Key validation needs of EU-DEMO HCPB Breeding Blanket and its mockup BLUME in IFMIF-DONES

Guangming Zhou, Lead Engineer & Coordinator of HCPB Breeding Blanket

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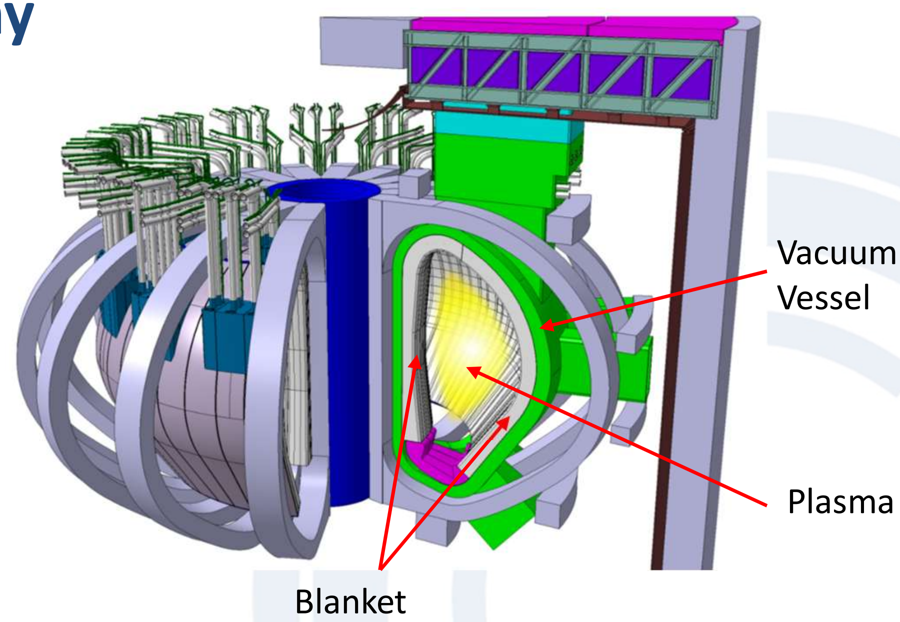
Outline of content

- History of HCPB design
- Update of HCPB
- Key validation needs of HCPB
- Testing goals of BLUME mockup
- Design of BLUME mockup
- Summary and outlook

Breeding Blanket: a key system in any D-T fusion electricity device

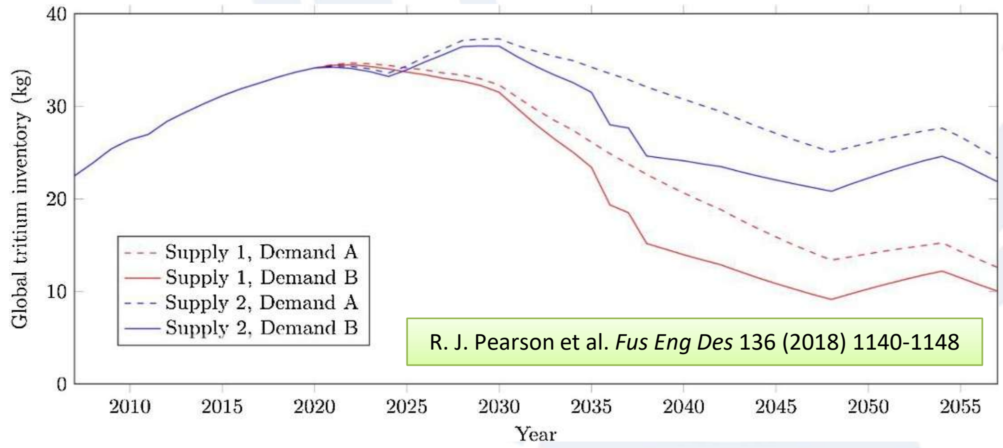
$${}^{2}_{1}D + {}^{3}_{1}\boldsymbol{T} \rightarrow {}^{4}_{2}He + \boldsymbol{n} + 17.6\ \mathrm{MeV}$$

Tritium breeding blanket is a nuclear component within vacuum vessel that surrounds the plasma like a blanket.



