Second DONES Users Workshop

19–20 Oct 2023
Parque de las Ciencias, Granada

EUROfusion

Solid Breeding Blankets: overview and key pending validation needs

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Breeding Blanket Project in EUROfusion

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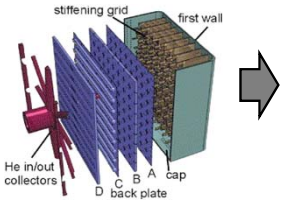
Outline of content

- Solid breeding blankets in Europe: Overview
  - ✓ Helium Cooled Pebble Bed (HCPB)
  - ✓ Water cooled Lead and Ceramic Breeder (WLCB)
- Key pending validation needs

Solid breeding blanket in Europe: HCPB – Helium Cooled Pebble Bed

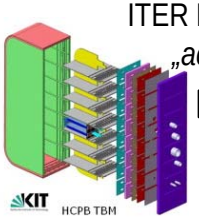
- HCPB and WCLL are two driver blanket concepts for EU DEMO

Pre-Concept Design Phase (FP8)



PPCS Model B (HCPB)

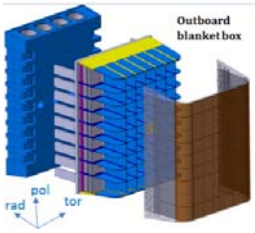
ITER HCPB TBM
„act-alike“



- Coolant: He @80 bar, 300-520°C
- T-breeder: Li-ceramic pebbles
- n-multiplier: Beryllide
- T-extraction: purge gas
- Structural steel: Eurofer97

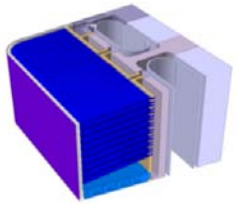
2014 — "Beer-box"

DEMO baseline 2014



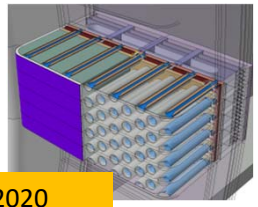
+ ↑↑ Robustness (in-box LOCA)
– ↓↓ TBR (1.06)
– ↑↑ Fabrication & assembly complexity
– ↑↑ Δp (P_{pump}≈250MW, low TRL BoP)

2015 / 2016 — DEMO baseline 2015 "Sandwich"



+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.15)
– ↑ Fabrication & assembly complexity
– ↑ Δp (P_{pump}≈150MW, low TRL BoP)

2017 / 2018 / 2019 / 2020 — DEMO baseline 2017 "Fuel-breeder pin"

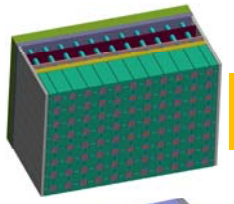


+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.20)
+ ↓ Fabrication & assembly complexity
+ ↓ Δp (P_{pump}≈ 90MW, high TRL BoP)
– Low reliability, low availibility of DEMO

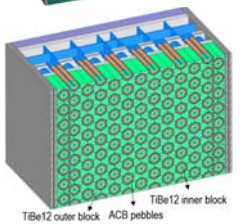
Hernández FA et al., 2020
Fusion Eng Des 157, 111614.

Concept Design Phase (FP9)

2021
2022
2023



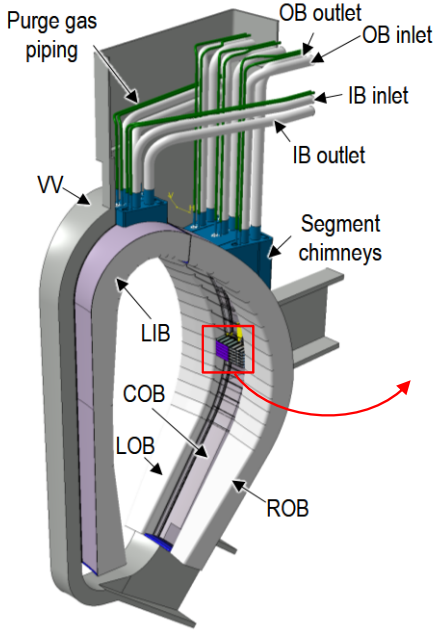
G. Zhou et al.
2022. TOFE 2022

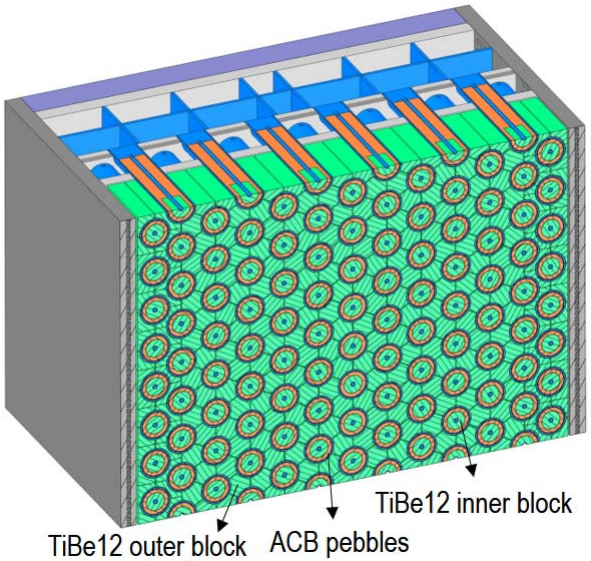


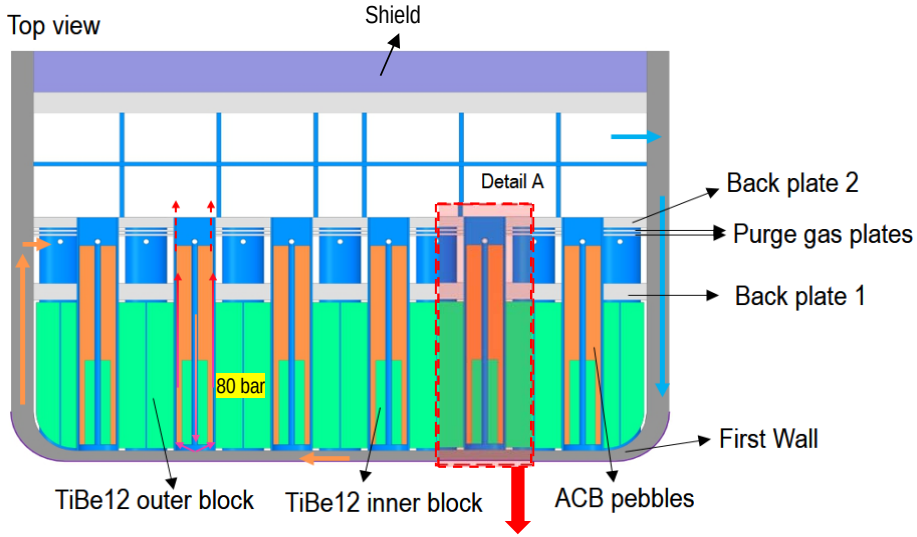
G. Zhou et al.
2023. ISFNT-15

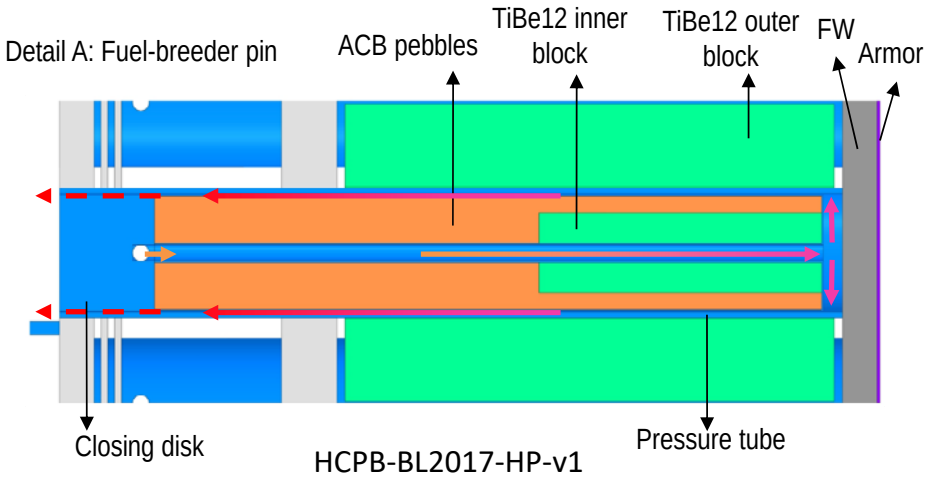
+ ↑ Robustness (in-box LOCA)
+ ↑ TBR (1.20)
+ ↓ Fabrication & assembly complexity
+ ↓ Δp (P_{pump}≈ 90MW, high TRL BoP)
+ ↑ High reliability

Solid breeding blanket in Europe: HCPB high pressure purge gas









- Coolant: He @80 bar, 300-520°C
- Structural steel: Eurofer97
- Fuel-breeder pins contain advanced ceramic breeder (ACB) pebble
- Beryllide neutron multiplier of triangular prism with lateral edges filleted
- T-extraction: He + 200 Pa H_2 @80 bar
- FW and critical structure thicker + cooler by fresh coolant
- Inner beryllide block inside ACB pebble
- Nuclear, thermal hydr. & thermal-mech. analysis confirmed soundness

Exploring variant: WLCB – Water coold Lead and Ceramic Breeder

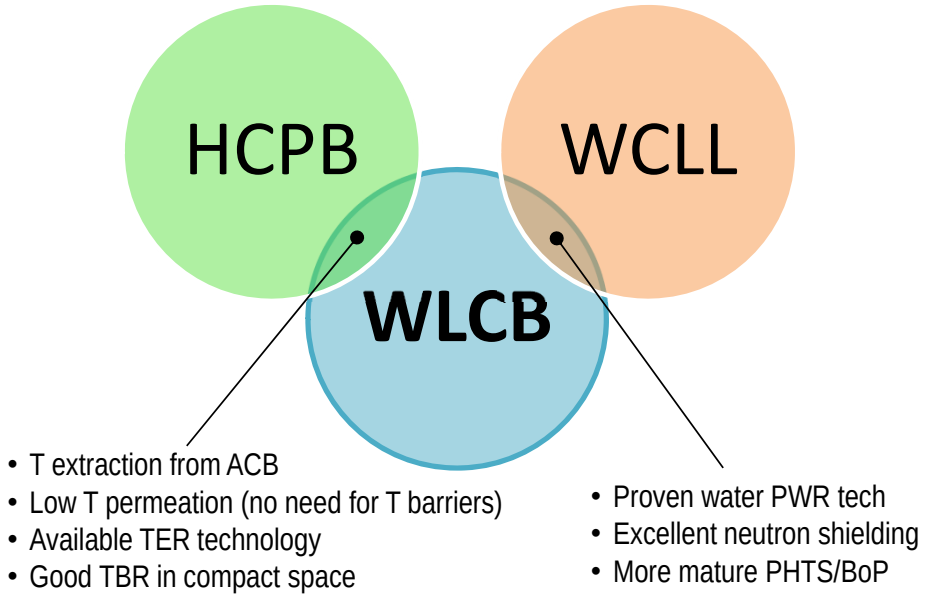
- Background:
  - Idea started in **FP8**: HCPB issue with beryllium -> deep exploration of alternative n-multipliers -> Pb/Pb-alloy
  - He-cooled molten lead and ceramic breeder blanket
  - Curiosity for a water cooled version -> WLCB, as radial fuel-breeder pins

Hernández FA et al. 2019, *Fusion Eng Des* 146:1186–1191

Zhou G et al. 2019, *Fusion Eng Des* 146:1029–1034

Zhou G et al. 2021, *Fusion Eng Des* 168: 112397

- Seen as a best trade-off between HCPB and WCLL:
  - To avoid current issues in HCPB with shielding, multiplier technology and costs
  - To mitigate issues with T-permeation and avoid T-extraction risks from PbLi in WCLL
  - To avoid use of anti-permeation barriers in BB
  - To use proven water PWR tech.

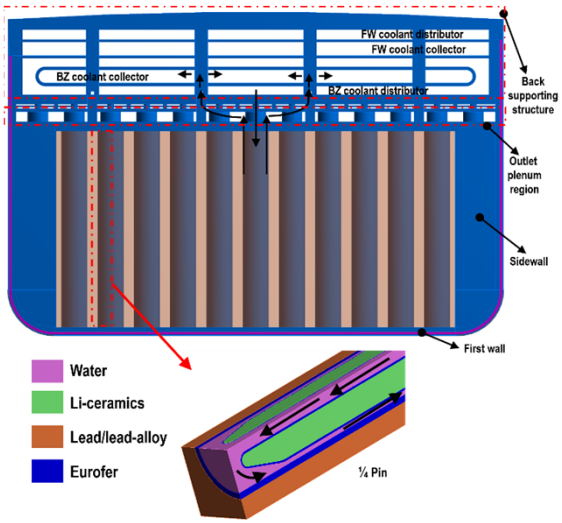


Hernández FA et al. 2023, *ISFNT-15*

HCPB: Helium Cooled Pebble Bed
WLCB: Water cooled Lead and Ceramic Breeder
WCLL: Water Cooled Lithium Lead

Exploring variant: WLCB Design evolution

Pre-Concept Design Phase (FP8)

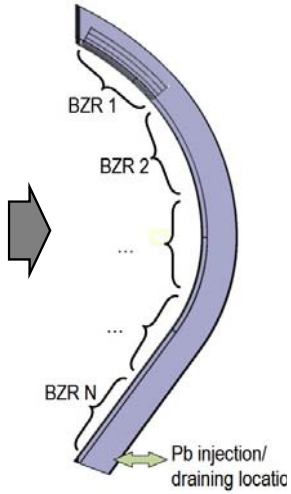


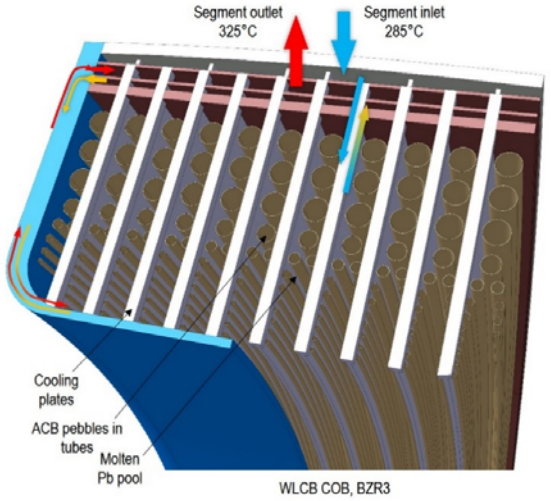
2019-2020

Zhou G et al. 2021, *Fusion Eng Des* 168: 112397.

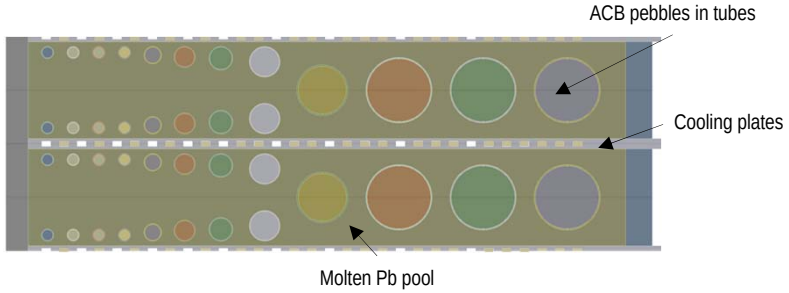
- Feasibility study of a WLCB based on the fuel-breeder pin architecture, in terms of T-breeding, temperature and stress limits.
- Too many welds, low reliability, low availiability

Concept Design Phase (FP9)



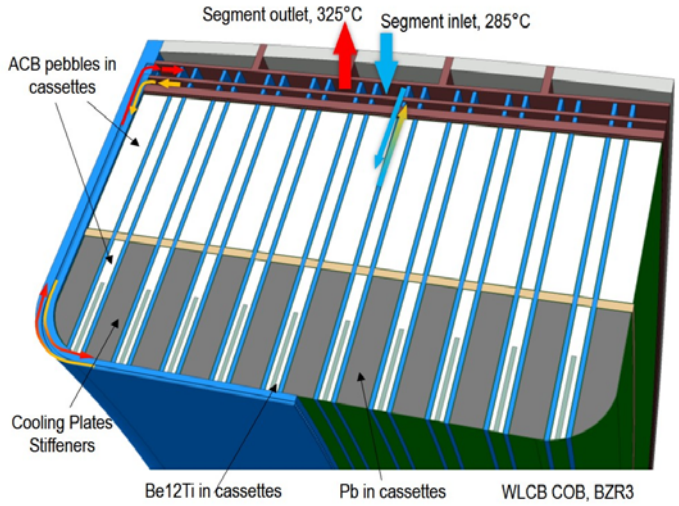


2021-2023

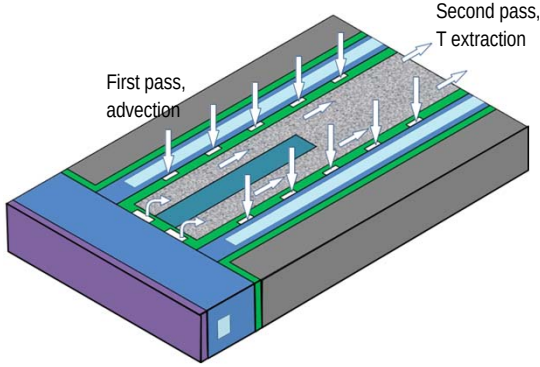


- High reliability
- Tritium breeding and T-permeation

Hernández FA et al. 2023, *ISFNT-15*



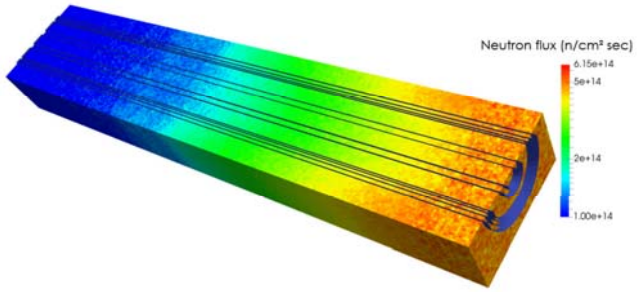
2023-



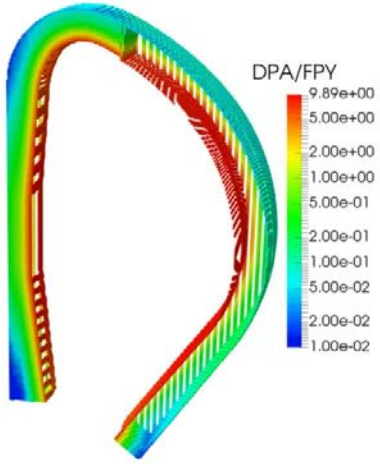
Challenging environment in fusion power plant

- High dose rate
- High pressure (80 bar for HCPB, 155 bar for WLCB)
- High temperature gradient

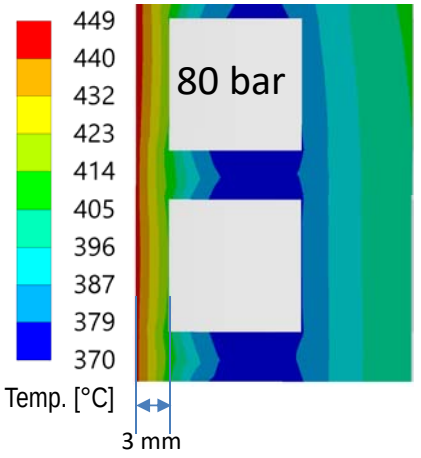
$$\frac{dT}{dx} = \frac{(449 - 413)°C}{3\ mm} = 120\frac{°C}{cm}$$



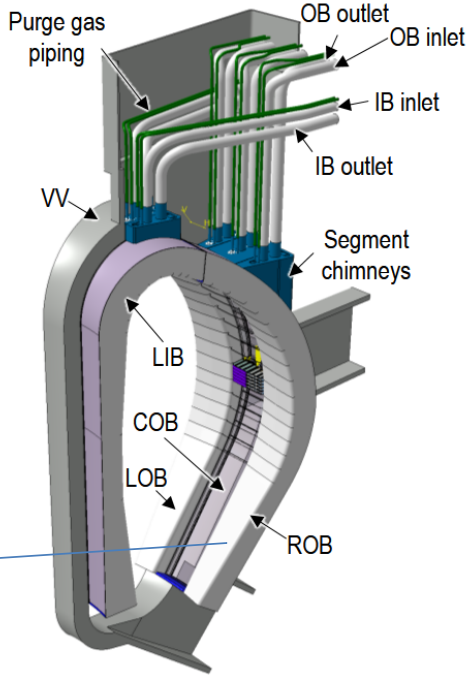
Neutron flux at breeding zone



Displacement per atom accumulation in the BB structure



Temp. on FW



Challenges and pending validation needs of HCPB & WLCB

Spagnuolo A et al., *this session*

Structure

- Changes in properties and behaviour of materials
  - *Effect of heat flux and cycling on fatigue or crack growth-related failure*
  - *Premature failure at welds*
  - *Effect of swelling, creep and thermal gradients on stress*
- Tritium permeation through the structure
  - *Tritium permeation through structure into coolant*
  - *Effect of radiation on tritium permeation*
- Structural activation product inventory
- Blanket supporting structure to Vacuum Vessel
- Failure modes & rates of blanket structure under fusion environ.

Solid Breeder / multiplier / structure interactions

- Solid breeder mechanical and materials interactions
  - *Pebble-steel interaction under purge gas environment*
  - *Load on wall induced by Pebble expansion/swelling*
  - *Dust formation and transport of pebble bed*
- Neutron multiplier mechanical interactions
  - *Beryllide swelling and interact with wall*
  - *Cracking of Beryllide block due to thermal stress*
  - *Compatibility of neutron multiplier and Li-ceramics*
- Thermal interactions
  - *Breeder/multiplier-structure heat transfer (gap conductance)*

Abdou MA et al. 1985, *Fusion Technology* 8:3, 2595-2645

Tungsten and EUROFER qualification & design code not included here, dealt in WPMAT.

