Seminar talk at Institute of Plasma Physics
Hefei, China, 13 June, 2023

EUROfusion

Overview of the design and R&D activities of the Helium Cooled Pebble Bed breeding blanket in Europe

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Breeding Blanket Project in EUROfusion

Outline

1. EUROfusion Organisation
2. WPBB Organisation
3. EU-DMEO Top-Level Requirements
4. The HCPB Breeding Blanket: Design Activities
5. The HCPB Breeding Blanket: R&D Activities
6. Challenges
7. Conclusions

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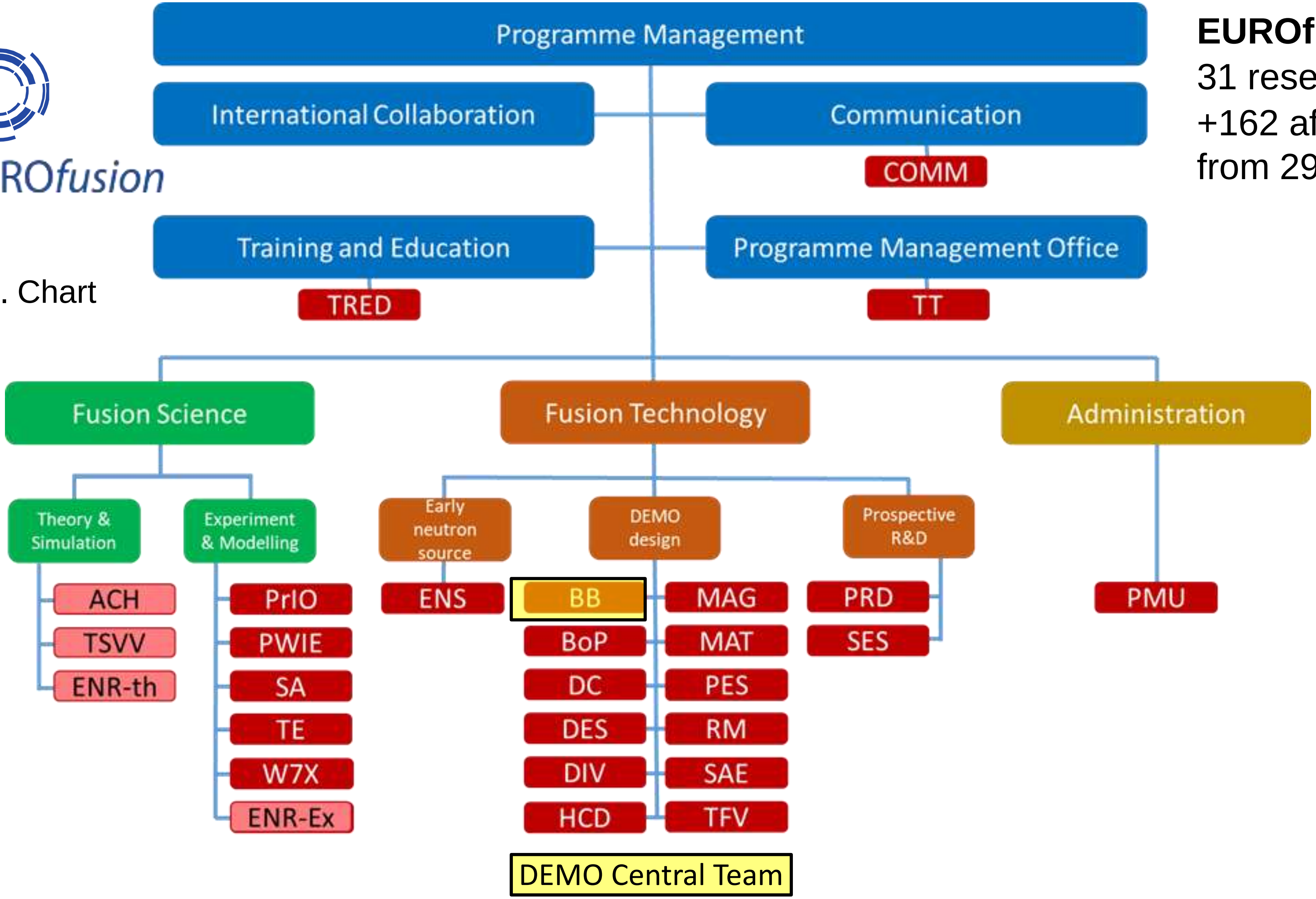
1. EUROfusion Organisation

Org. Chart



EUROfusion: Headquarters - Garching

31 research institutes
+162 affiliated universities + companies
from 29 countries.

EUROfusion coordinates the joint European efforts on developing fusion energy.

Budget:
Pre-Concept Design Phase (2014-2020): 1.2 billion Euro

Concept Design Phase (2021-2025): 1.0 billion Euro

Source: T. Donné, 2021

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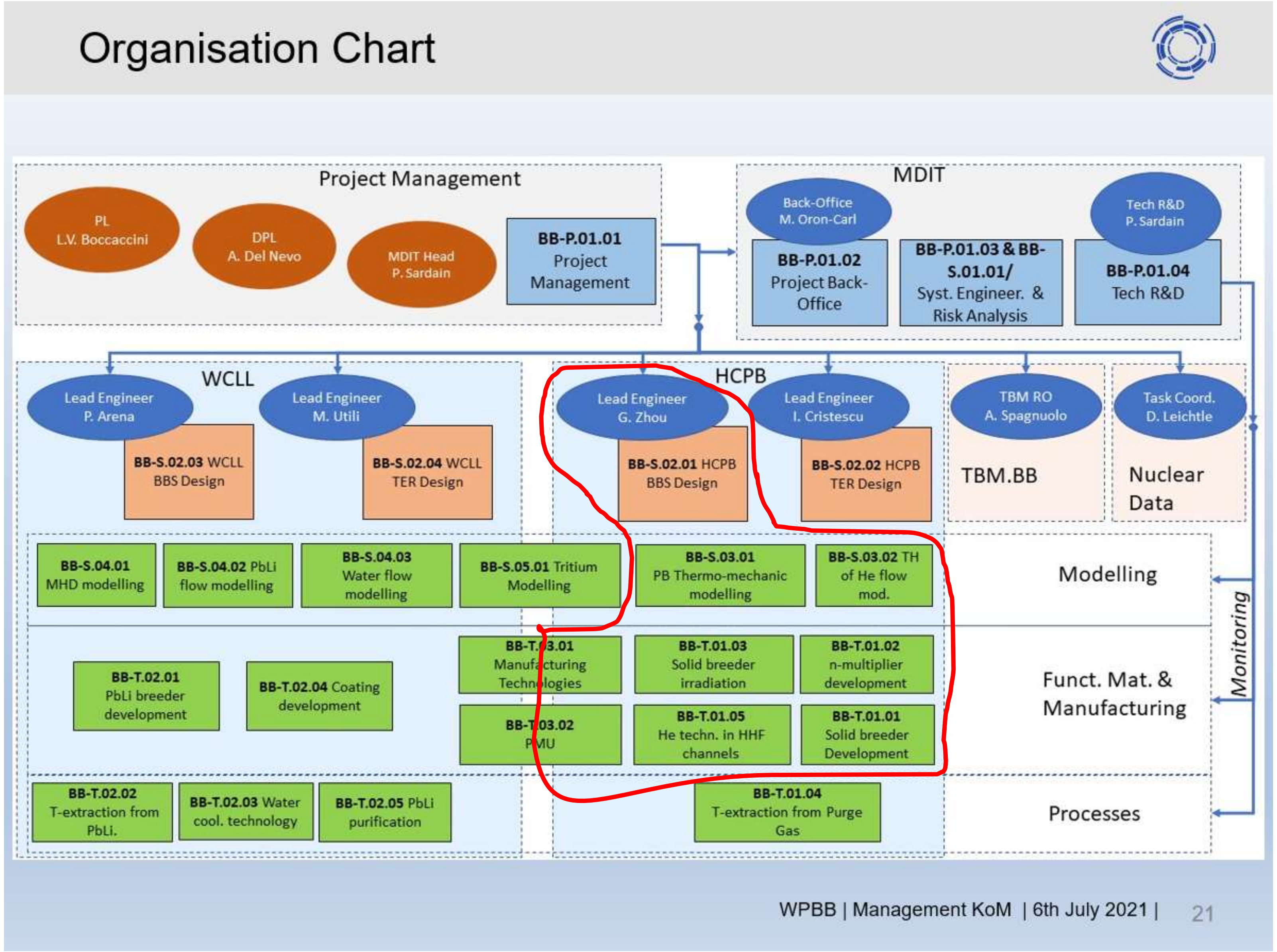
2. WPBB Organisation



Source: L. Boccaccini. Scope, Budget and Organisation of the WPBB in FP9, Kick-off Meeting of WPBB, 6th July 2021.

2021 – 2025: WPBB
Manpower: 96 ppy, over 160 contributors

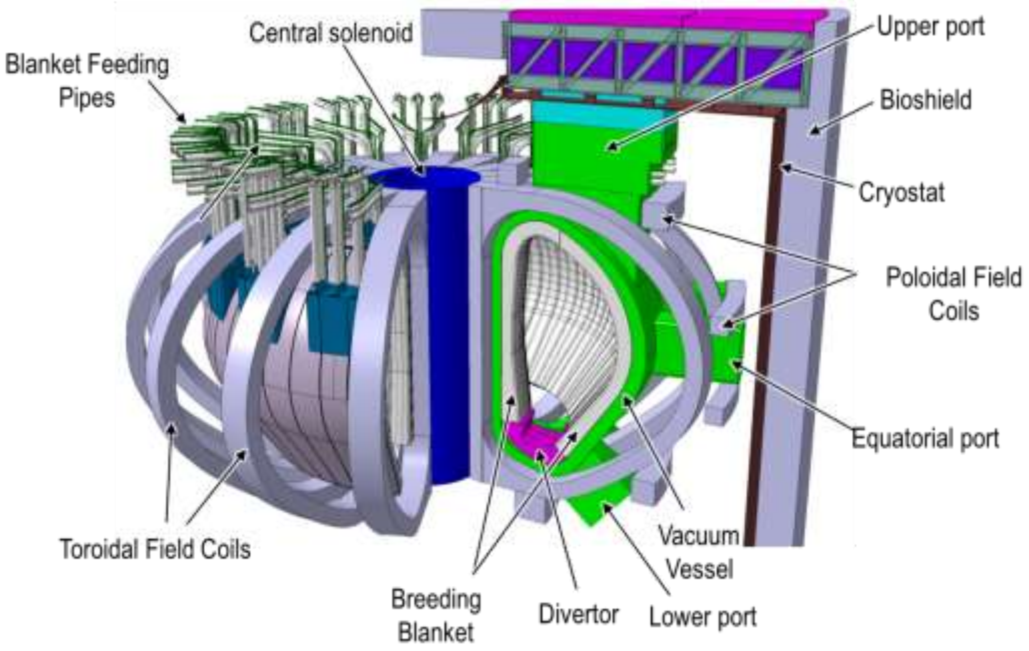
Average annual budget in HCPB BBS:
4.40 million Euro
Manpower: 25 ppy, over 50 contributors

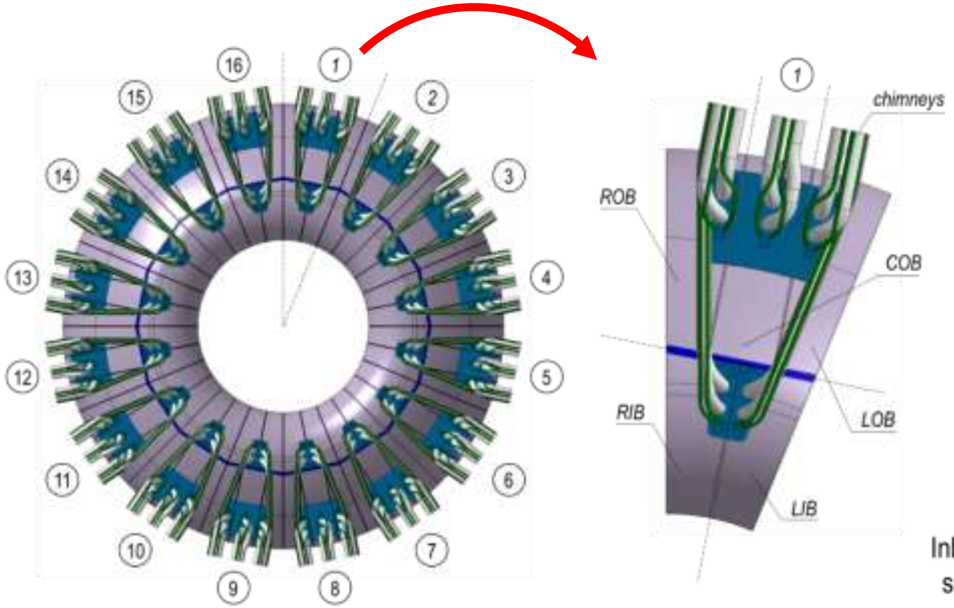
3. EU-DMEO Top-Level Requirements (selected)

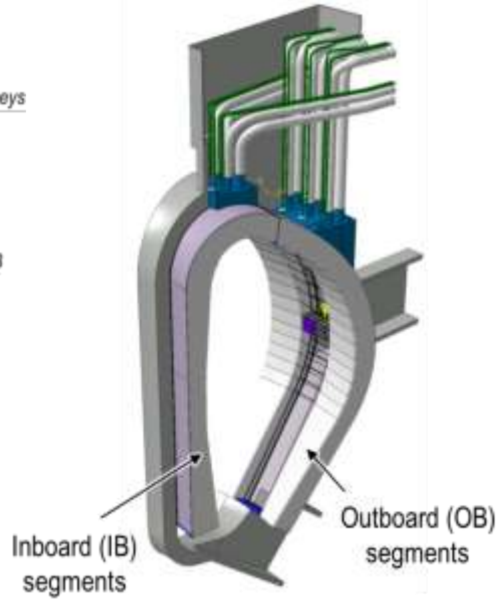
- **Reactor availability** > 30%
- **Tritium self-sufficiency:** TBR ≥ 1.15 (w/o BB loss of coverage)
- **Shielding:**
  - Nuclear heating in Toroidal Field Coil < 50 W/m^3
  - Vacuum vessel irradiation damage < 0.2 dpa/fpy
- **Design and manufacturing**
  - Component design, manufacturing and joining following rules defined in nuclear codes

3. EU-DEMO Blanket Segmentation

- 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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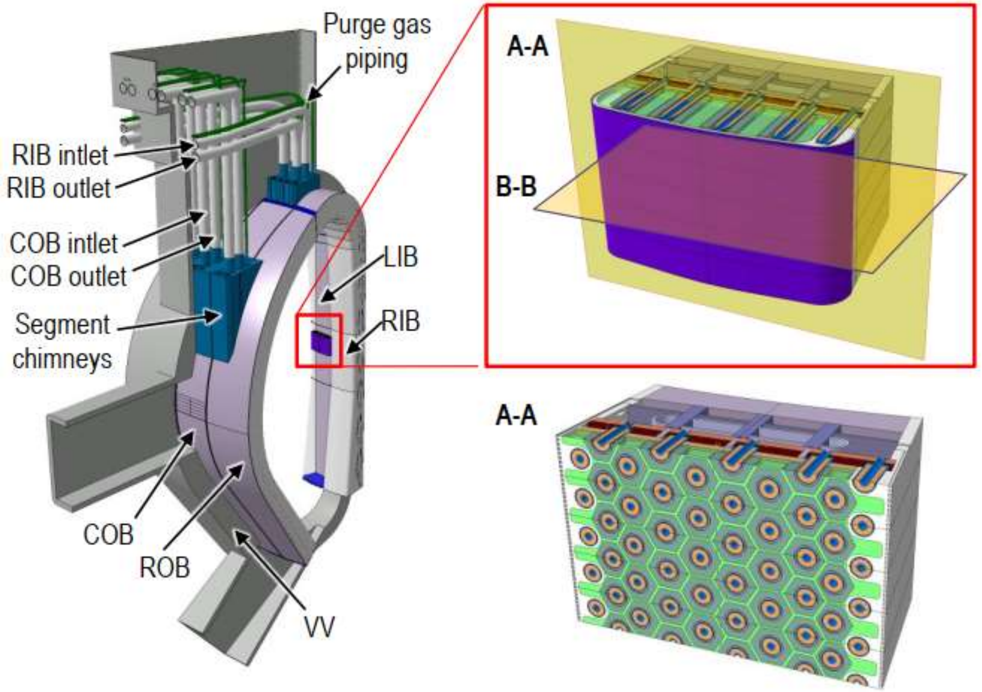
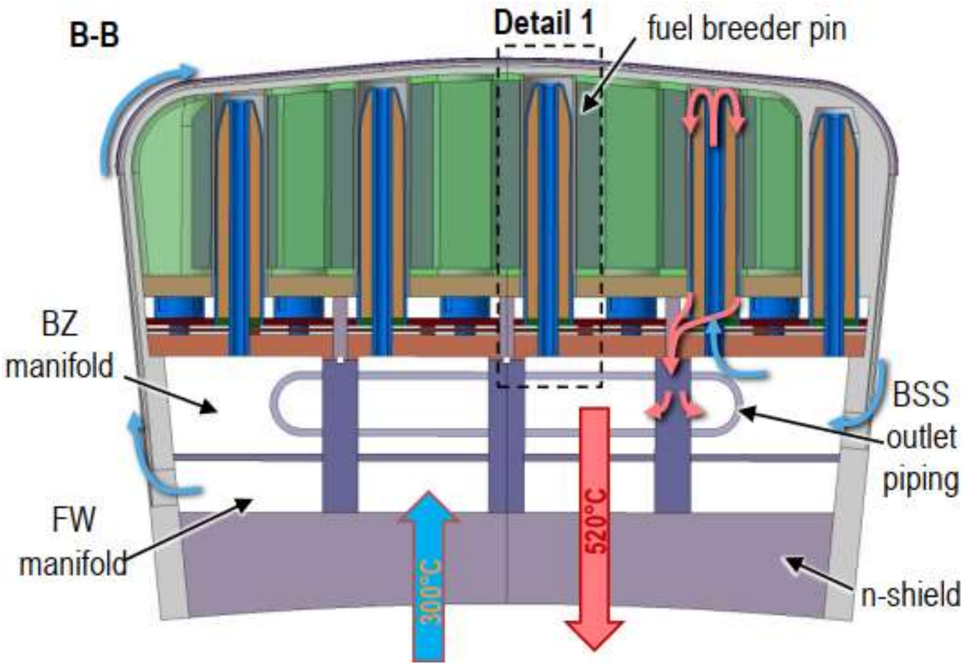
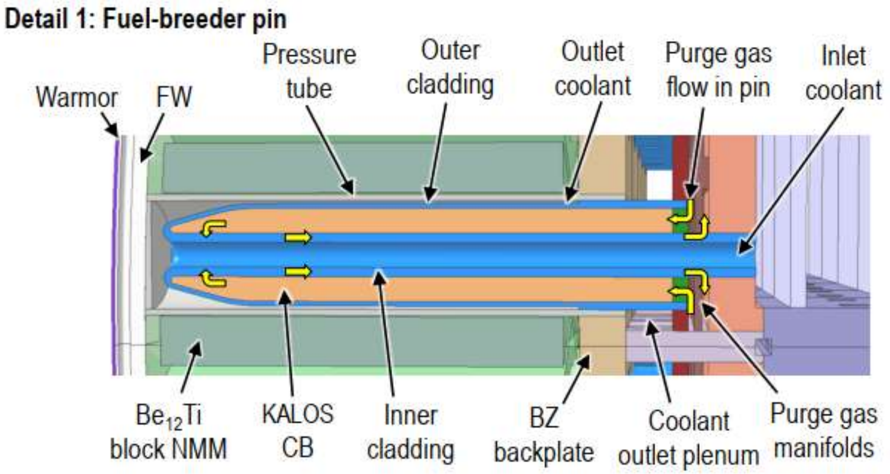
4. Status at the end of Pre-Concept Design Phase (2014-2020)

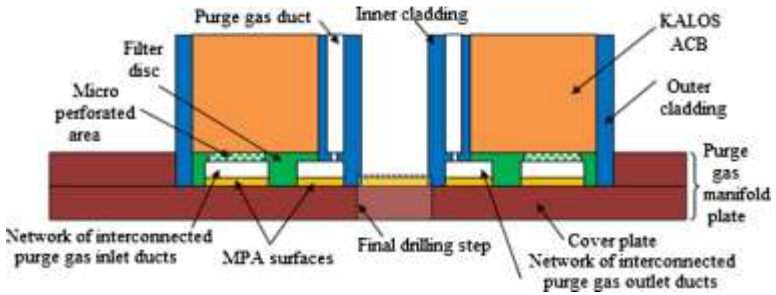






- Fuel-breeder pin concept, simple design, easier manufacturing, triangle arrangement
- Tritium breeder: advanced ceramic breeder (ACB)
- Neutron multiplier: Be12Ti block
- Structural steel: Eurofer97
- Coolant: He @8MPa, 300-520°C
- Purge gas: He + 0.1vol% H_2 @0.2 MPa
- NA, TH & TM; TBR = 1.20

4. Identified design issues related to HCPB BB & Measures



Low reliability of BB system under DEMO conditions [due to welds failure]

- ✓ Equalize purge gas and coolant to eliminate in-box LOCA welds, to improve reliability

Large tritium permeation rates at the interface of breeder-coolant loop

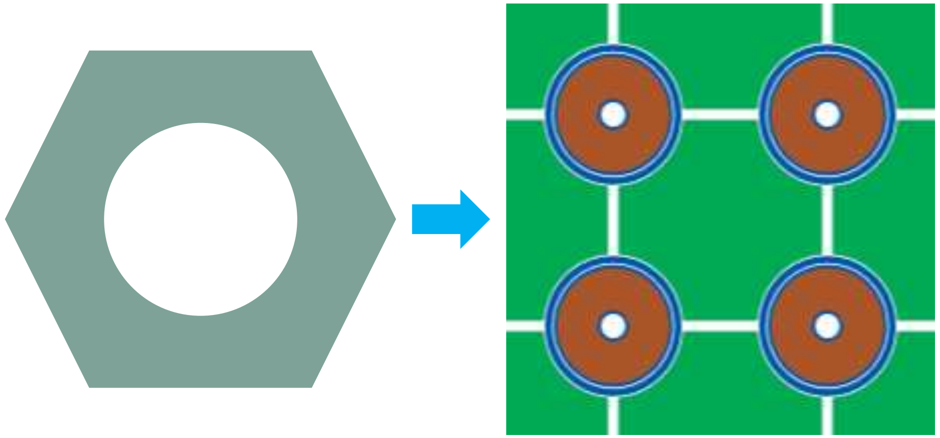
- ✓ Different purge gas schemes (steam, counter-permeation) to reduce permeation

Low BB shielding capability

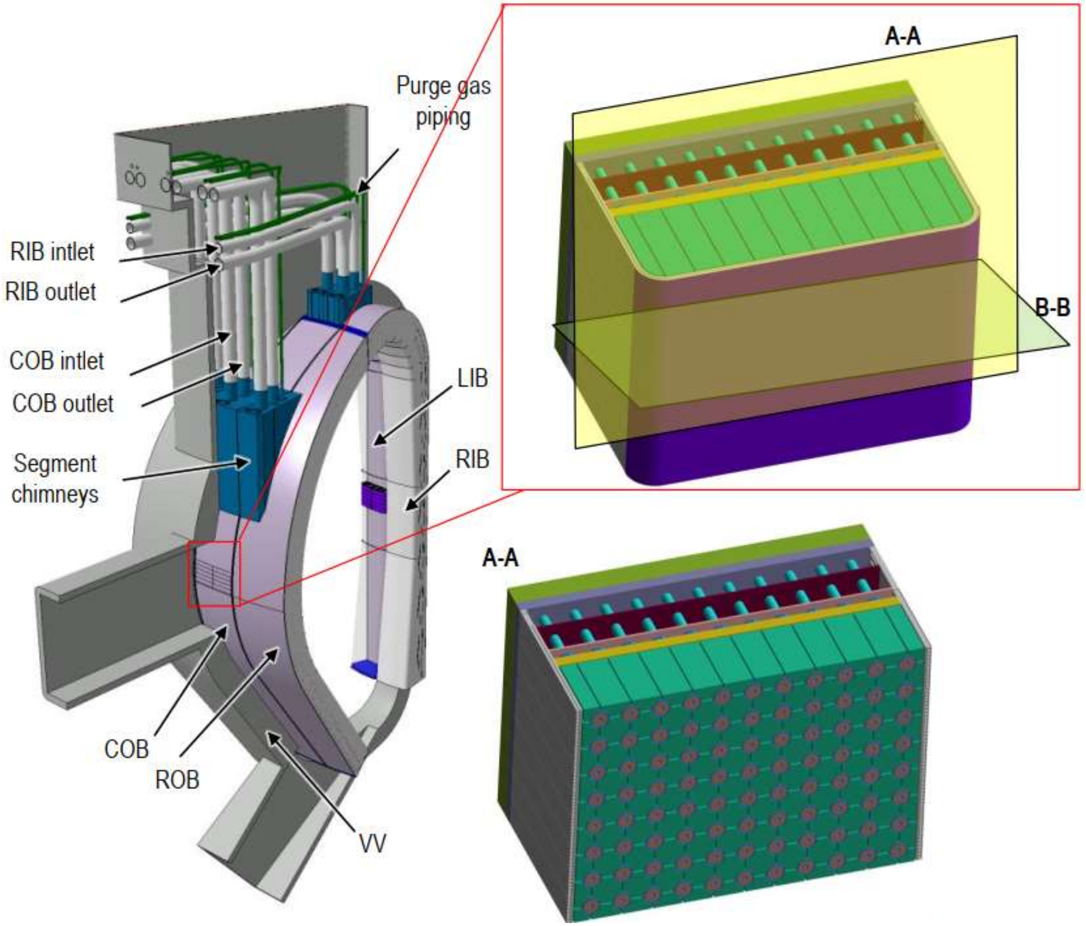
- ✓ Explore more efficient shielding materials

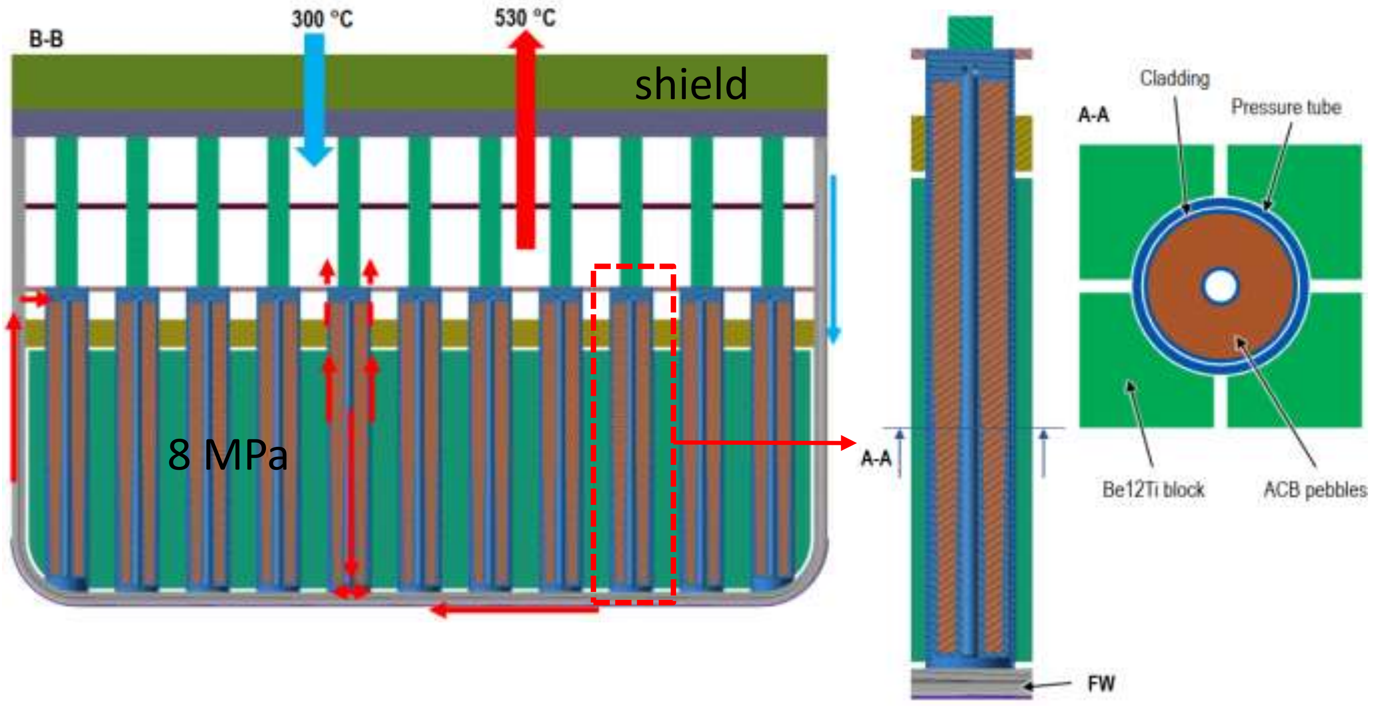
Loss of structural integrity of beryllide blocks with a central hole