Tritium (*T*) has a half-life of 12.3 years. About 55 g *T* is lost per year for 1 kg *T*.

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



Need to produce ***T***, in order to be economically viable!

Why blanket?

- **Main functions of the blanket:**

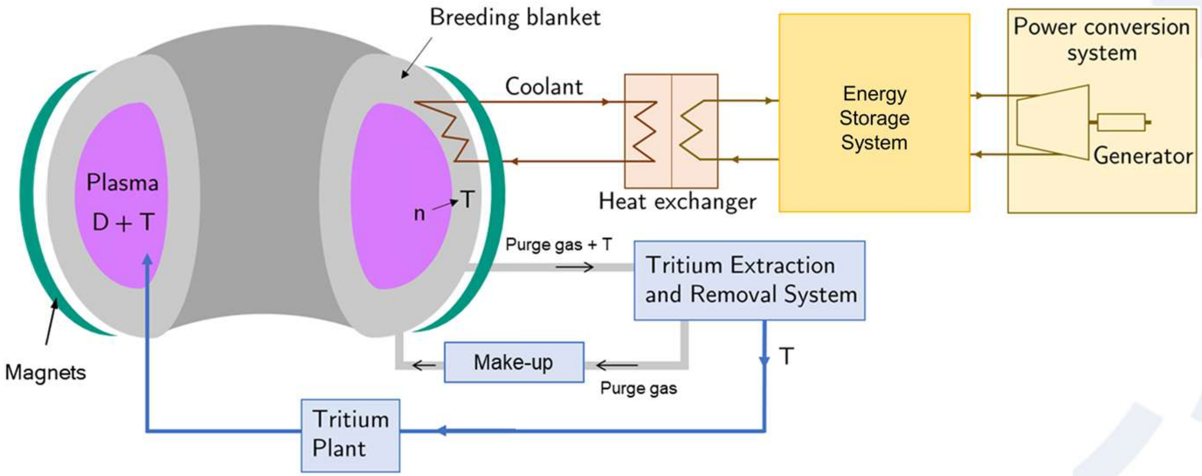
➢ tritium breeding => tritium self-sufficiency

➢ heat removal => electricity production

➢ shielding => protect magnets

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

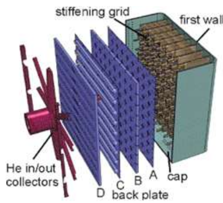
$$^{3}_{1}\boldsymbol{T} + {}^{2}_{1}D \rightarrow {}^{4}_{2}He + \boldsymbol{n} + 17.6\ \mathrm{MeV}$$



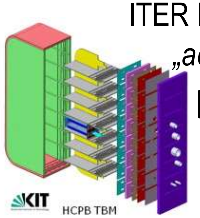
Solid breeding blanket in Europe: HCPB – Helium Cooled Pebble Bed

- HCPB, WCLL and WLCB are candidate driver blanket concepts for EU DEMO

Pre-Concept Design Phase (FP8)



PPCS Model B (HCPB)

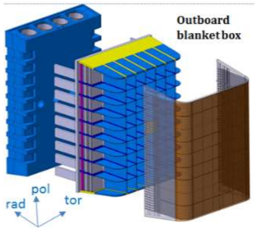


ITER HCPB TBM „act-alike“

2014

"Beer-box"

DEMO baseline 2014



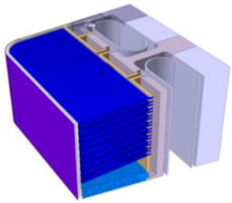
- + ↑↑ Robustness (in-box LOCA)
- – ↓↓ TBR (1.06)
- – ↑↑ Fabrication & assembly complexity
- – ↑↑ Δp (P_{pump}≈250MW, low TRL BoP)

2015

2016

DEMO baseline 2015

"Sandwich"



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

2017

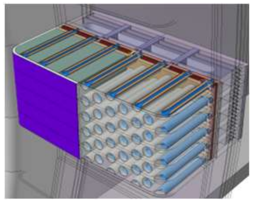
2018

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

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

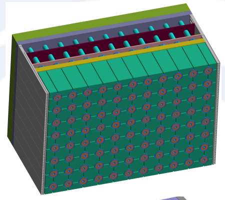
Concept Design Phase (FP9)

2021

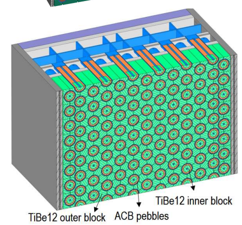
2022

2023

2024



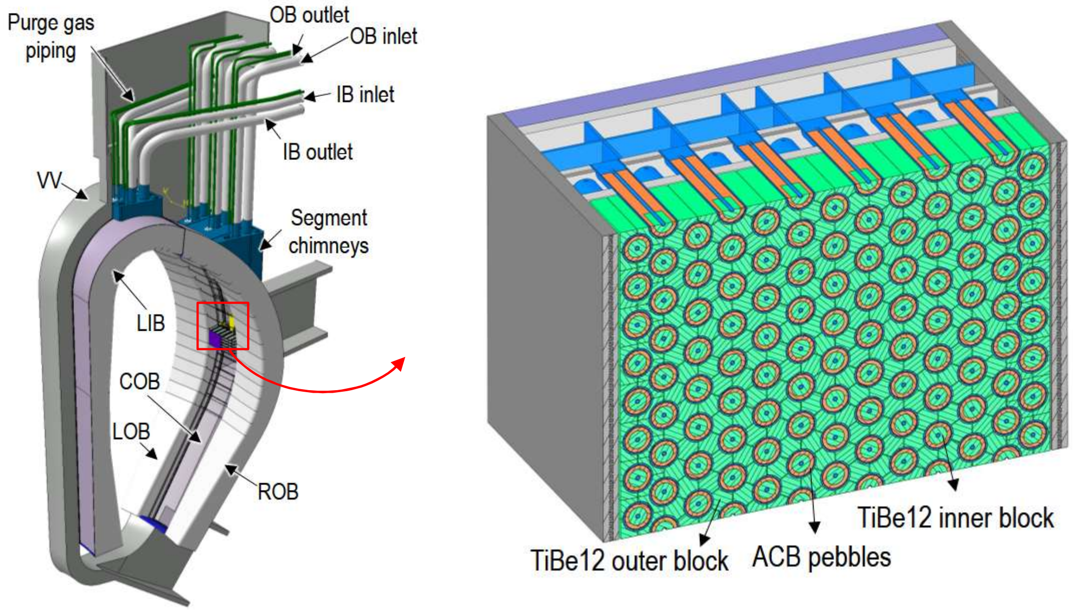
G. Zhou et al. 2022. TOFE 2022

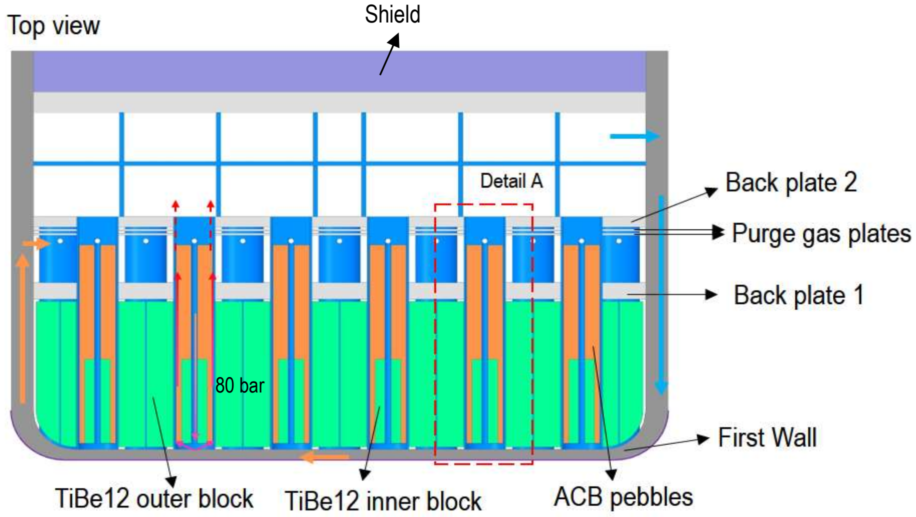


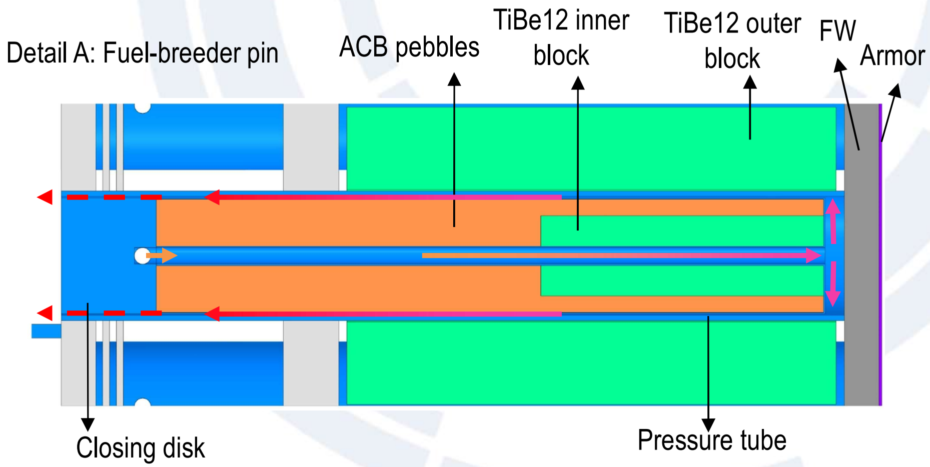
G. Zhou et al. 2023. ISFNT-15

