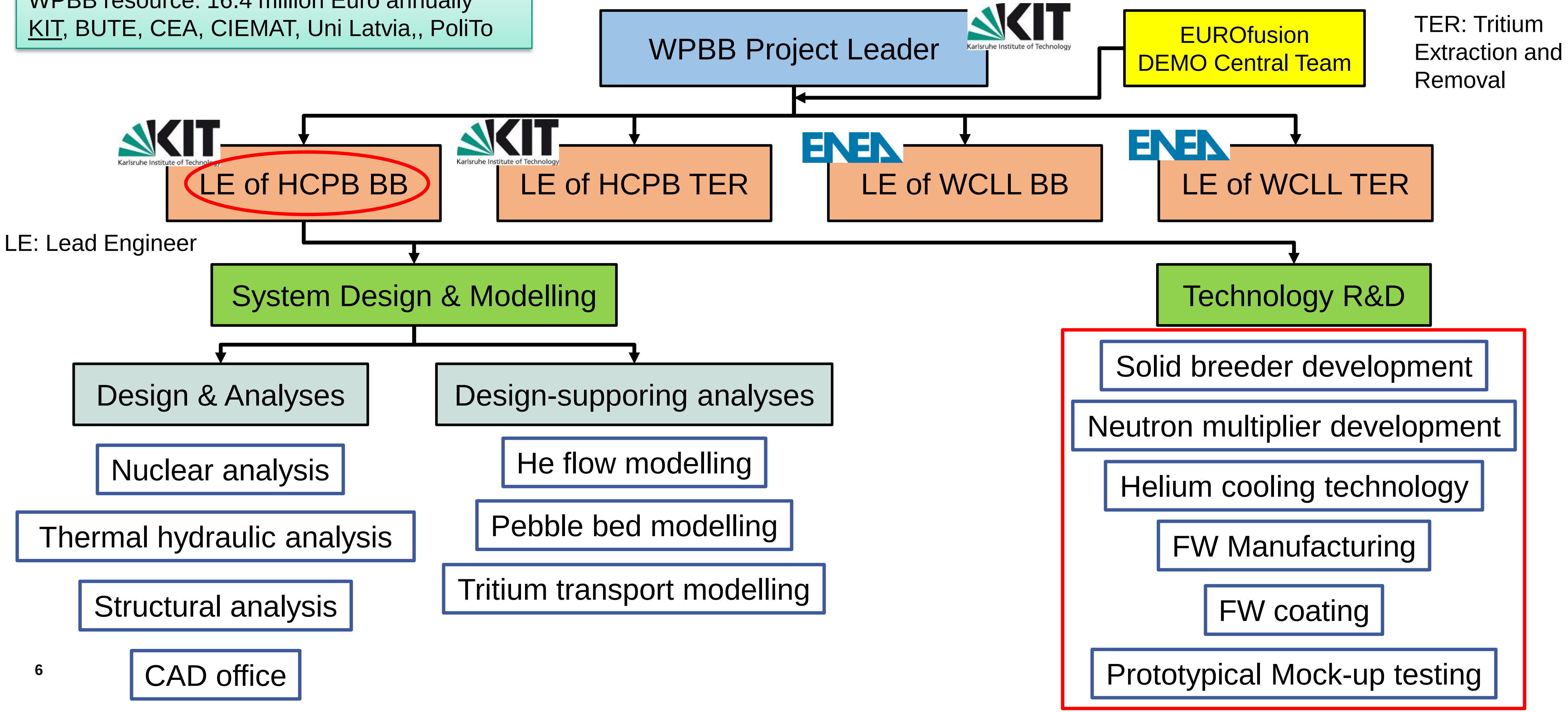
HCPB BB in Work Package Breeding Blanket (WPBB)

2021-2025
WPBB resource: 16.4 million Euro annually
KIT, BUTE, CEA, CIEMAT, Uni Latvia,, PoliTo



Outline

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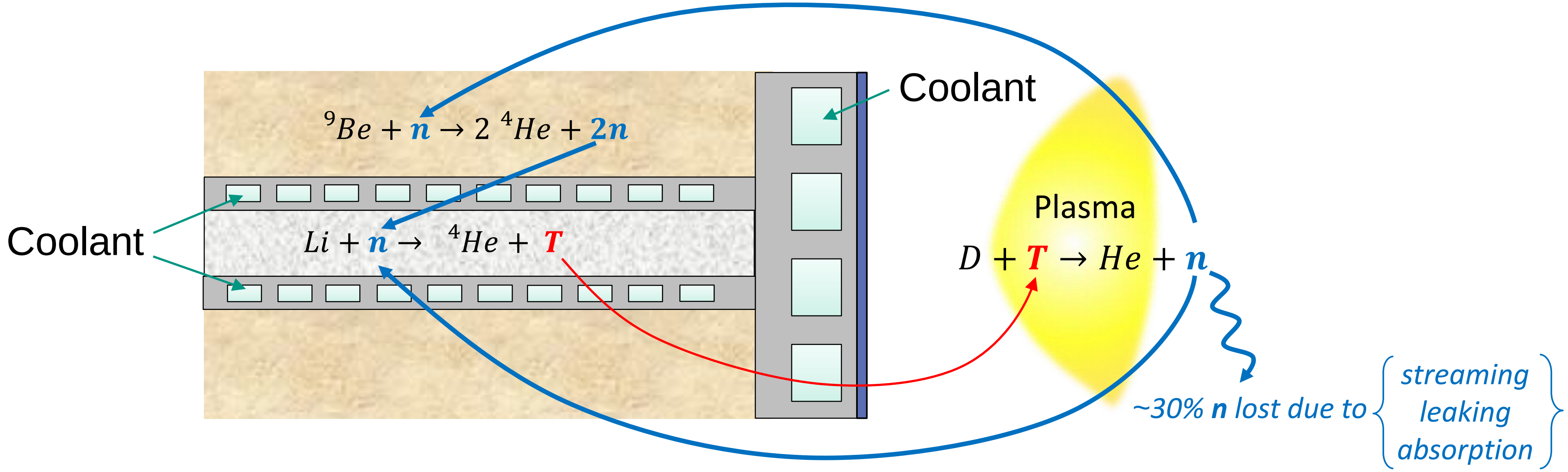
2. What is a HCPB?

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



- Tritium Breeding Function

  $^{6}_{3}Li + ^{1}_{0}n \rightarrow\ ^{4}_{2}He + ^{3}_{1}T + 4.8\ MeV$

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

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

- Neutron multiplier (NM) function:

  $^{9}_{4}Be + ^{1}_{0}n \rightarrow 2^{4}_{2}He + 2^{1}_{0}n - 1.8\ MeV$

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

- Heat extraction: Helium (HTR-like)

  Coolant Temp: 300°C – 520°C

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3. 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/m^3
  - Vacuum vessel (VV) damage < 0.2dpa/fpy
  - He production in steel structures to be rewelded < 1appm/fpy
- **Temperature design limits:**
  - 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,…)
  - 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 following rules defined in codes

*DBTT – Ductile Brittle Transition Temperature

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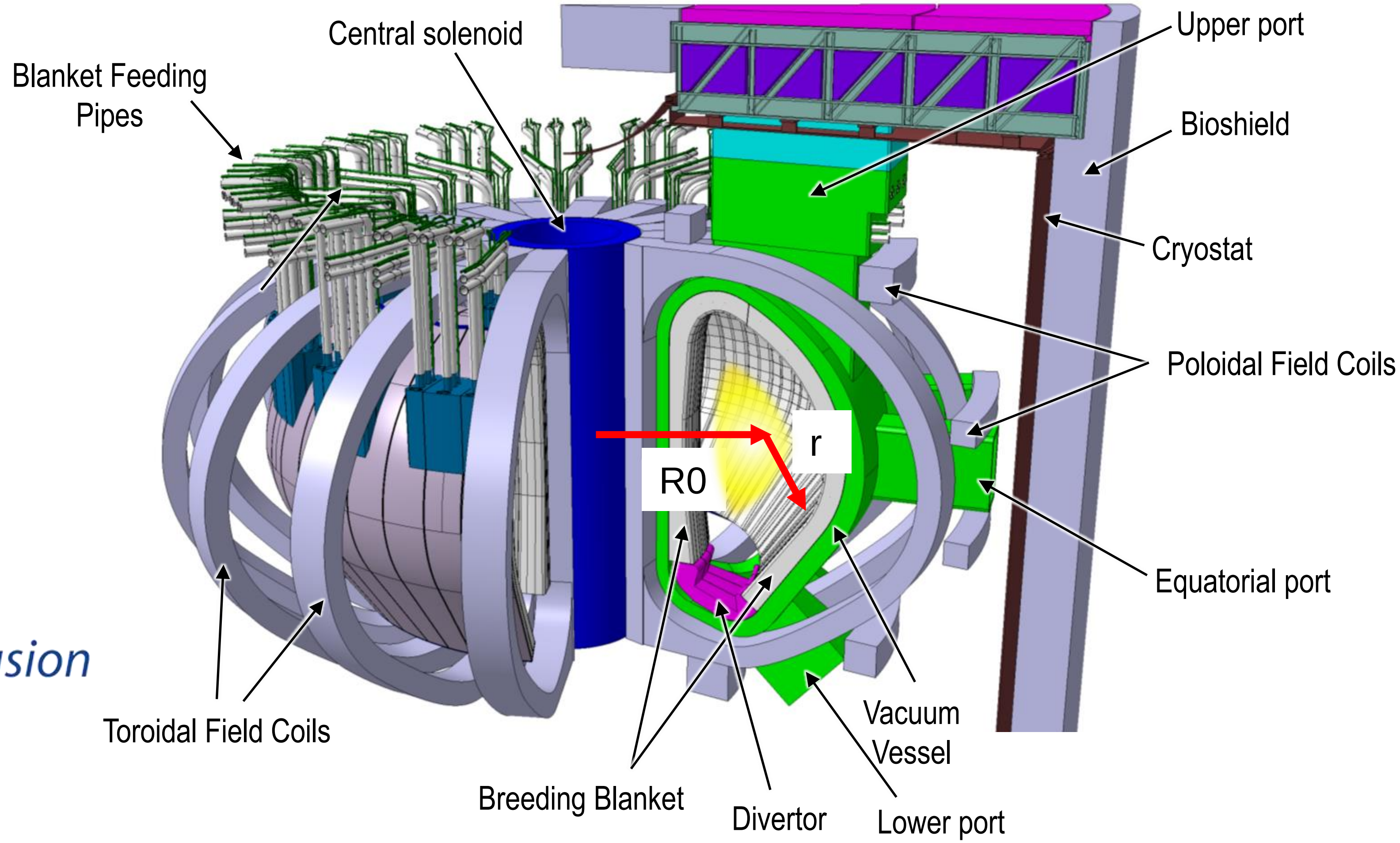
3. EU-DEMO Blanket Segmentation (1/2)

- EU DEMO Tokamak Baseline 2017 (latest reference, R_0=9m, r=2.9m, P_{fus}≈2GW)



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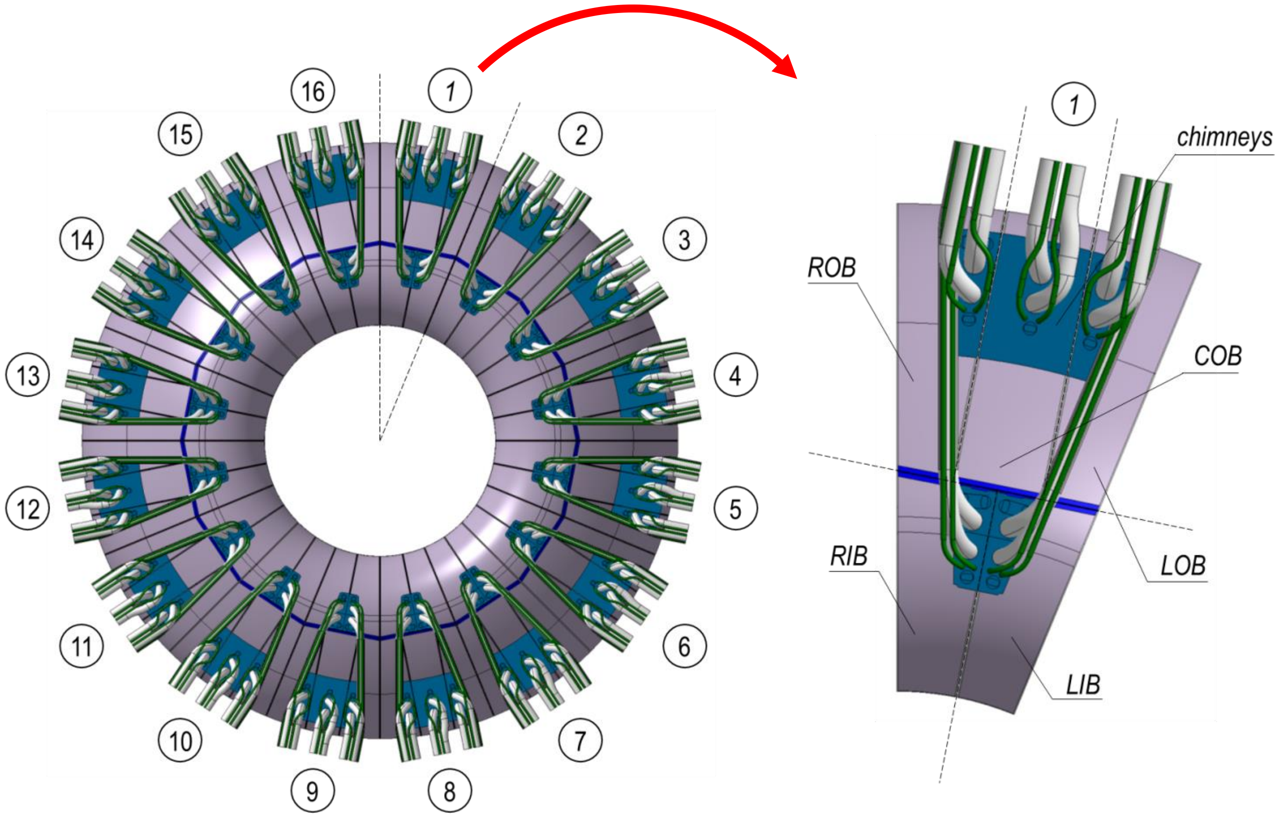
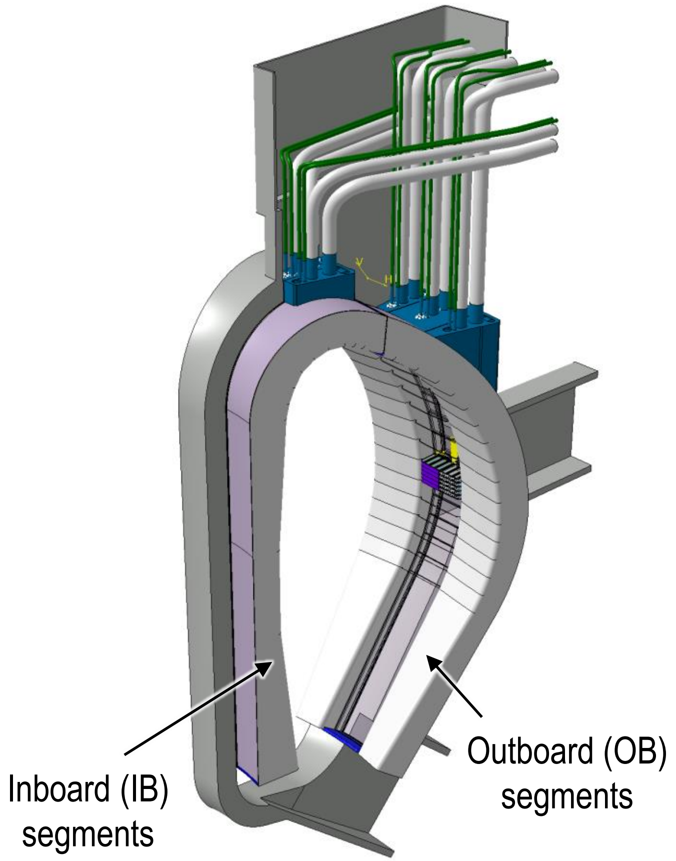
3. EU-DEMO Blanket Segmentation (2/2)