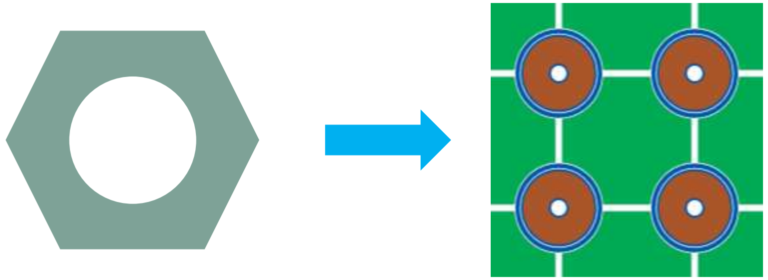
- ✓ New shaping of block to reduce breakage



4. Proposed design changes for improvements



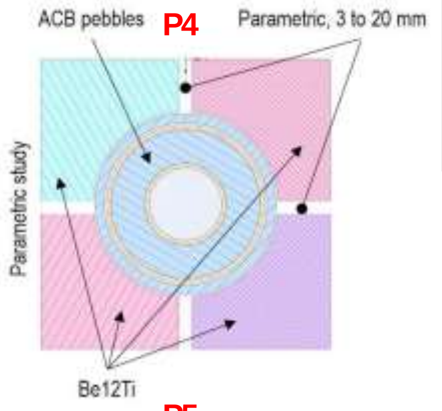


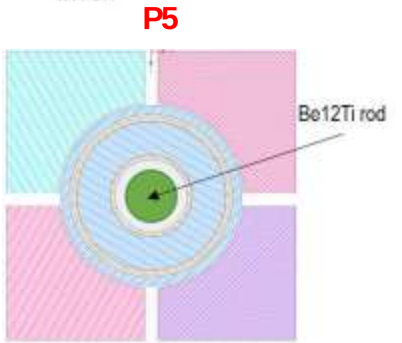


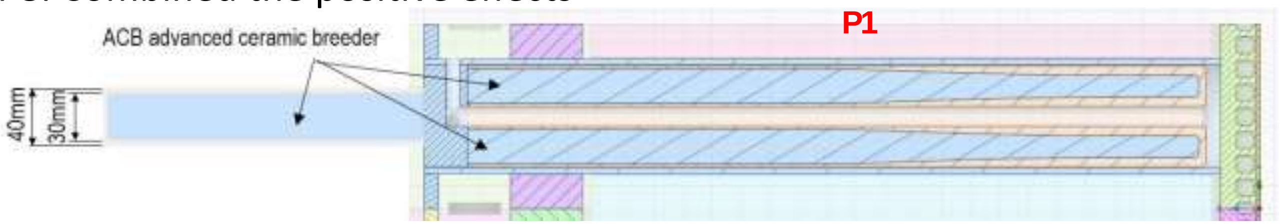
- Equalize purge gas and coolant pressure to eliminate in-box LOCA welds to improve reliability
- Shape of Be12Ti block to square to reduce fracture
- Add a more efficient shield
- 8 MPa purge gas requires thicker structure

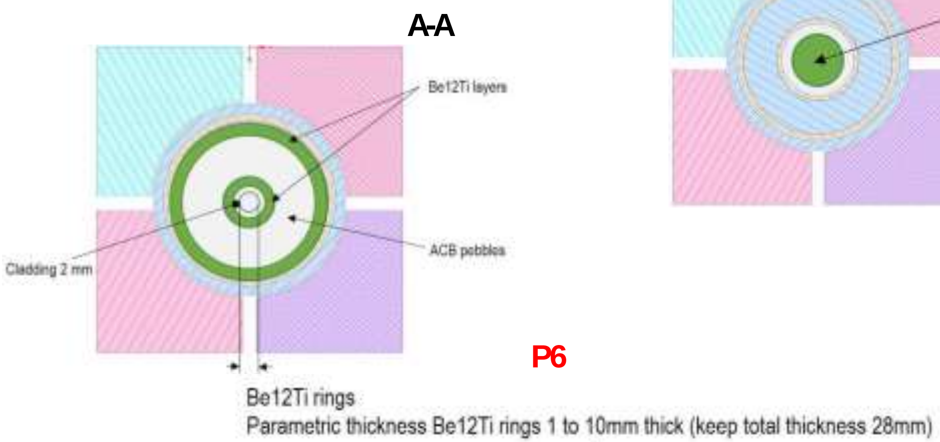
4. Tritium breeding ratio (TBR) optimization

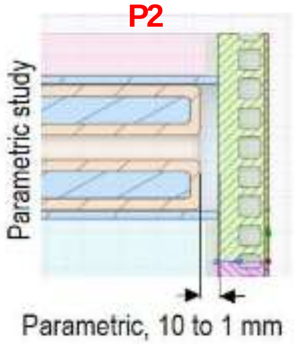
P1. Study influence of ACB in back side of the pin (whole length of back side of pin)
P2. Study reduction of the front pin cladding distance to FW
P3. Study influence of Be12Ti radial length
P4. Study influence of Be12Ti block gaps
P5. Introduction of a Be12Ti rod in the inner tube
P6. Introduce Be12Ti in pin
P7. Like P6, but ACB thickness 35 mm and introduce Be12Ti only one side
P8. Combined the positive effects