Coolant / structure interactions

- Mechanical and materials interactions
  - *Corrosion*
  - *Failure of coolant wall due to stress corrosion cracking*
  - *Failure of coolant wall due to liquid-metal embrittlement*
- Neutron-induced sputtering transp. of activated mat.
- Coolant/coatings/structure interactions

Breeder/multiplier and purge

- Tritium release, recovery and inventory in solid breeder and multiplier
- Thermal conduct. changes of Breeder and Multiplier under irradiation
- Tritium transport in blanket system
- Breeder behaviour under high dpa
- Solid multiplier behaviour under high dpa

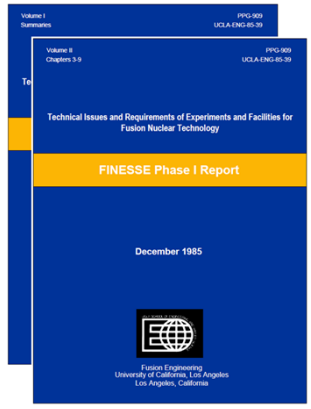
General for all concepts

- Uncertainties in required T breeding ratio
- Uncertainties in achievable T breeding ratio
- Tritium trapping
- Tritium permeation to blanket coolant
- Failure modes and rates
- Nuclear heating rate predictions
- Prediction and control of radioactive effluent

w/o neutrons

w/ neutrons

Fusion environment



Ongoing activities

Structure

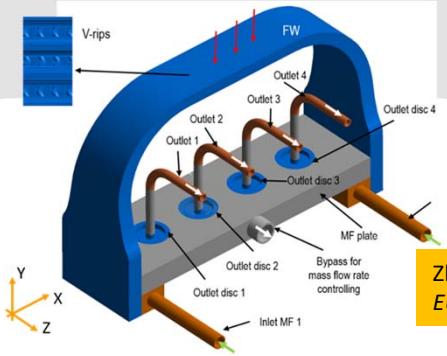
- ❖ Changes in properties and behaviour of materials
  - ➢ *Effect of heat flux and cycling on fatigue or crack growth-related failure*
  - ➢ *Premature failure at welds*
  - ➢ *Effect of swelling, creep and thermal gradients on stress*
- ❖ Tritium permeation through the structure
  - ➢ *Tritium permeation through structure into coolant*
  - ➢ *Effect of radiation on tritium permeation*
- ❖ Structural activation product inventory
- ❖ Blanket supporting structure to Vacuum Vessel
- ❖ Failure modes & rates of blanket structure under fusion environ.

w/o neutrons

w/ neutrons

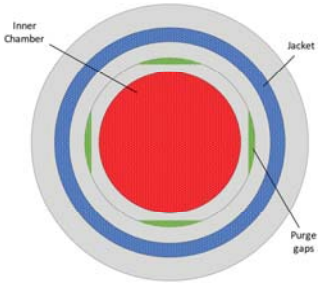
Fusion environment

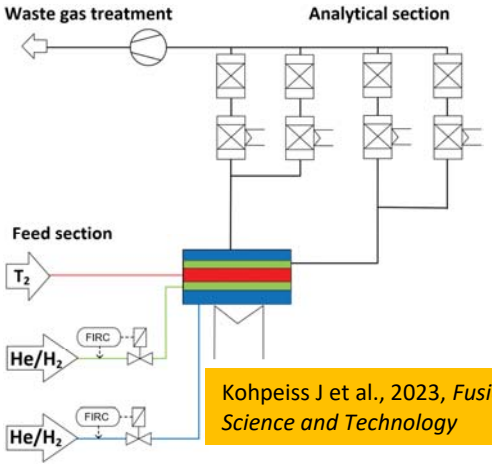
Thermomechanic cycling of FW at HELOKA



Zhou G et al., 2021, *EUROfusion report*

Tritium permeation cell at Tritium Laboratory Karlsruhe

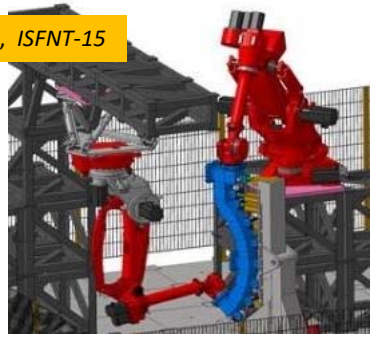




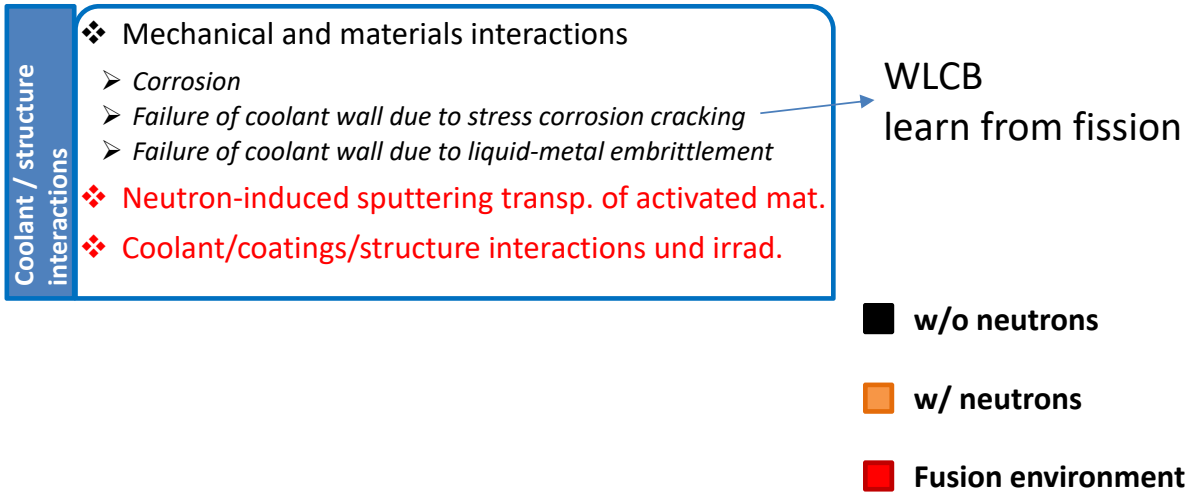
Kohpeiss J et al., 2023, *Fusion Science and Technology*