- EU DEMO Tokamak Baseline 2017 (latest reference, R_0=9m, r=2.9m, 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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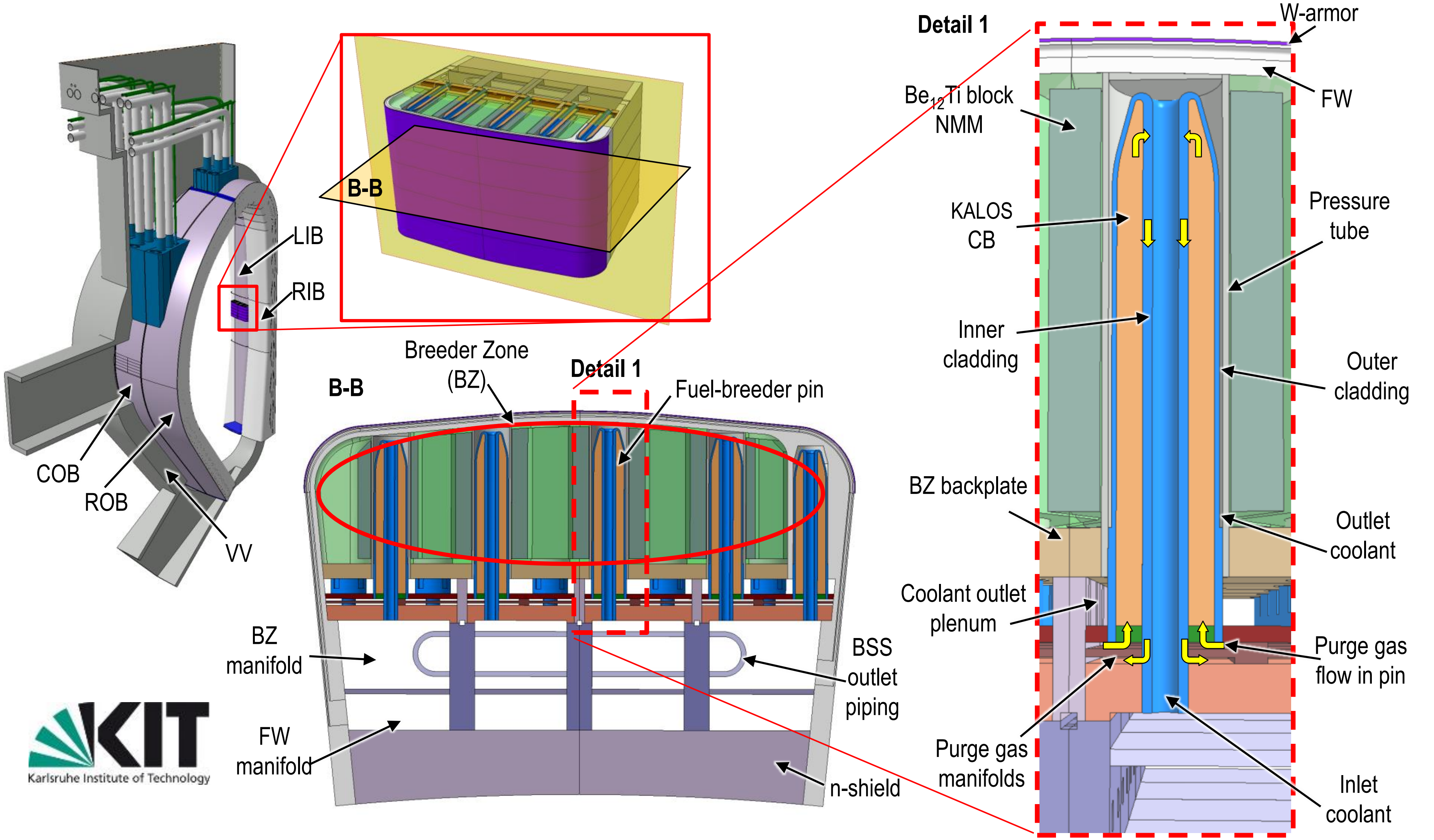
Outline

