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
Tritium ($^3T$) has a half-life of 12.3 years. $^3T$ decays at a rate of 5.5%/yr.

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

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)

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

Need to produce $T$
Why Breeding Blanket (BB)?

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

\[
\begin{align*}
\frac{3}{2}Li + n &\rightarrow \frac{4}{2}He + \frac{3}{1}T \\
\frac{3}{1}T + \frac{2}{1}D &\rightarrow \frac{4}{2}He + n + 17.6 \text{ MeV}
\end{align*}
\]

Credit: L.V. Boccaccini

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

WPBB: One of the twelve Work Packages in EUROfusion DEMO programme.
HCPB BB in Work Package Breeding Blanket (WPBB)

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

LE of HCPB BB
LE of HCPB TER
LE of WCLL BB
LE of WCLL TER

System Design & Modelling

Design & Analyses
Design-supporting analyses

Nuclear analysis
Thermal hydraulic analysis
Structural analysis

He flow modelling
Pebble bed modelling
Tritium transport modelling

CAD office

Technology R&D

Solid breeder development
Neutron multiplier development
Helium cooling technology
FW Manufacturing
FW coating
Prototypical Mock-up testing

TER: Tritium Extraction and Removal
EUROfusion DEMO Central Team
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2. What is a HCPB?

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

- Tritium Breeding Function
  \[ \frac{6}{3}Li + \frac{1}{0}n \rightarrow \frac{4}{2}He + \frac{3}{1}T + 4.8 \text{ MeV} \]
  
  *Li compound (Li ceramics) as T breeder*

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

- Neutron multiplier (NM) function:
  \[ _2^9Be + \frac{1}{0}n \rightarrow 2_2^4He + 2^1_0n - 1.8 \text{ MeV} \]
  
  *Be/Beryllides as n multiplier*

- Heat extraction: Helium (HTR-like)
  
  Coolant Temp: 300°C – 520°C
Outline

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3. Top-Level Requirements

- **Reactor Availability** > 30%
- **Tritium Breeding Ratio (TBR):** $TBR_{\text{required}} \geq 1.05$, $TBR_{\text{design}} \geq 1.15$ (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
- **Temperature design limits:**
  - Eurofer-97: 350°C ($DBTT^*$) – 550°C ($S_{\text{creep}}$)
- **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*
3. EU-DEMO Blanket Segmentation (1/2)

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

- 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. The HCPB BB: General Description

HCPB Breeding Blanket design
4. The HCPB BB: Coolant Scheme

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

4. Design analysis: Performance figures

- Neutronics: nuclear analysis
  - Fully heterogeneous MCNP model
- Tritium Breeding:
  - $^6$Li 60%: $\text{TBR}_{\text{design}} \approx 1.20$, $^6$Li 40%: $\text{TBR}_{\text{design}} \approx 1.16$
- Neutron shielding:
  - $\text{dpa}_{\text{VV}} \approx 0.130\text{dpa/fpy}$
  - Best shielding materials: B$_4$C, TiH$_2$, ZrH$_{1.6}$, YH$_{1.75}$, WC

- Detailed local CFD Thermohydraulic analyses:
  - Temperature limits compliance
  - Input for further TM analyses

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

4. Design-supporting analyses

Tritium transport at system level

Tritium transport at component level

He flow modeling using in-house code

4. Technology R&D – Solid breeder development

Upgrade of KALOS facility

KALOS - KArlsruhe Lithium OrthoSilicate

Pebbles characterization

4. Technology R&D – Neutron multiplier development

Be12Ti block withstand over 200 thermal cycles.

Thermal cycling testing

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.

Large Eddy Simulation

V-rip

High Heat Flux testing
Patented technology: additive manufacturing for manufacturing turbulence promoters. Charpy-test shows that USE and DBTT comparable.
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 between W and EUROFER can be mitigated with a functionally graded W/EUROFER interlayer, manufactured by vacuum plasma spraying.

1000 thermal cycles testing

Coating surfaces up to 500×250 mm²
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/m^2, 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

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

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission.

This work is also funded by the Fusion Programme of the Helmholtz Association of German Research Centres.

HCPB BB Team: