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

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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
1. EUROfusion Organisation
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1. EUROfusion Organisation

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
Outline

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2. WPBB Organisation


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/m³
  - 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, $R_0=9\text{m}$, $r=2.9\text{m}$, $P_{\text{fus}} \approx 2\text{GW}$)
  - 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% H₂ @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

Stress field (P)

Power density

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 H2 partial pressure
  - Wetted purge gas vs dry purge gas

<table>
<thead>
<tr>
<th>Purge gas</th>
<th>Permeation to coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Pa H2, no H2O</td>
<td>0.077% of T generated</td>
</tr>
<tr>
<td>200 Pa H2, 200 Pa H2O</td>
<td>0.022% of T generated</td>
</tr>
</tbody>
</table>

A reduction factor of 3.5 is obtained.
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5. Technology R&D – Solid breeder development

KALOS-UP facility

**Advanced Ceramic Breeder:**
Li$_4$SiO$_4$ + 35% mol. Li$_2$TiO$_3$
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.

**Status:**
Increased the production rate to 2 kg per batch. In 2025, fully upgraded.
5. Technology R&D – Neutron multiplier development

Be12Ti block withstand over 500 thermal cycles.

Thermal cycling testing

5. Technology R&D – Helium cooling technology

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.

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 between W and EUROFER can be mitigated with a functionally graded W/EUROFER interlayer, manufactured by vacuum plasma spraying.

Small scaled mockup tested in the HELOKA helium facility.

Currently the largest area: 500 × 250 mm²

1000 thermal cycles testing with 0.7 MW/m²

Tmax = 800 °C
Te97 = 520 °C

1st Prize

SOFT Innovation Prize 2022
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