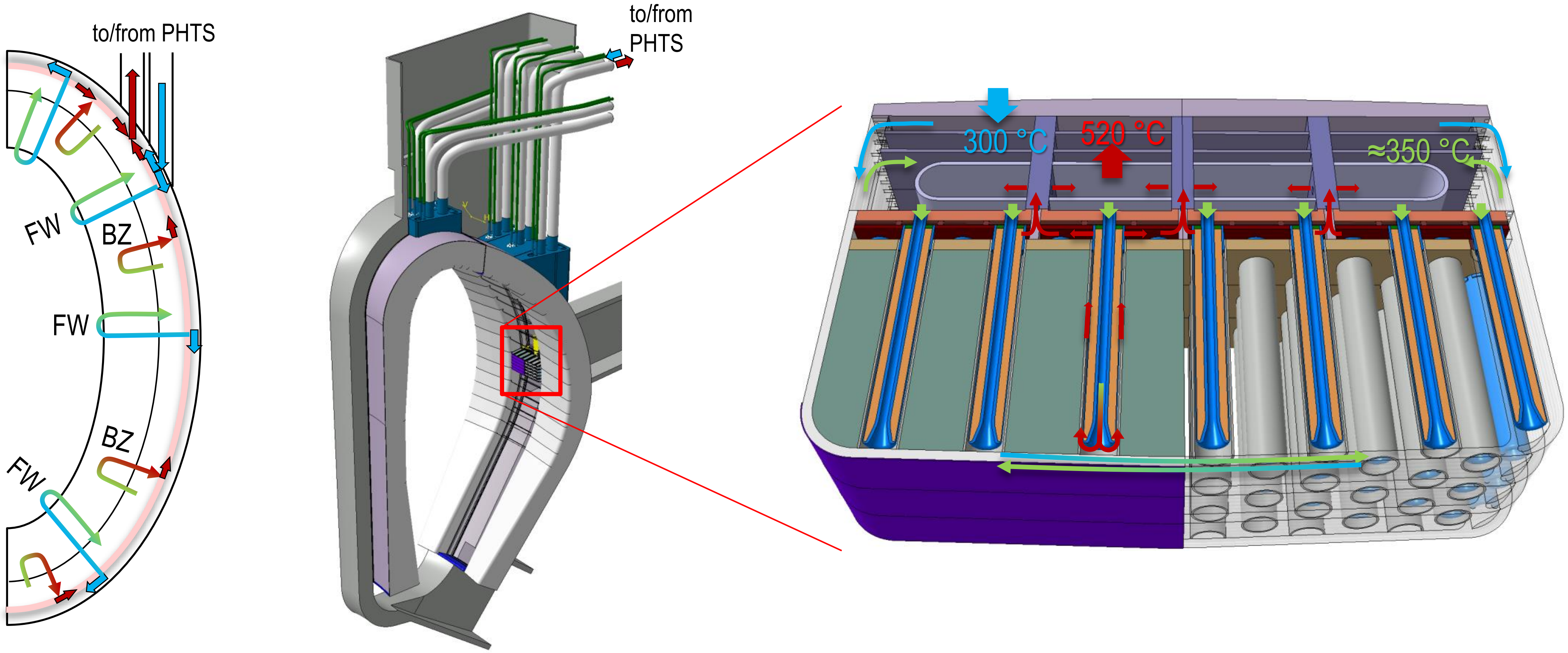
4. The HCPB BB: General Description



HCPB Breeding Blanket design

4. The HCPB BB: Coolant Scheme

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



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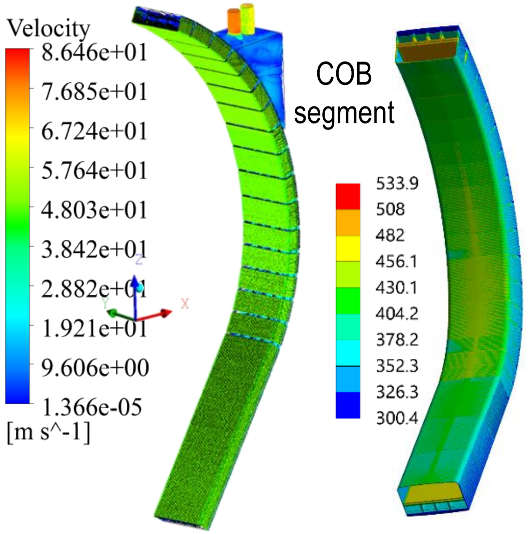
4. Design analysis: Performance figures

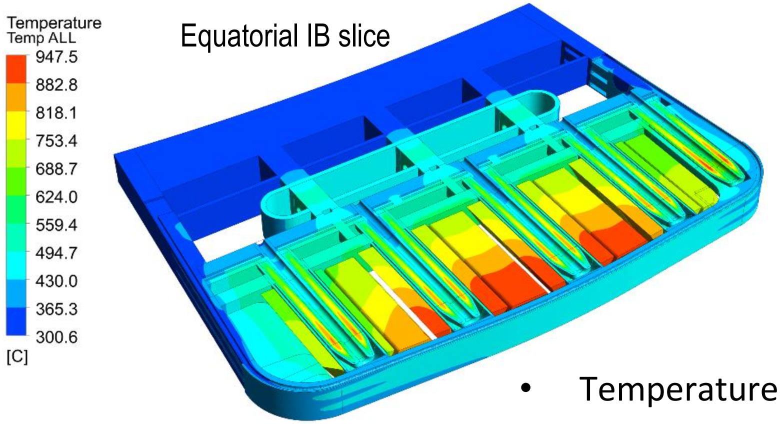
- Neutronics: nuclear analysis
  - Fully heterogeneous MCNP model
  - Tritium Breeding:
    - ^{6}Li 60%: $TBR_{design} \approx 1.20$, ^{6}Li 40%: $TBR_{design} \approx 1.16$
  - Neutron shielding:
    - $dpa_{VV} \approx 0.130$dpa/fpy
    - Best shielding materials: B_4C, TiH_2, $ZrH_{1.6}$, $YH_{1.75}$,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

- Global FEM & CFD Thermohydraulic analyses:



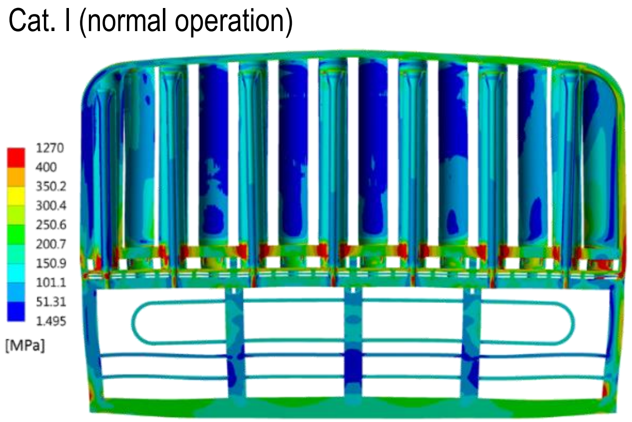
  - Input for further TM analyses
  - Total BB pressure drops (0.8 bar!)
  - Benchmark/ calibration of TH models (RELAP5)

- Detailed local CFD Thermohydraulic analyses:



  - Temperature limits compliance
  - Input for further TM analyses

- Detailed local Thermomechanical analyses:



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

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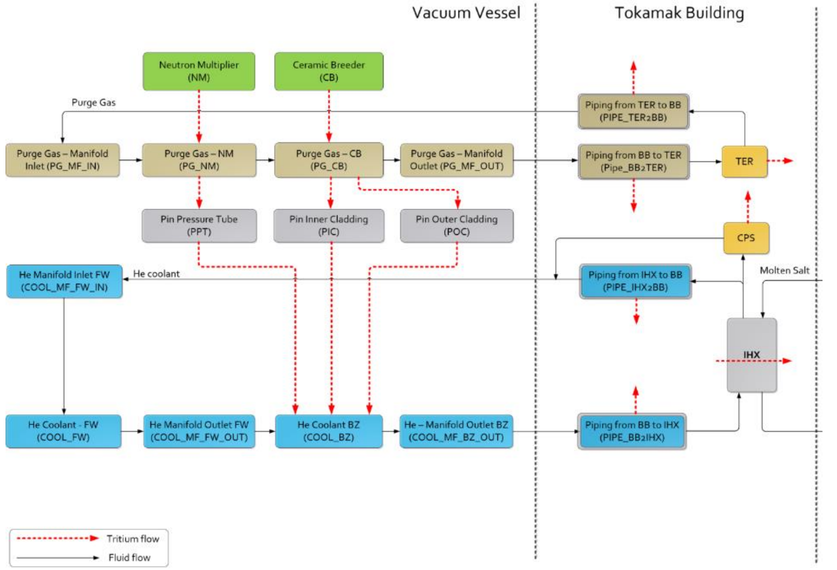
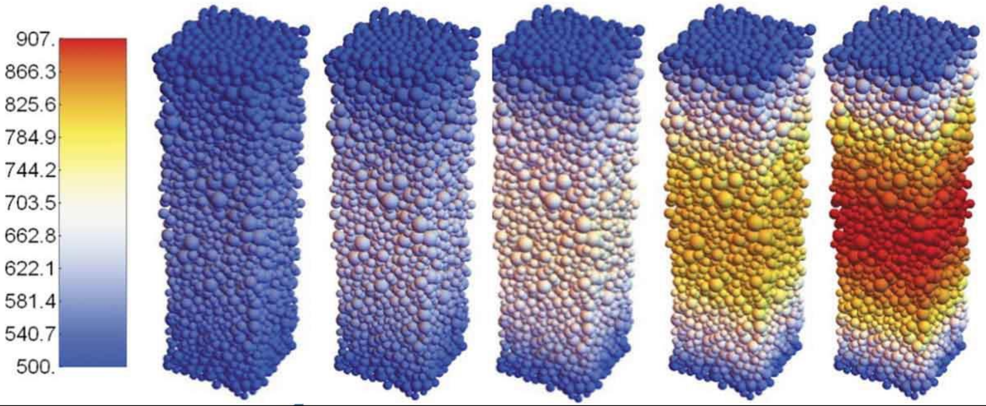
4. Design-supporting analyses

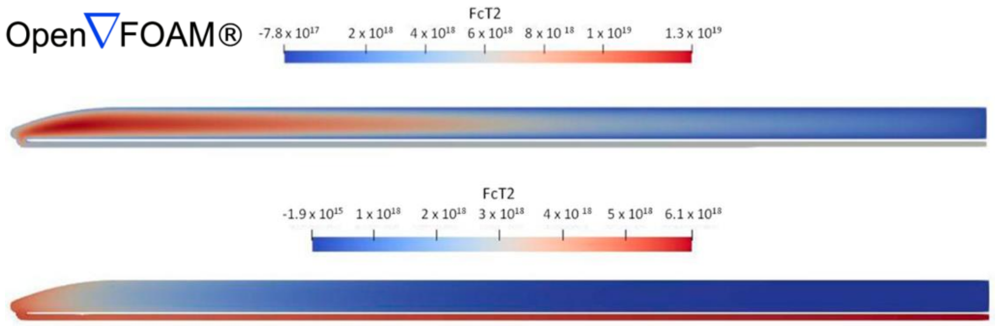
Tritium transport at system level



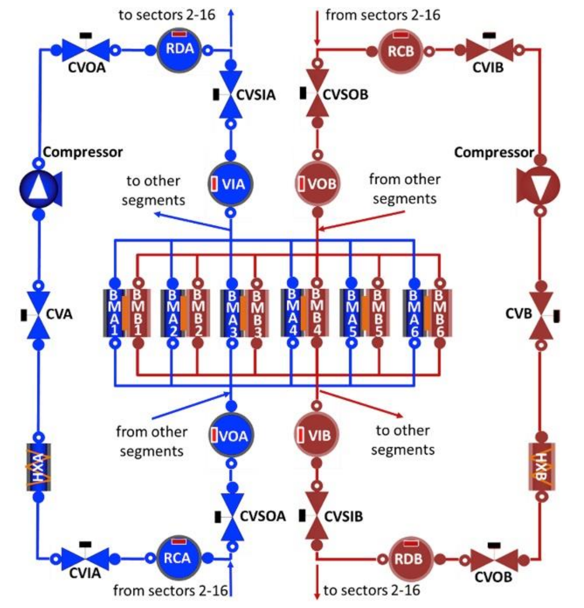
Pebble bed mechanical analysis



Tritium transport at component level



He flow modeling using in-house code



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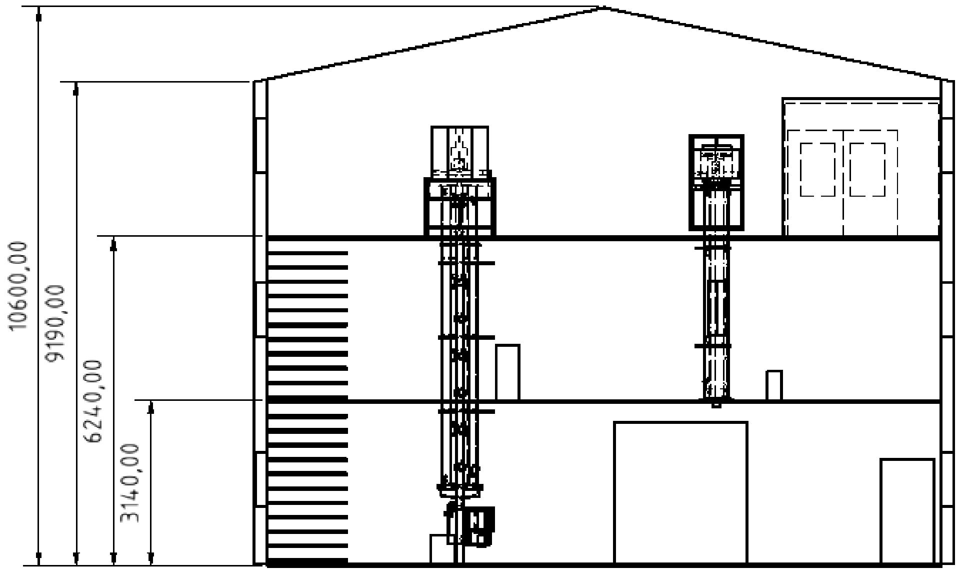
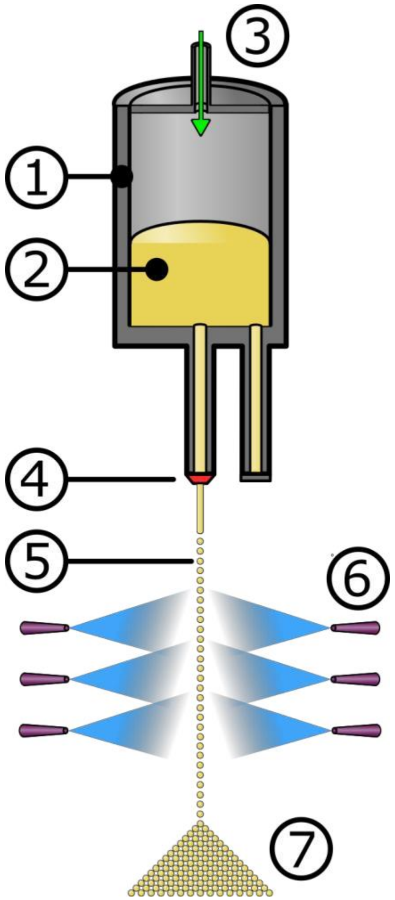
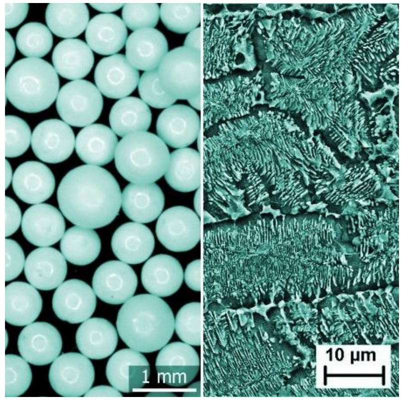
Upgrade of KALOS facility