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

Design of high pressure purge gas HCPB (HCPB-BL2017-HP-v1)







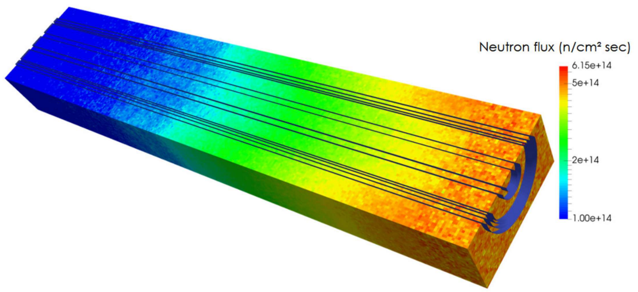
HCPB-BL2017-HP-v1

- 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; He + 200 Pa H_2O @80 bar (backup)
- FW and critical structure thicker + cooler by fresh coolant
- Inner beryllide block inside ACB pebble
- Nuclear, thermal hydr. & thermal-mech. analysis to confirm soundness

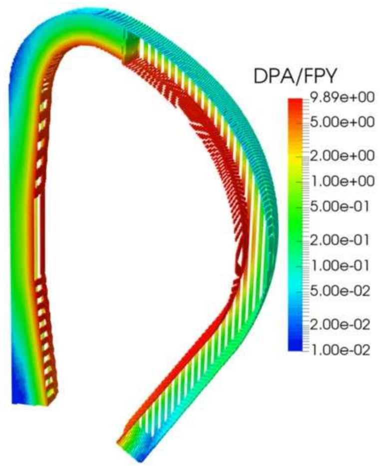
Challenging environment in fusion power plant