Remote Handling Test Facility

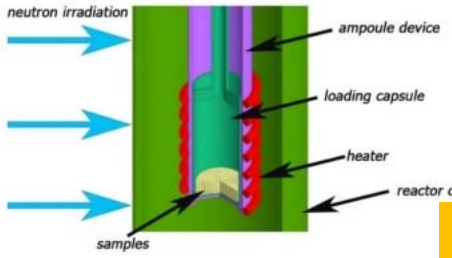
Crofts O. 2023, *ISFNT-15*



Ongoing activities



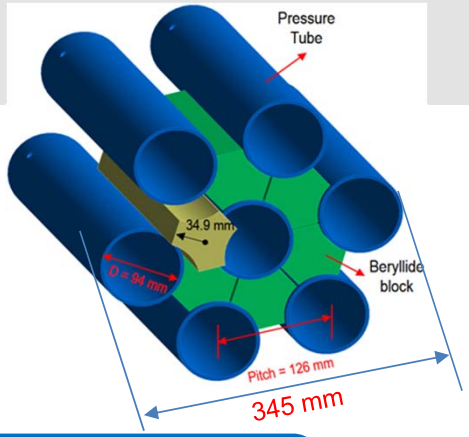
Ongoing activities



Kulsartov T et al., 2022, *Nucl. Mat. Energ.*, 30:101115

Irradiation campaigns at BR2, Belgium and WWR-K, Kazakhstan

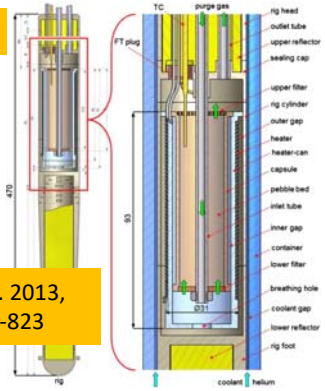
Limited irradiation space
Φ22 mm in WWR-K



Tritium Release Test Module in IFMIF/DONES

Arbeiter F, this session

Abou-Sena A, Arbeiter F. 2013, *Fusion Eng. Des*. 88: 818-823



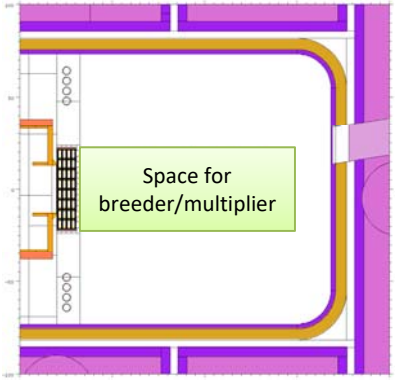
Breeder/multiplier and purge

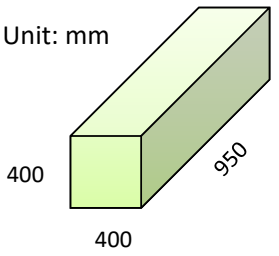
- Tritium release, recovery and inventory in solid breeder and multiplier
- Thermal conduct. changes of Breeder and Multiplier under irradiation
- Tritium transport in blanket system
- Breeder behaviour under high dpa
- Solid multiplier behaviour under high dpa

w/o neutrons

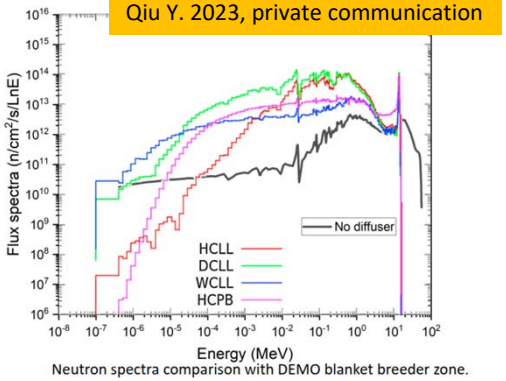
w/ neutrons

Fusion environment





Qiu Y. 2023, private communication

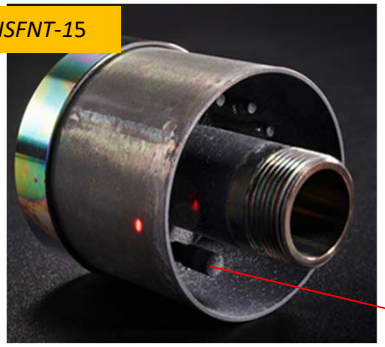


Neutron spectra comparison with DEMO blanket breeder zone.

Ongoing activities

Ageing of Eurofer97 in contact with pebbles under purge gas environment, 550°C, HELOKA-HEMAT

Krüssmann R et al., 2023, *ISFNT-15*



8d 16d 32d 64d

HEMAT

Solid Breeder / multiplier / structure interactions

- ❖ Solid breeder mechanical and materials interactions
  - ➢ *Pebble-steel interaction under purge gas environment*
  - ➢ *Load on wall induced by Pebble expansion/swelling*
  - ➢ *Dust formation and transport of pebble bed*
- ❖ Neutron multiplier mechanical interactions
  - ➢ *Beryllide swelling and interact with wall*
  - ➢ *Cracking of Beryllide block due to thermal stress*
  - ➢ *Compatibility of neutron multiplier and Li-ceramics*
- ❖ Thermal interactions
  - ➢ *Breeder/multiplier-structure heat transfer (gap conductance)*

Pebble Bed Test Module in DONES?

Solid Neutron Multiplier Test Module in DONES?