KALOS - KArlsruhe Lithium OrthoSilicate





KALOS process schematic



Pebbles characterization

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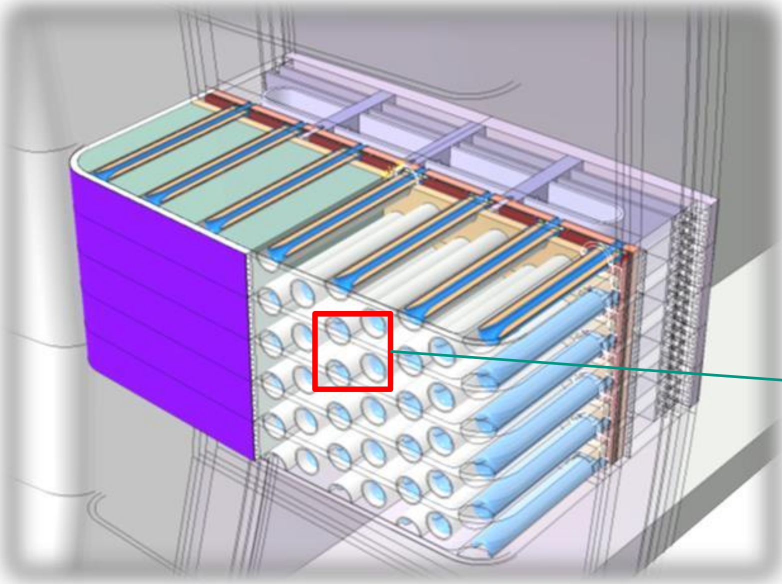
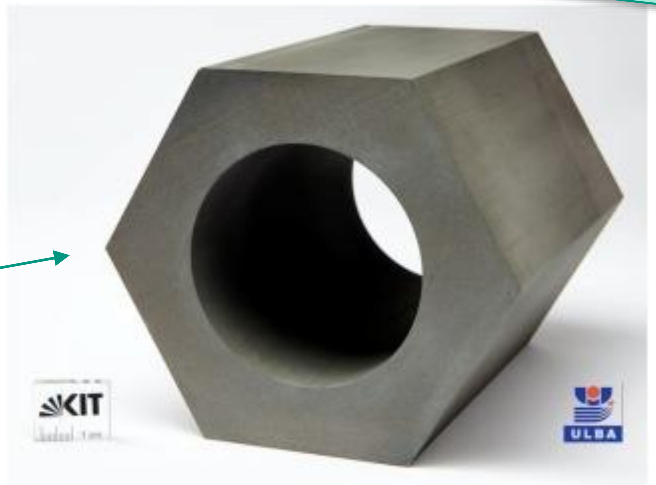
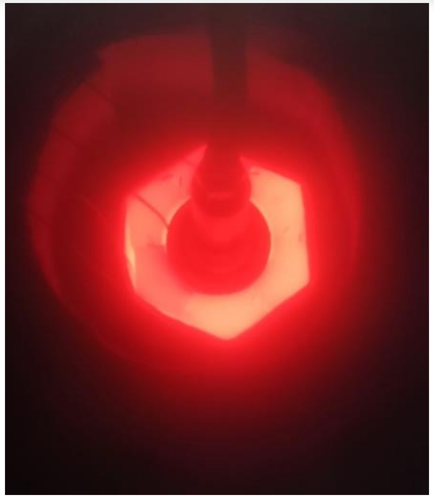
4. Technology R&D – Neutron multiplier development

European Commission SOFT Innovation Prize



Be12Ti block





Thermal cycling testing

Be12Ti block withstand over 200 thermal cycles.

NEWS | 21 September 2020 | Brussels, Belgium | Research and Innovation

Fusion research and innovation: three researchers awarded

Today, the European Commission revealed the winners of the 2020 edition of the SOFT Innovation Prize. This prize, awarded at the 31st Symposium on Fusion Technology (SOFT2020), gives recognition to outstanding researchers or industries who have found innovative ideas or proposed new solutions in fusion research.

This year's winners of the SOFT Innovation Prize are:

- **Second prize** (€25 000): **Dr. Pavel Vladimirov**, **Karlsruher Institut für Technologie (KIT)**, for the development of advanced solid neutron multiplier in support of innovative tritium-breeding blanket design. Future nuclear fusion reactors consuming tritium and deuterium should produce their fuel by themselves. The production of fuel shall be facilitated by neutron multiplier, which is an essential part of tritium-breeding blanket.

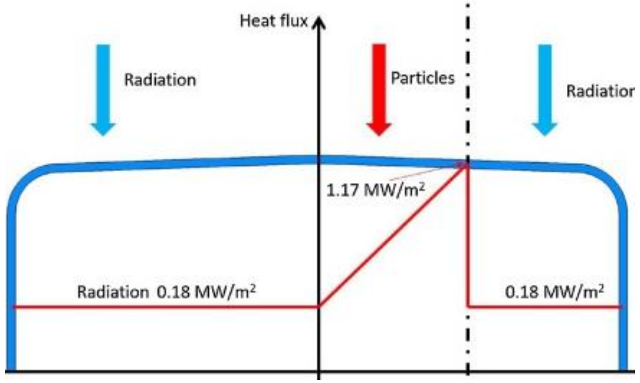
Source: https://ec.europa.eu/info/news/fusion-research-and-innovation-three-researchers-awarded-2020-sep-21_en

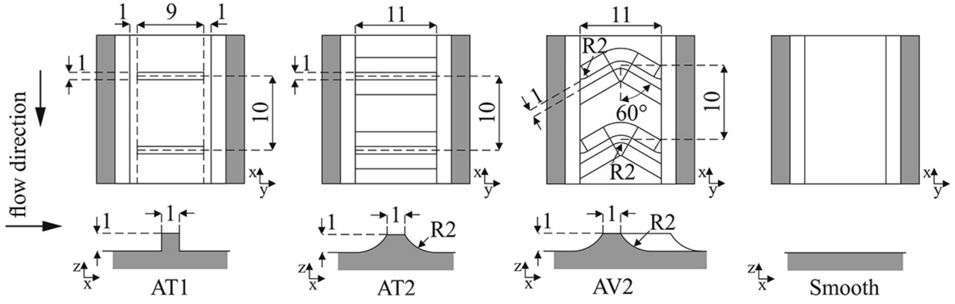
4. Technology R&D – HHF Helium cooling technology

High heat flux up to 1200 kW/m², using rips to enhance the heat transfer performance

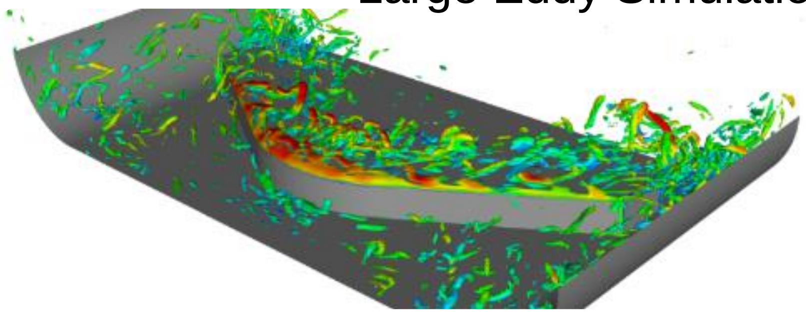
Summer heat flux of PV panel @UCSD: ca. 300 W/m², UCSD thesis 2011.

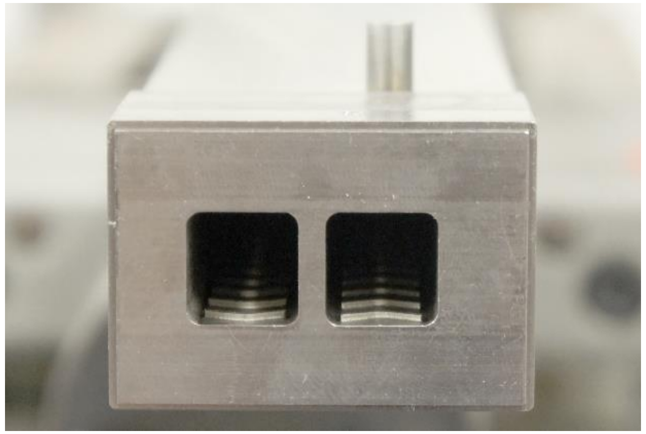
4000 x





Large Eddy Simulation





V-rip

High Heat Flux testing

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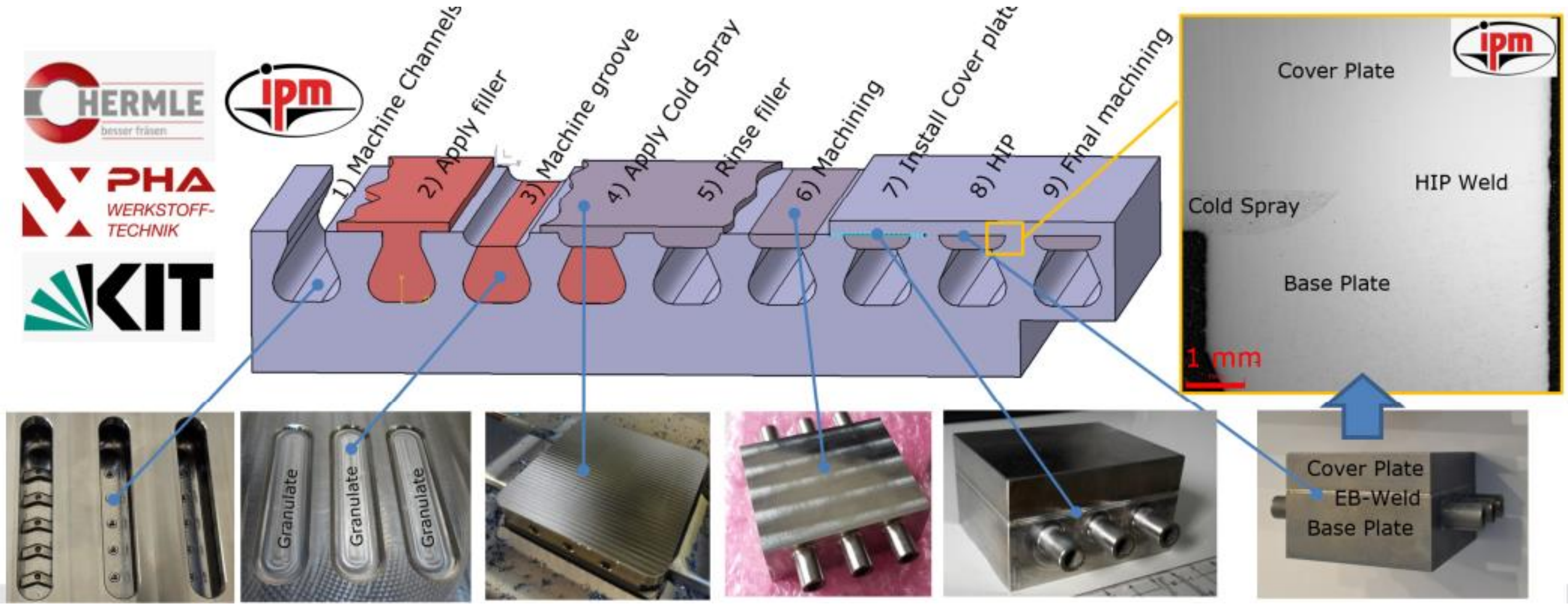
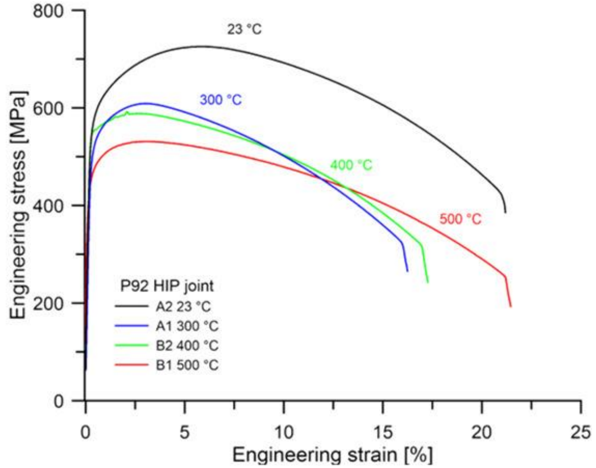
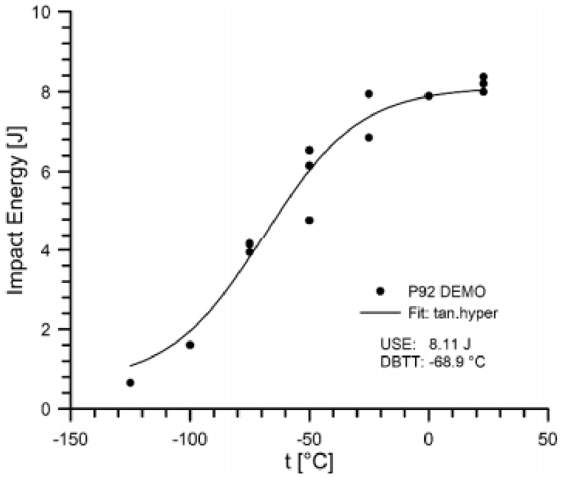
4. Technology R&D – FW manufacturing

Patented technology: additive manufacturing for manufacturing turbulence promoters.