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

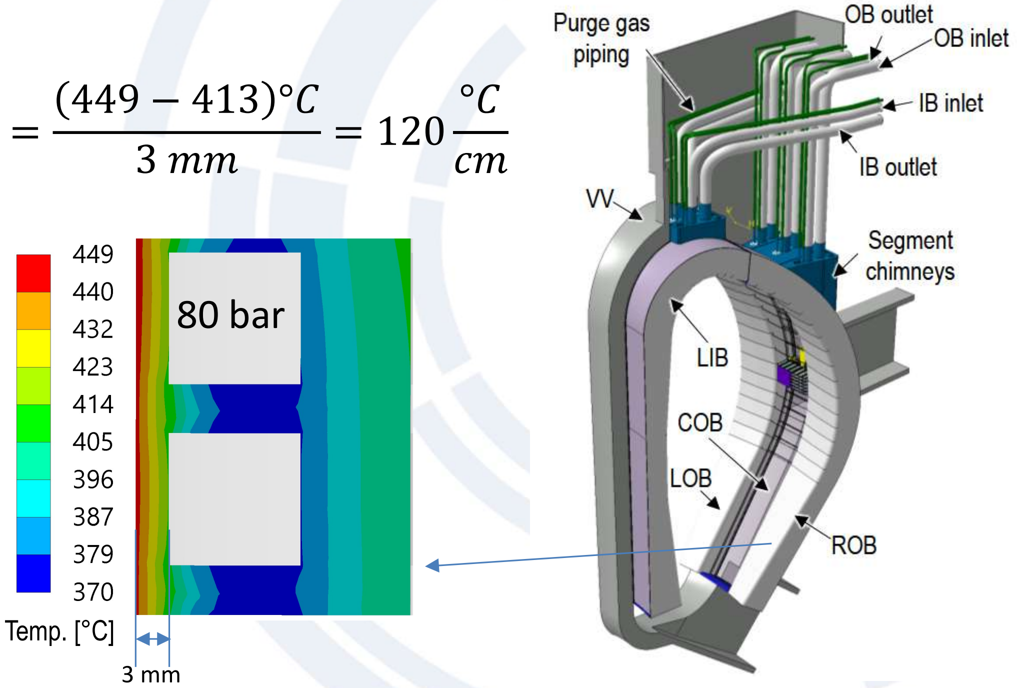
$$\frac{dT}{dx} = \frac{(449 - 413)°C}{3\ mm} = 120\frac{°C}{cm}$$



Neutron flux at breeding zone



Displacement per atom accumulation in the BB structure



Temp. on FW

Challenges and pending validation needs of HCPB

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)*

M. Abdou et al., Fusion Technology 8:3 (1985) 2595-2645

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

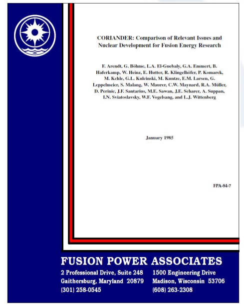
General for all concepts

- ❖ 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

■ **no neutrons**

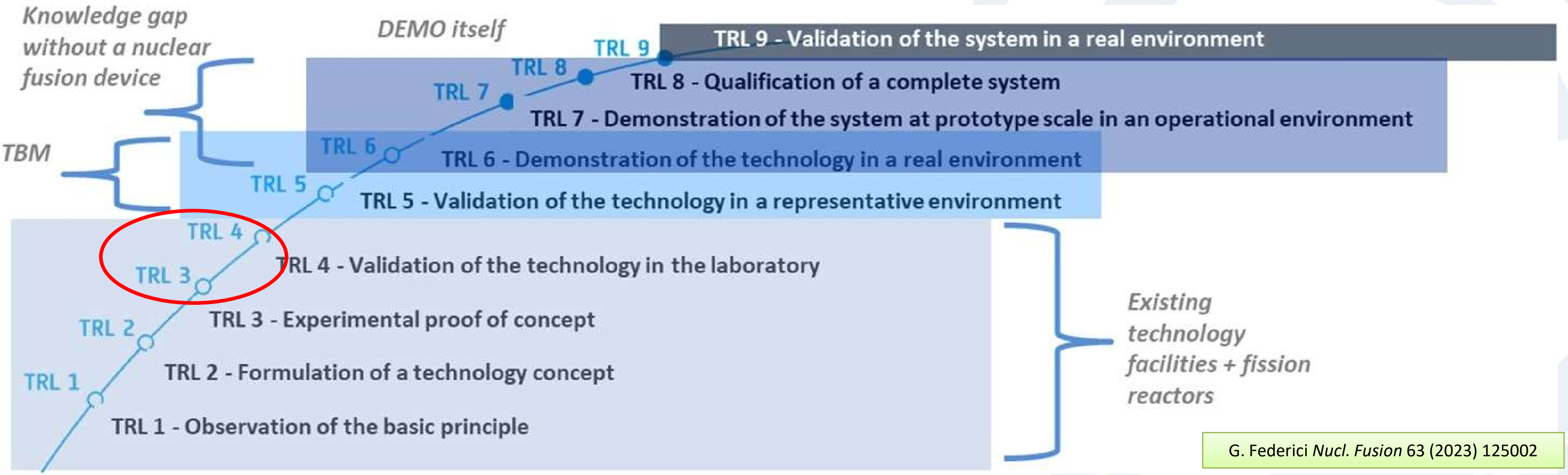
■ **Neutrons (fission/ IFMIF-DONES)**

■ **Fusion (VNS)**



Why test Breeding Blanket mockup in IFMIF-DONES?

- Despite the importance of blanket, maturity level of breeding blanket is still very low.
- Feasibility concerns and uncertainties exist in all explored breeding blanket concepts.
- Significant research and development are needed to address these issues.



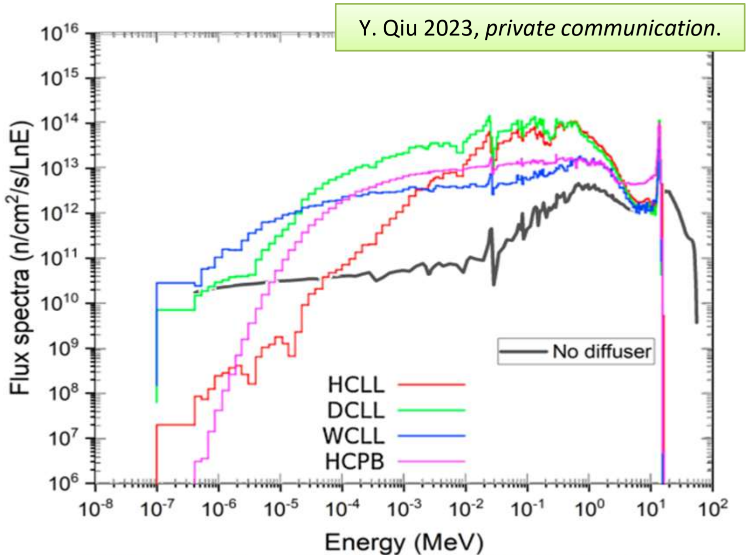
G. Federici *Nucl. Fusion* 63 (2023) 125002

In European DEMO program, Helium Cooled Pebble Bed (HCPB) breeding blanket is under development.

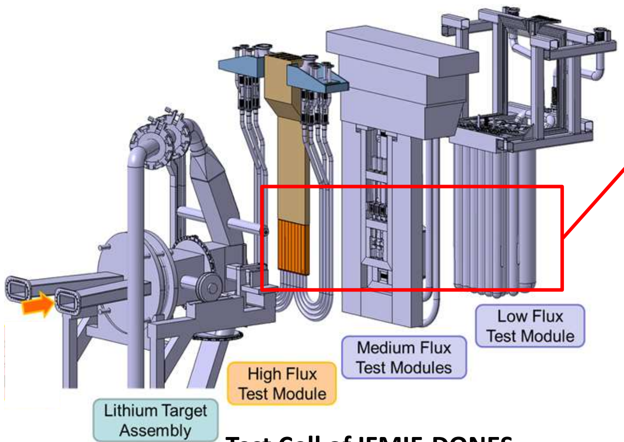
We propose a <u>bl</u>anket f<u>u</u>nctional <u>m</u>aterials modul<u>e</u> (BLUME) for HCPB blanket to be tested in IFMIF-DONES.

Neutron flux spectra and volume for testing in IFMIF-DONES

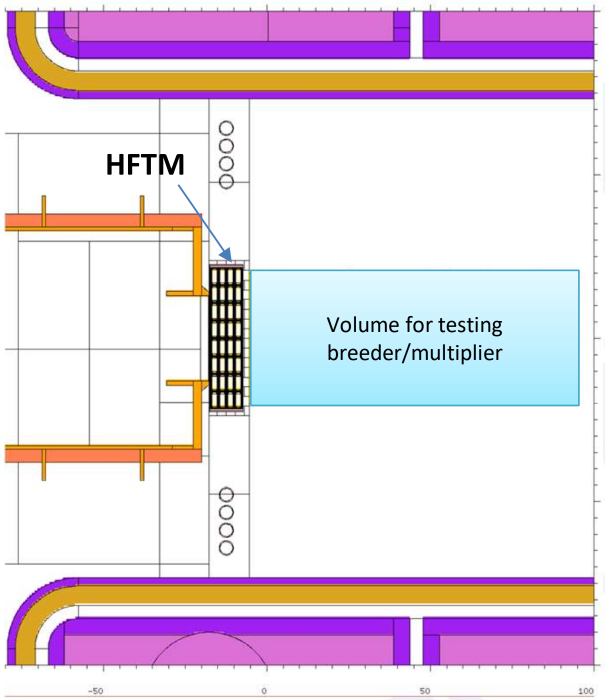
Y. Qiu 2023, *private communication*.



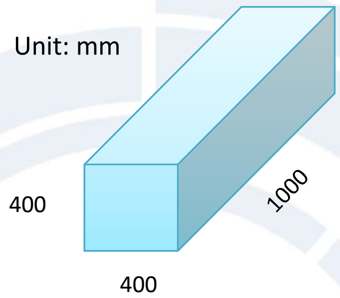
Neutron spectra comparison with EU-DEMO Breeding Blanket