Gaisin R et al., 2022, *15th International Workshop on Beryllium Technology*

After 200 cycles

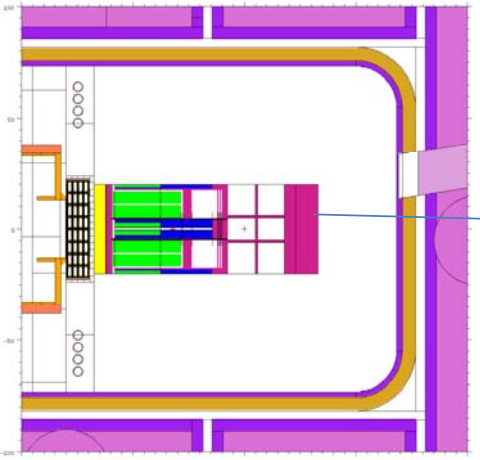
Thermal cycling using induction heating at Ulba/KIT

w/o neutrons

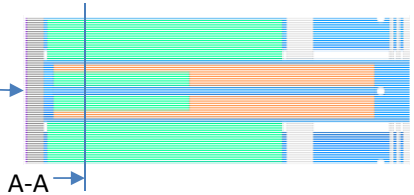
w/ neutrons

Fusion environment

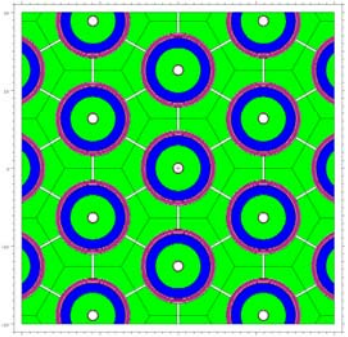
Challenges and pending validation needs of HCPB & WLCB



DONES Test Cell



Fuel-breeder pin of HCPB



A-A view

Solid Breeder / multiplier / structure interactions

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Pebble Bed Test Module in DONES?

Solid Neutron Multiplier Test Module in DONES?

Blanket Functional Materials Module in DONES?

w/o neutrons

w/ neutrons

Fusion environment

Challenges and pending validation needs of HCPB & WLCB

- w/o neutrons
- w/ neutrons
- Fusion environment

General for all concepts

- Uncertainties in required T breeding ratio
- Uncertainties in achievable T breeding ratio
- Tritium trapping
- Tritium permeation to blanket coolant
- Failure modes and rates
- Nuclear heating rate predictions
- Prediction and control of radioactive effluent

Fusion neutrons with sufficient space for qualifying blankets

Conclusions

Structure

- Changes in properties and behaviour of materials
  - *Effect of heat flux and cycling on fatigue or crack growth-related failure*
  - *Premature failure at welds*
  - *Effect of swelling, creep and thermal gradients on stress*
- Tritium permeation through the structure
  - *Tritium permeation into coolant*
  - *Effect of radiation on tritium permeation*
- Structural activation product inventory
- Blanket supporting structure to Vacuum Vessel
- Failure modes & rates of blanket structure under fusion environ.

Solid Breeder / multiplier / structure interactions

- Solid breeder mechanical and materials interactions
  - *Pebble-steel interaction under purge gas environment*
  - *Load on wall induced by Pebble expansion/swelling*
  - *Dust formation and transport of pebble bed*
- Neutron multiplier mechanical interactions
  - *Beryllide swelling and interact with wall*
  - *Cracking of Beryllide block due to thermal stress*
  - *Compatibility of neutron multiplier and Li-ceramics*
- Thermal interactions
  - *Breeder/multiplier-structure heat transfer (gap conductance)*

- Out-of-pile and in-pile tests in MTRs for basic tests
- DONES could offer unique test platform for irrad. function. mat.
- Fusion neutron source is needed for blanket qualification

Coolant / structure interactions

- Mechanical and materials interactions
  - *Corrosion*
  - *Failure of coolant wall due to stress corrosion cracking*
  - *Failure of coolant wall due to liquid-metal embrittlement*
- Neutron-induced sputtering transp. of activated mat.
- Coolant/coatings/structure interactions

Breeder/multiplier and purge

- Tritium release, recovery and inventory in solid breeder and multiplier
- Thermal conduct. changes of Breeder and Multiplier under irradiation
- Tritium transport in blanket system
- Breeder behaviour under high dpa
- Solid multiplier behaviour under high dpa

General for all concepts

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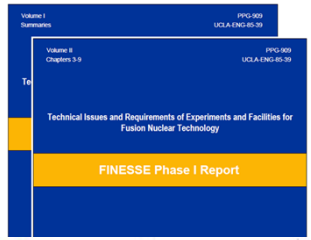
w/o neutrons

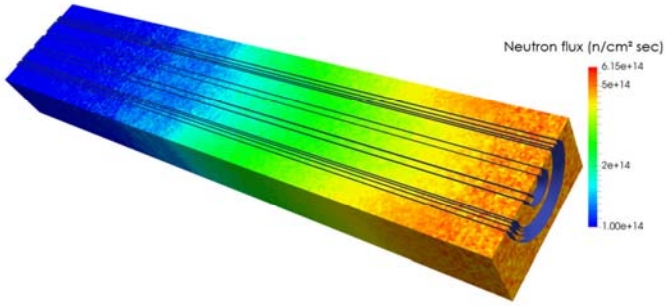
w/ neutrons

Fusion environment

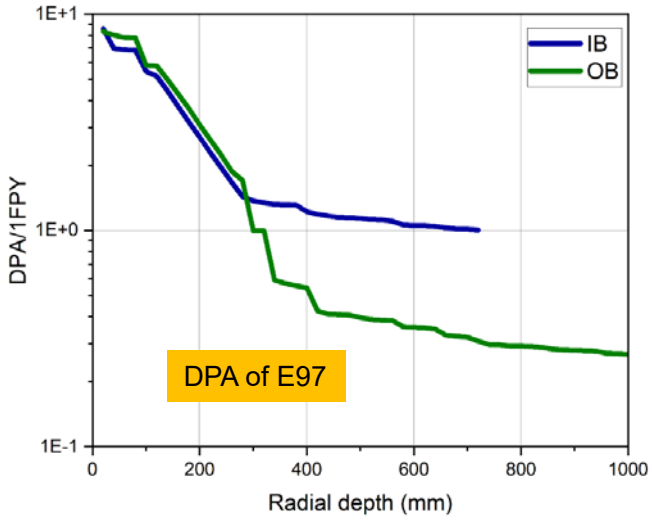


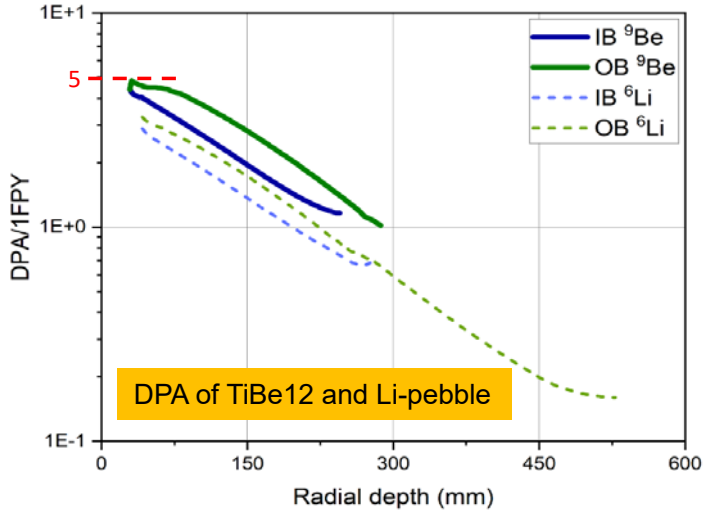
Backup slides: Nuclear responses of HCPB BB

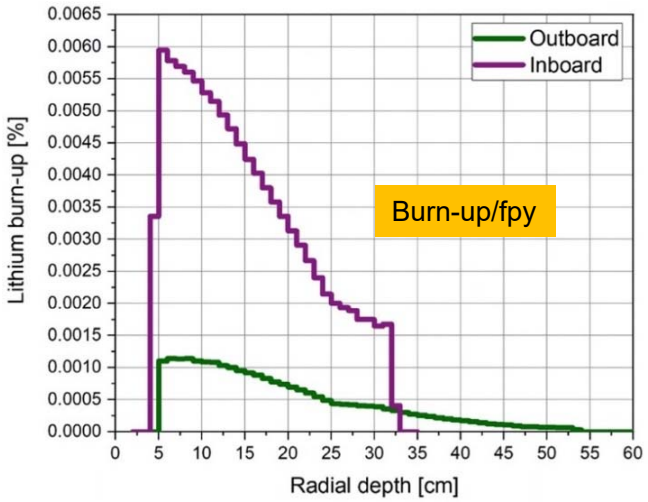
Zhou G et al., 2023, *HCPB Design and Analysis Report*

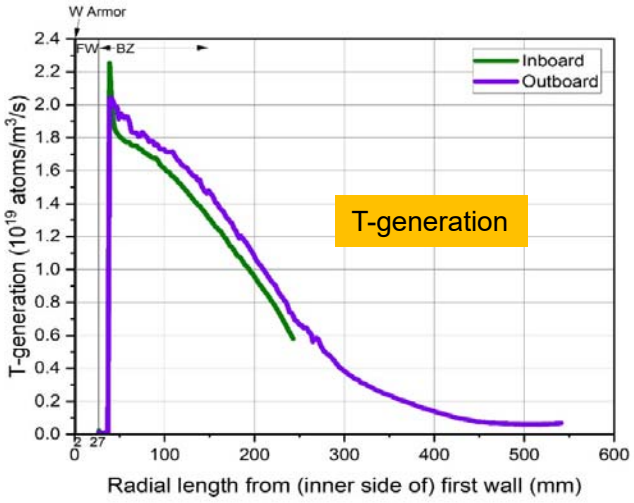


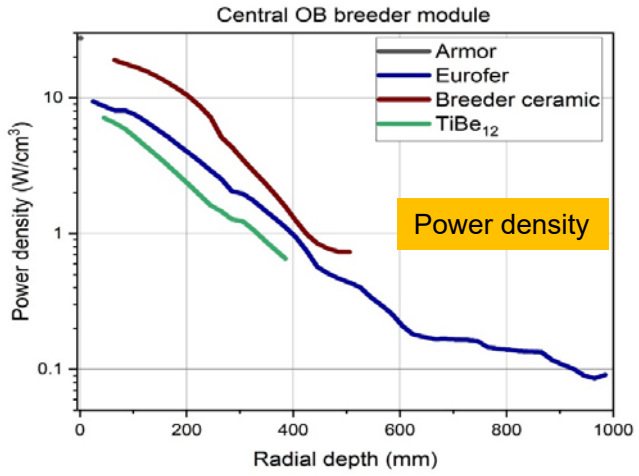
Neutron flux at breeding zone at contral IB











Backup slides

- Investigating the evolving behavior of the pebble bed and beryllide neutron multiplier together, for example, it can be that the breeder undergoes chemical processes (due to burn-up and due to contact to other material), the pebble bed can change its thermal conductivity and consequently shift the temperature field which is decisive for the tritium release residence times
- The pebbles will mechanically deform and it will be interesting to study their interacting within the bed and also with the walls
- Dust formation and transport of pebble bed in the purge gas flow path
- Measuring the time structure of tritium release from this complex setup with broad temperature spread and realistic (not 1-D) purge flow path (as opposed to the well-defined "academic type" TRTM)
- A specific question concerns the cracking/blistering of the berillyde block, which is larger than a TRTM capsule