Charpy-test shows that USE and DBTT comparable







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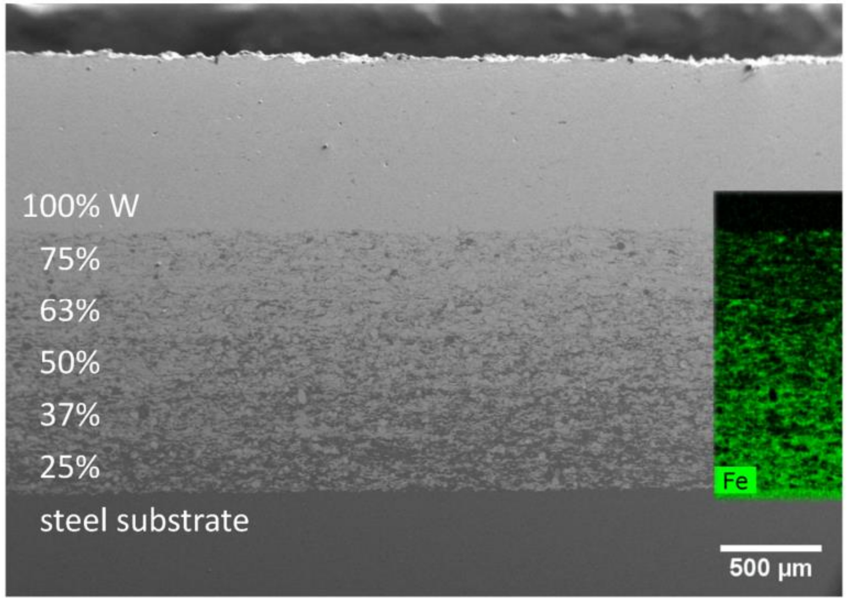
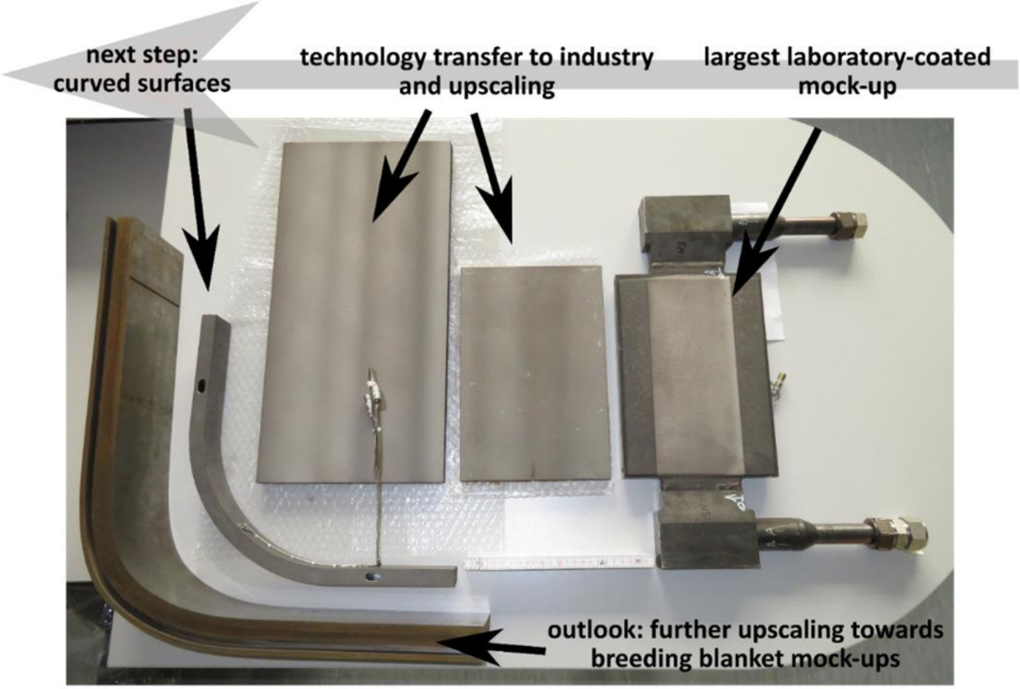
4. Technology R&D – FW coating

The coating of the breeding blanket's first wall with a tungsten layer is of key importance for the protection of the TBM and for minimisation of wall erosion.

Thermal expansion mismatch beween W and EUROFER can be mitigated with a **functionally graded W/EUROFER interlayer**, manufactured by vacuum plasma spraying.



1000 thermal cycles testing



W-coating development: Approaching fusion-relevant size and shape

Coating surfaces up to 500×250 mm²

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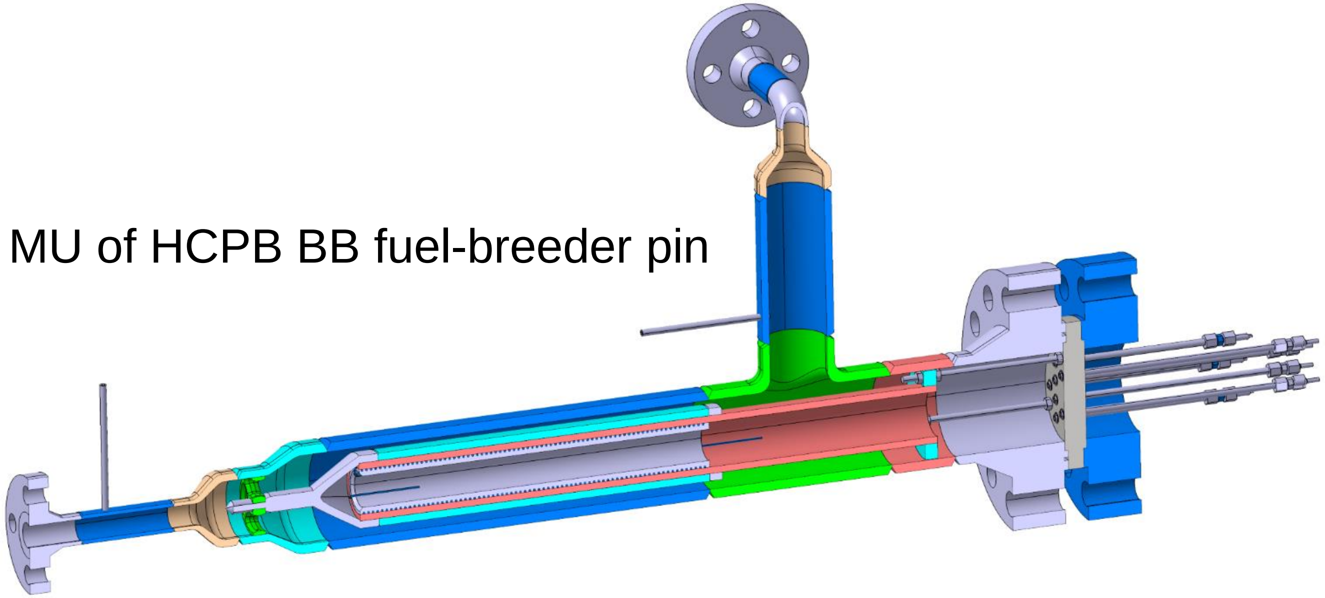
4. Technology R&D – Prototypical Mock-up testing

MU of HCPB BB fuel-breeder pin



Assembly

Integration into HELOKA

First test runs completed.

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5. Challenges

- Reliability, Availability, Inspectability, Maintainability (RAMI)
  - BB structures very complex (requires a lot of welds) that can fail => reliability ↓
- Limited FW heat flux capability
  - About ≈1-1.5MW/m², strongest limiting factor: Eurofer-97 steel
- 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 (fabrication and welding tech.) 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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6. Conclusions

- 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)
- 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…

Many interesting topics for master and doctoral theses!

Background: Mechanical Engineering or related

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Acknowledgements

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

HCPB BB Team:

Karlsruhe Institute of Technology · Ciemat · cea · MŰEGYETEM 1782 · Centrum výzkumu Řež s.r.o. Research Centre Řež · Politecnico di Torino · ESTEYCO