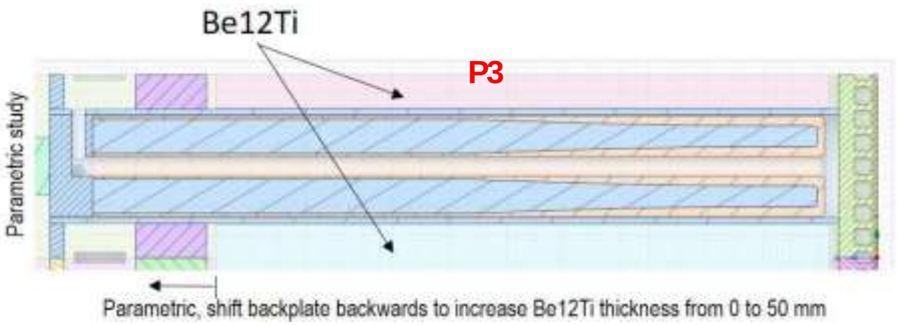


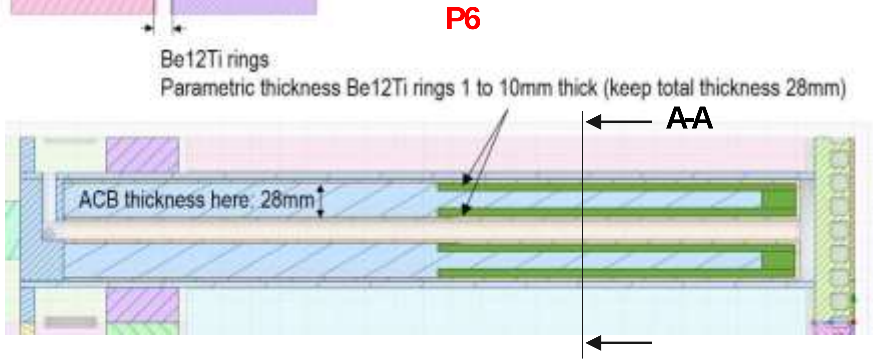


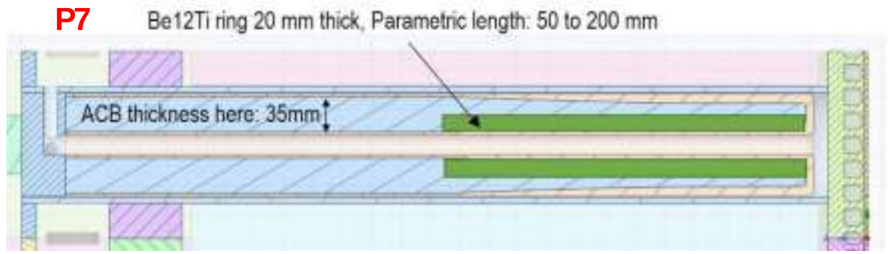






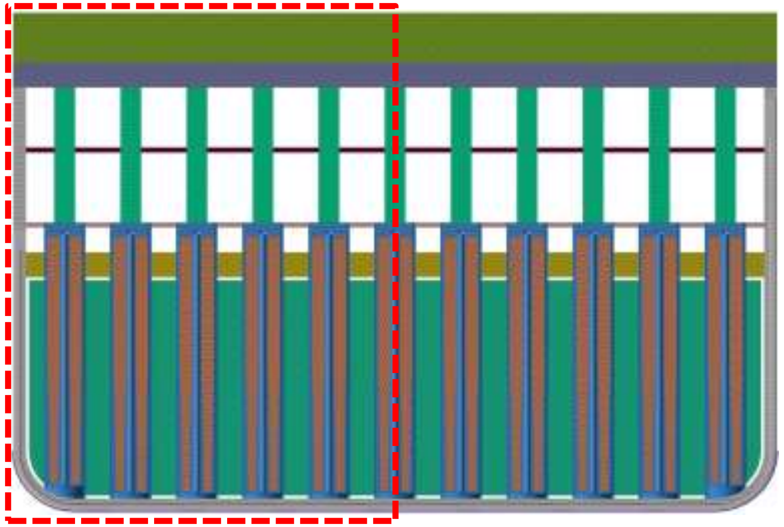




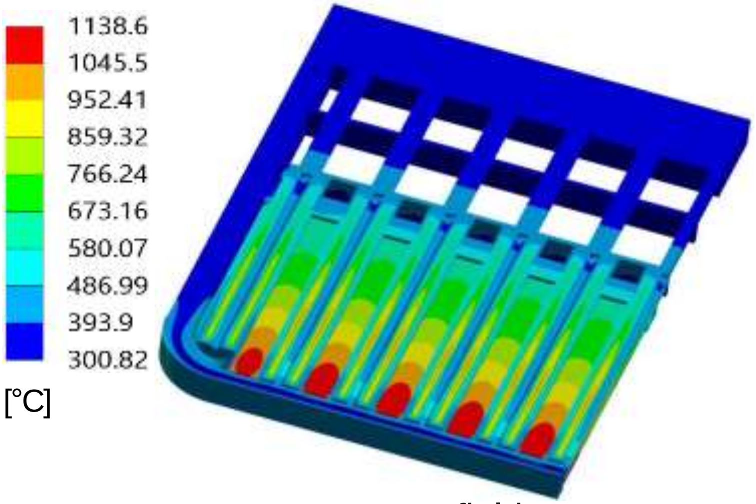


- Combined all positive effects TBR = 1.17

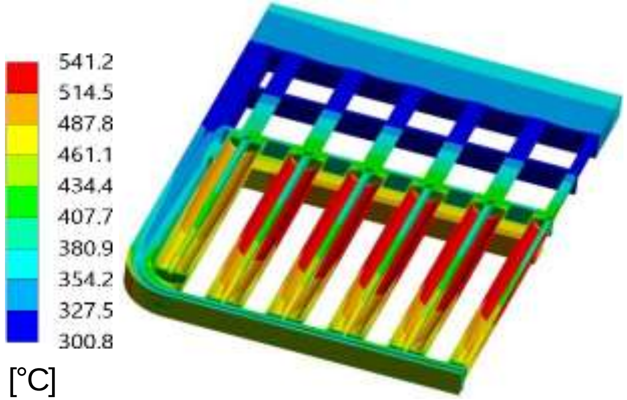
4. Thermal and structural analysis

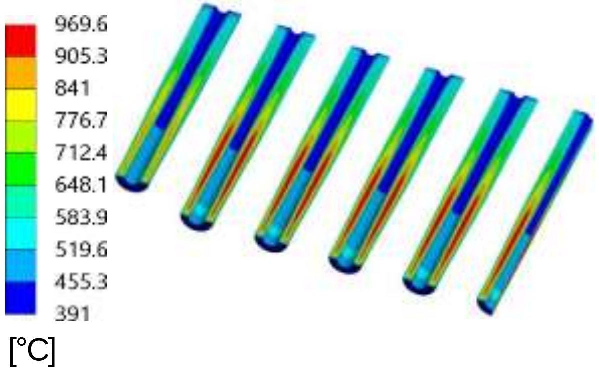


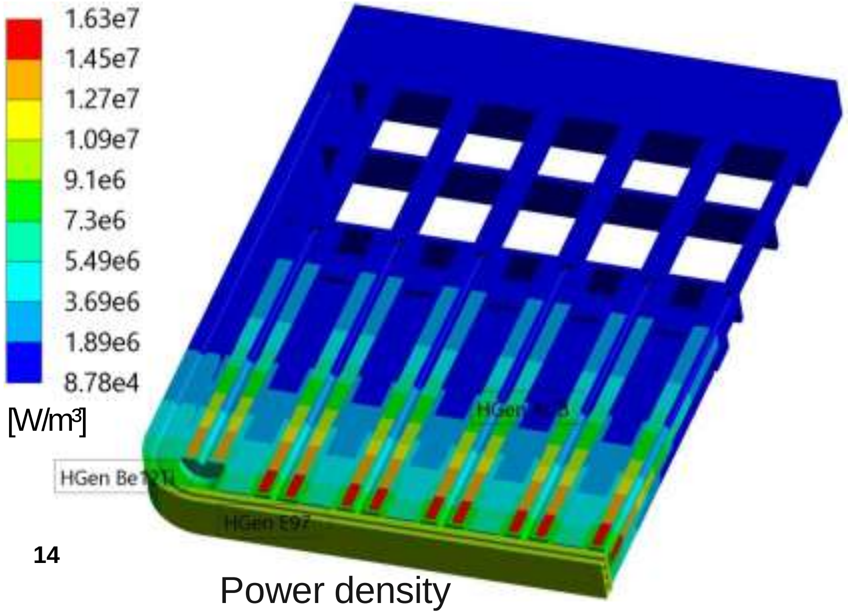
FEM model



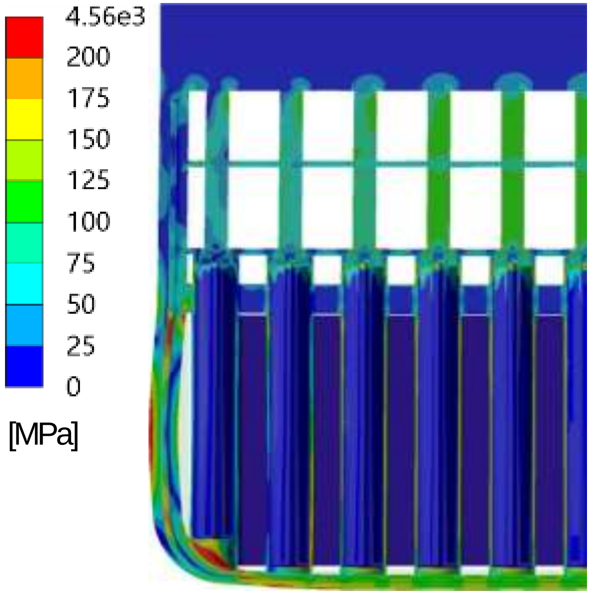
Temperature field







Power density

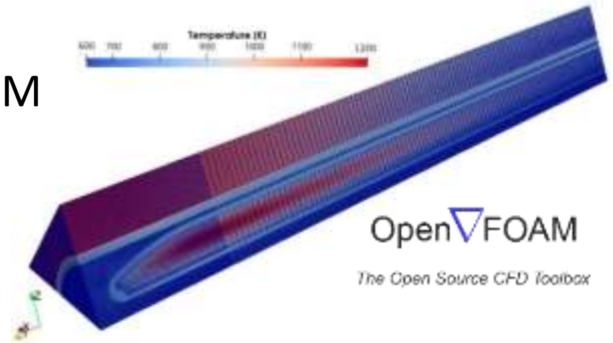


Stress field (P)

Tin / Tout = 300 / 530 °C
Temp. within design limits
Stresses of steel are within allowables of code

4. Tritium transport analysis

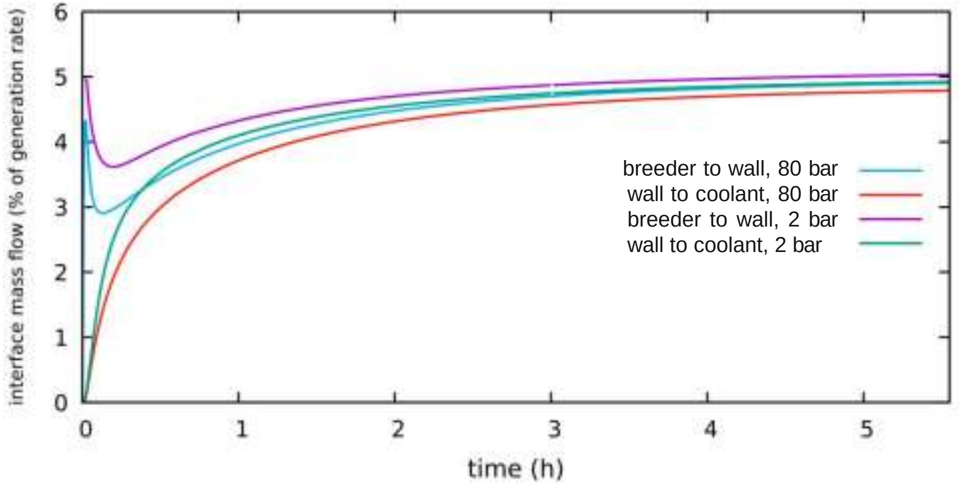
- 3D component level solver
  - Developed based on the OpenFOAM and benchmarked with TMAP 7



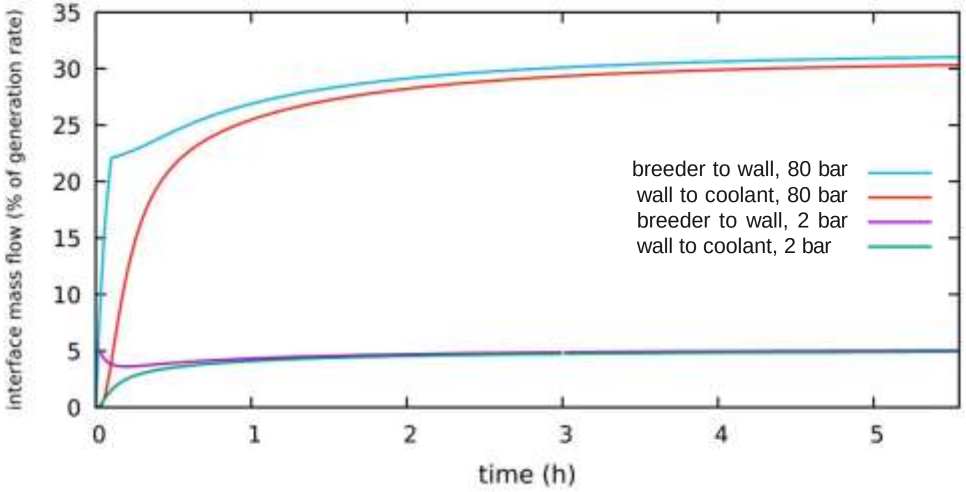
- T permeation analysis
  - T permeation analysis under 8 MPa pressure purge gas vs 0.2 MPa pressure purge gas, with same H_2 partial pressure
  - Wetted purge gas vs dry purge gas

Purge gas	Permeation to coolant
200 Pa H_2, no H_2O	0.077% of T generated
200 Pa H_2, 200 Pa H_2O	0.022% of T generated

A reduction factor of 3.5 is obtained.



Permeation under equal volumetric flow



Permeation under equal mass flow

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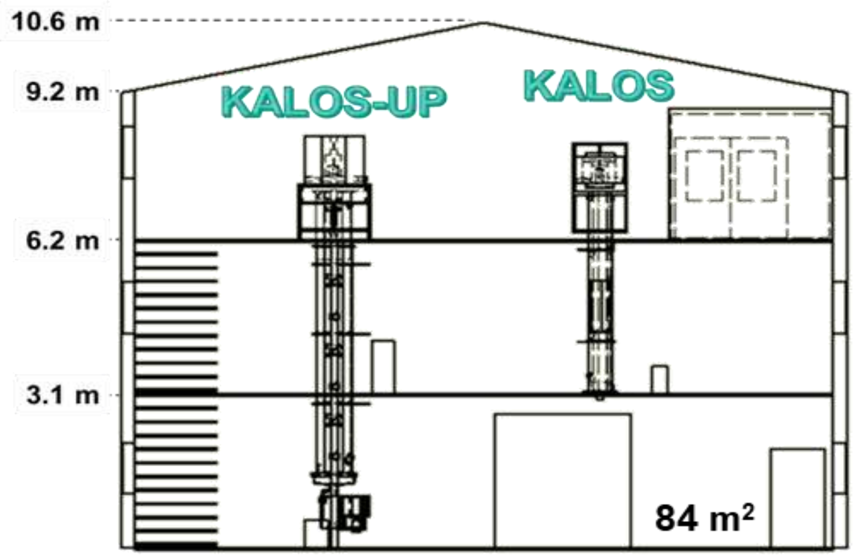
5. Technology R&D – Solid breeder development

KALOS-UP facility



Advanced Ceramic Breeder:

Li_4SiO_4 + 35% mol. Li_2TiO_3

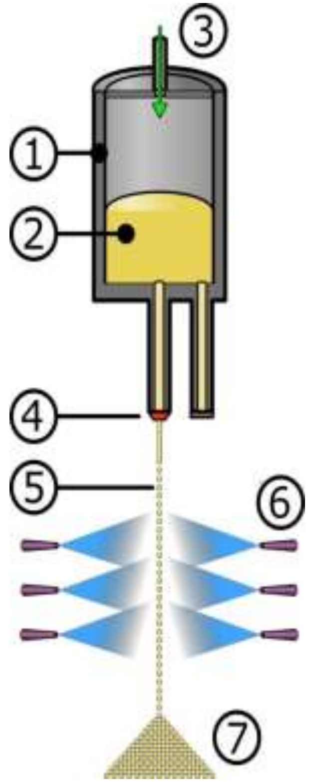
Better mech. & T-release

Motivation:

Established KALOS processing is a batch process, limited by 1 kg per batch, not economic to provide 100 kg ACB pebbles for HCPB TBM

Objective:

1. Increase the production rate to 5 kg/d.
2. Transition from batch to continuous operation involving the continuous feeding and melting of pre-reacted starting powders.

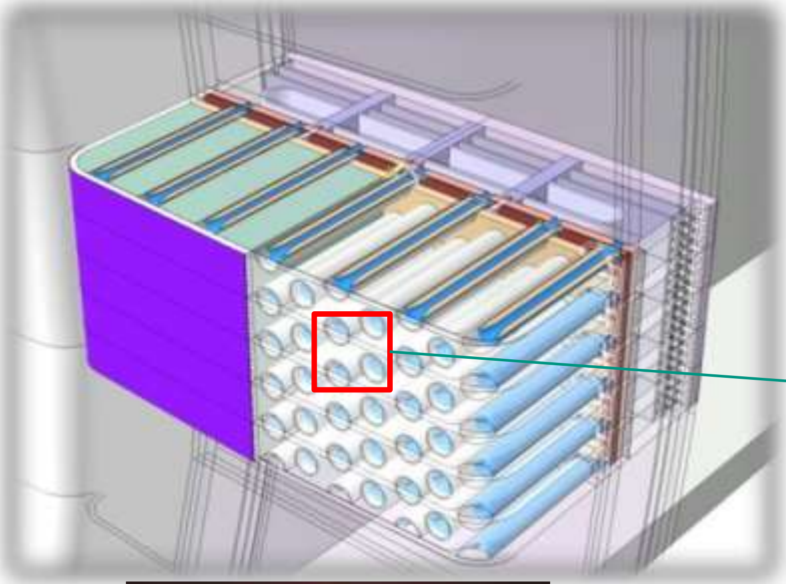


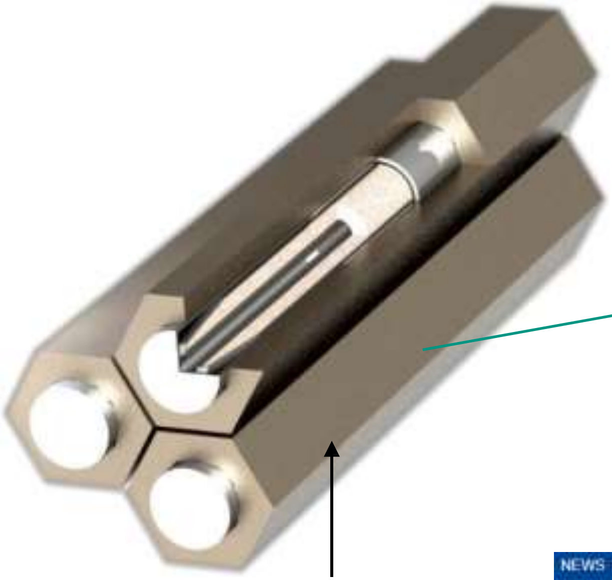
Process schematic

Status:

Increased the production rate to 2 kg per batch. In 2025, fully upgraded.

5. Technology R&D – Neutron multiplier development





Be12Ti block

SOFT Innovation Prize 2020
2nd Prize

Thermal cycling testing

Be12Ti block withstand over 500 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:

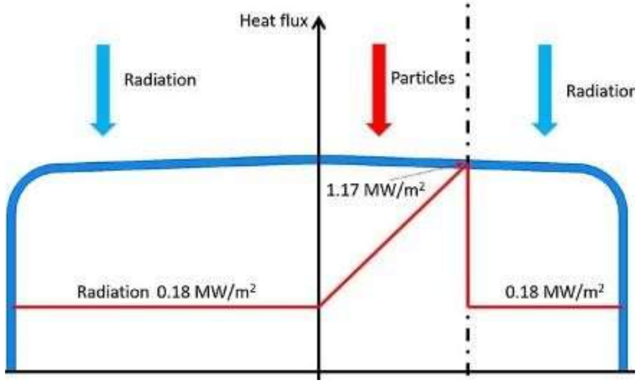
- **Second prize** (€25 000): **Dr. Pavel Vladimirov**, **Karlsruher Institut für Technologie (KIT)**, for the development of advanced solid neutron multiplier in support of innovative tritium-breeding blanket design. Future nuclear fusion reactors consuming tritium and deuterium should produce their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

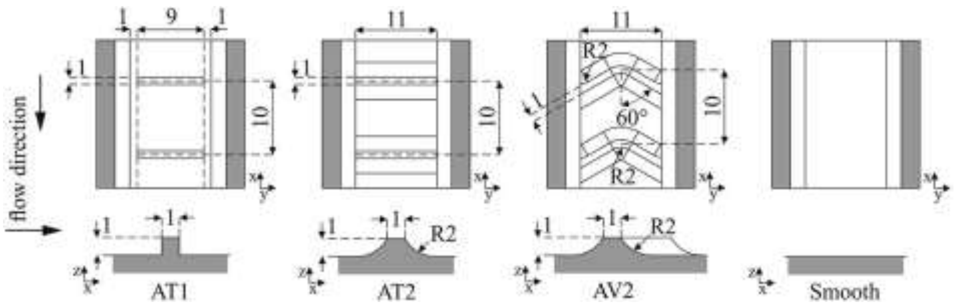
Source: https://ec.europa.eu/info/news/fusion-research-and-innovation-three-researchers-awarded-2020-sep-21_en

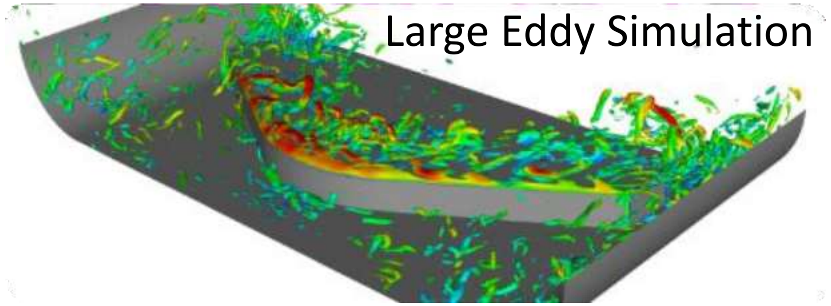
Peak heat flux up to 1.2 MW/m², using rips to enhance the heat transfer performance.

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

4000 x

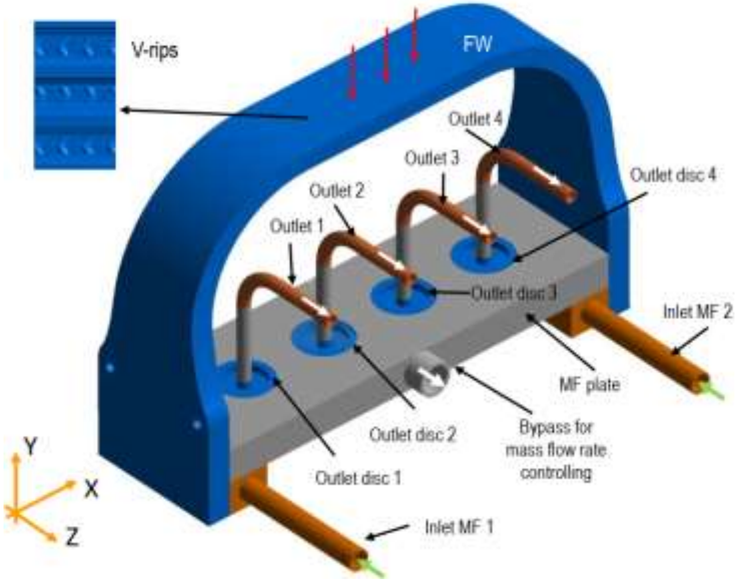






V-rip

High Heat Flux testing

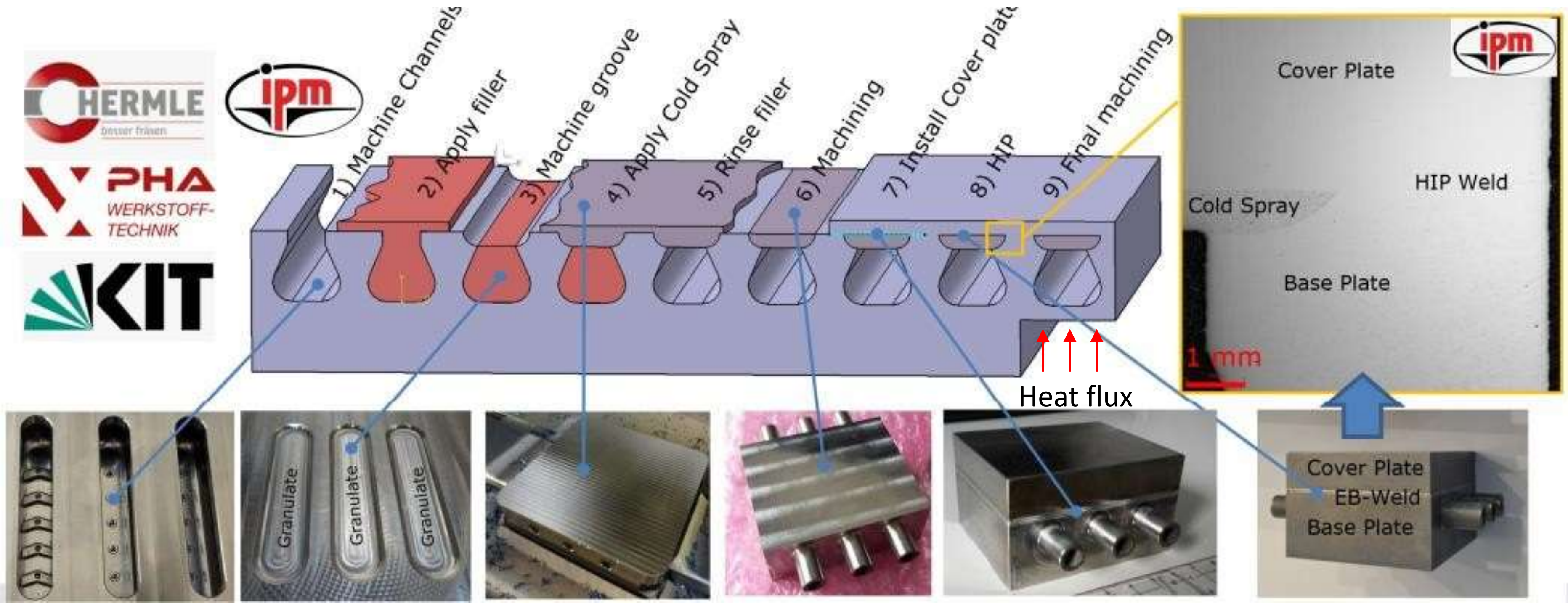


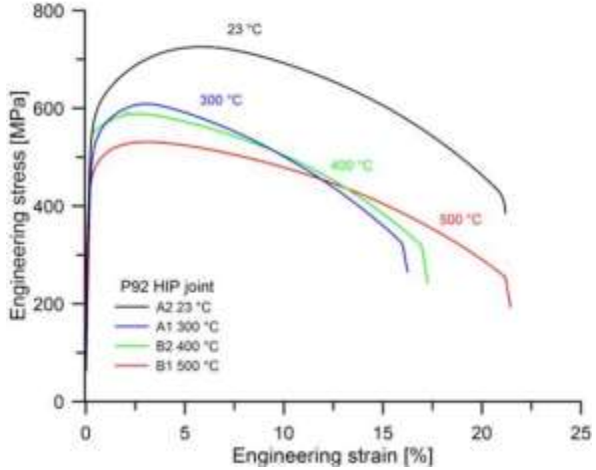
Benchmark with CFD done, now design and fabricate mid-scale FW mockup, test in 2025

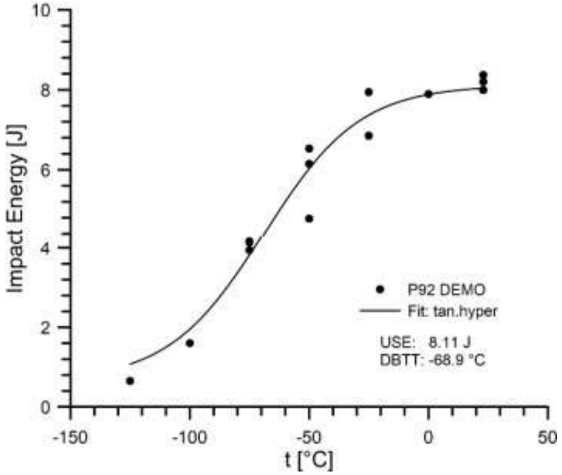
5. Technology R&D – FW manufacturing

Patented technology: additive manufacturing for manufacturing turbulence promoters.

Charpy-test shows that USE and DBTT are comparable to base material.





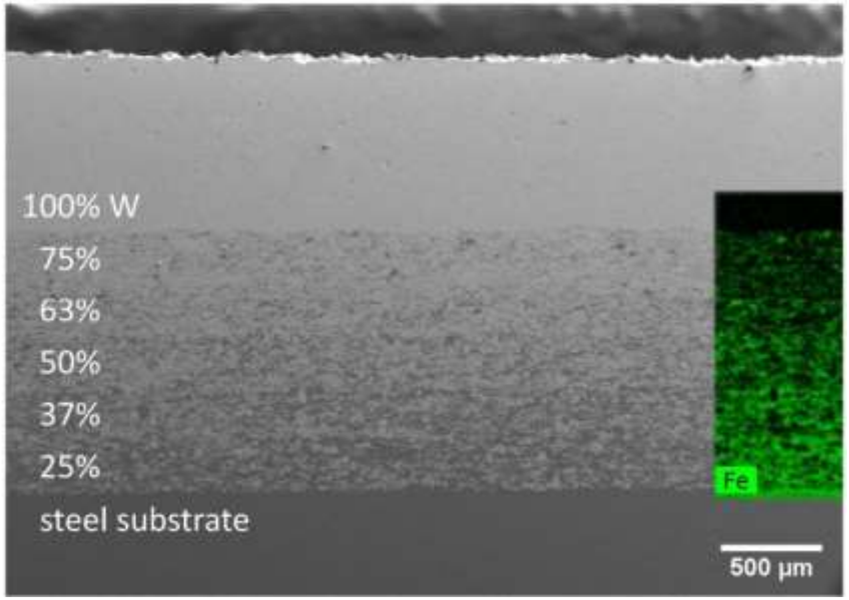


5. Technology R&D – FW coating

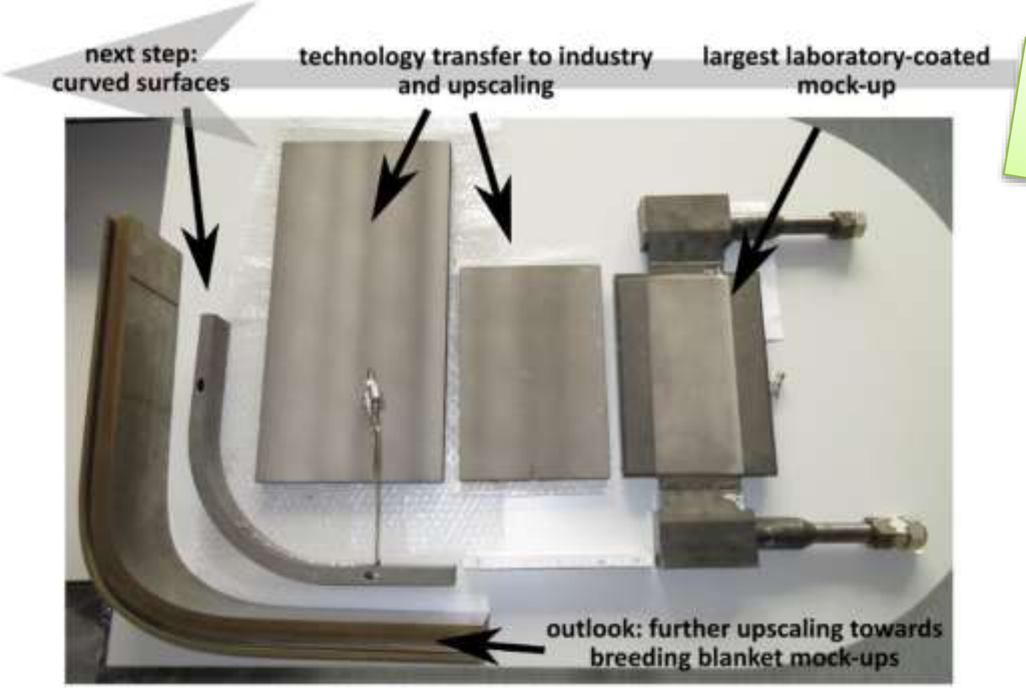
The coating of the breeding blanket’s first wall with a tungsten layer is of key importance for the protection of the blanket and for minimisation of wall erosion.

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

SOFT Innovation Prize 2022
1st Prize

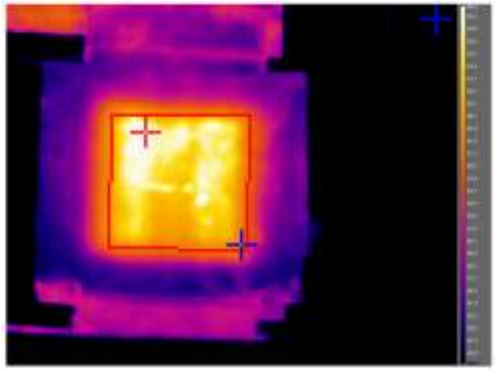


Small scaled mockup tested in the HELOKA helium facility.



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

Currently the largest area: 500 × 250 mm²



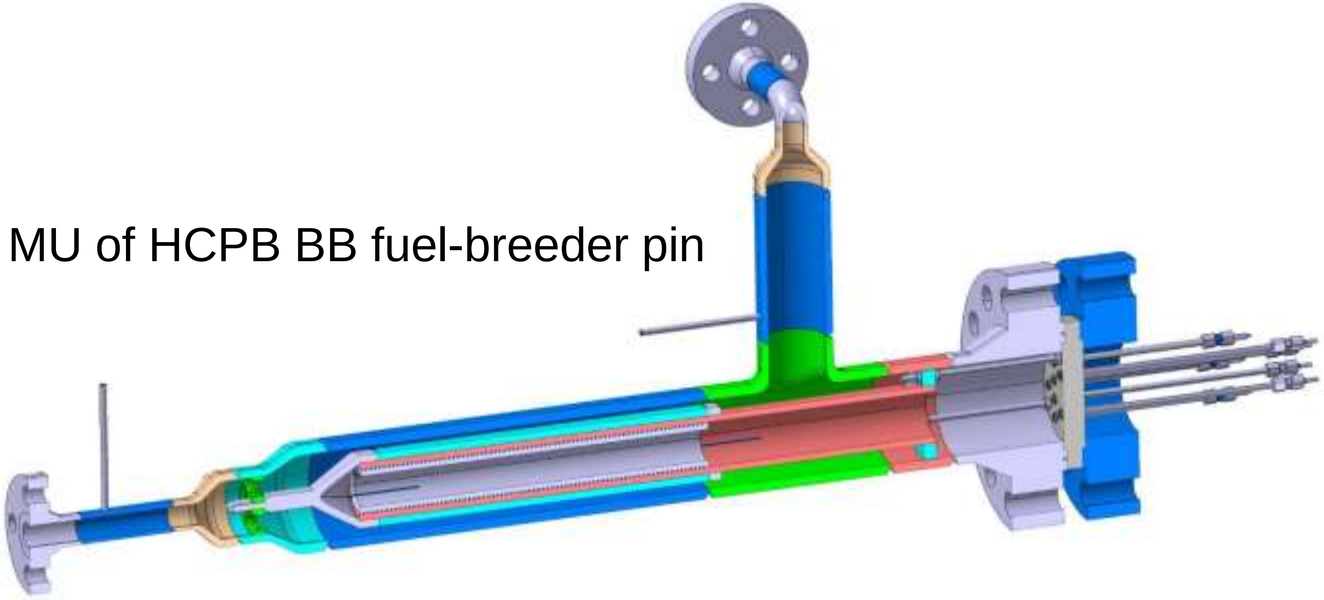
1000 thermal cycles testing with 0.7 MW/m²

T_{max} = 800 °C

Te97 = 520 °C

5. Technology R&D – Prototypical Mock-up manufacturing & testing

MU of HCPB BB fuel-breeder pin



Assembly

Integration into HELOKA

First test runs completed.

Validation of CFD and system codes. To be presented at ISFNT.

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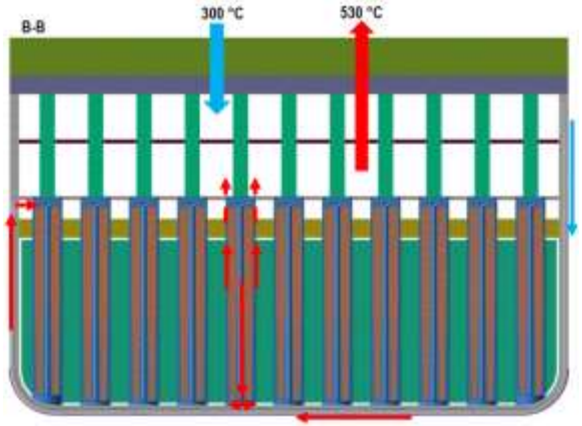
Challenges

Common challenges:

- Low reliability due to too many welds
- Manufacturing at DEMO scale
- Costs
- Integration into DEMO machine
- Lack of suitable volumetric fusion neutrons to test
- …

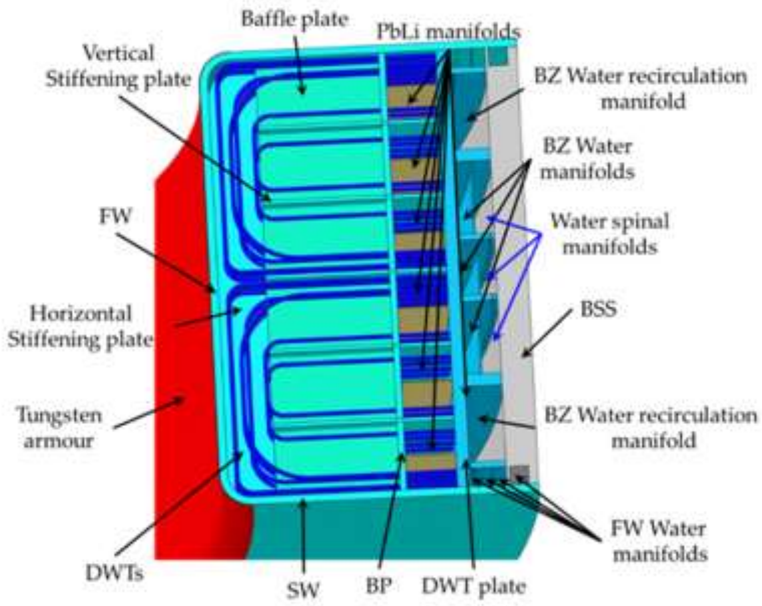
Key HCPB-related challenges:

- n-shielding
- Thermal control
- Thermo-mechanics of functional materials
- Production costs
- Complex Primary Heat Transfer System layout and piping
- …



Key WCLL-related challenges:

- T breeding capability
- Irradiation embrittlement
- Need for permeation barriers
- Corrosion due to PbLi and Water
- Liquid metal embrittlement
- Water-PbLi reaction
- Water activation
- Tritium extraction from PbLi
- …



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6. Conclusions

- The EU-DEMO programme and Breeding Blanket Project (WPBB) was briefly introduced.
- The EU-DEMO Top-Level Requirements related to BB was listed.
- Major design issues facing HCPB BB were identified during the Gate Review.
- Measures to tackle the identified were proposed.
- Proposed new design of HCPB aiming at improving reliability seems to be feasible from the aspects of nuclear, thermal hydr., thermo-mech., tritium extraction and tritium permeation.
- Status of accompanied R&D Programme to maturate the HCPB was presented.
- Challenges facing HCPB and WCLL were listed.

Q & A