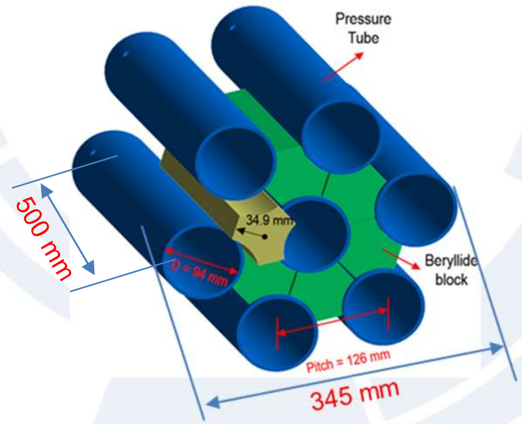
Test Cell of IFMIF-DONES



Volume for testing in Test Cell of IFMIF-DONES

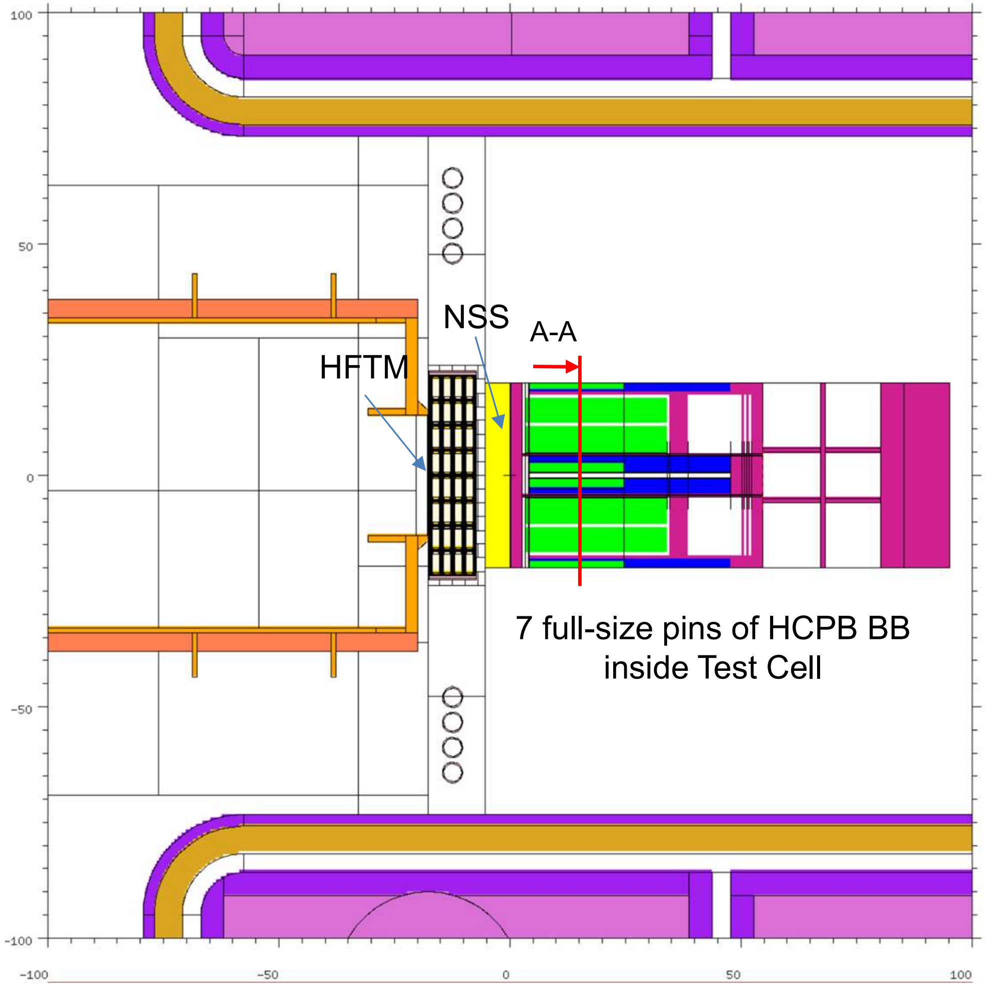


Volume: 400 x 400 x 950 mm³



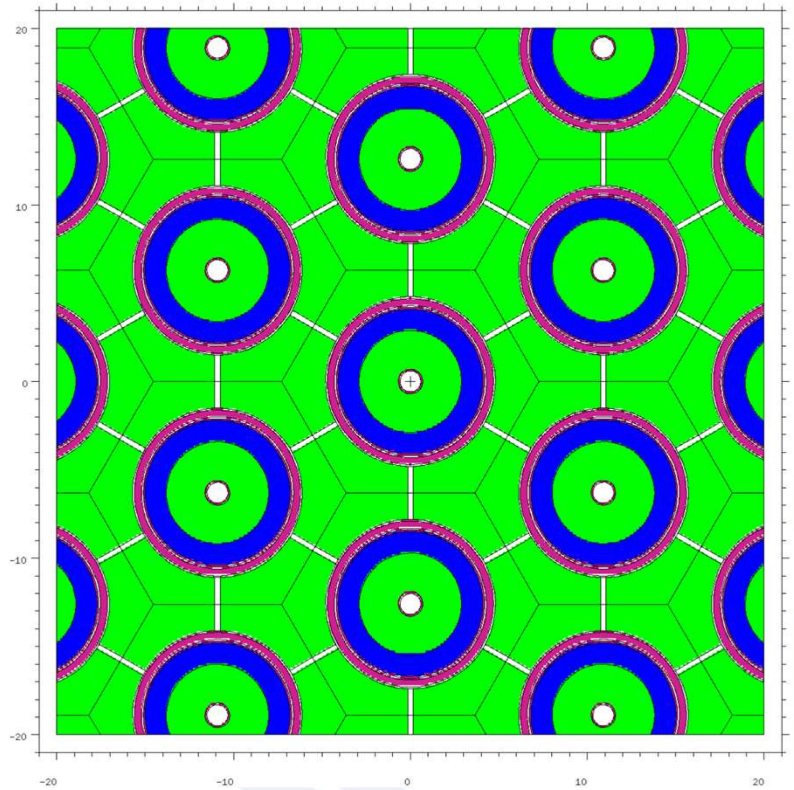
Dimensions of HCPB blanket breeder zone

Preliminary neutronics analyses



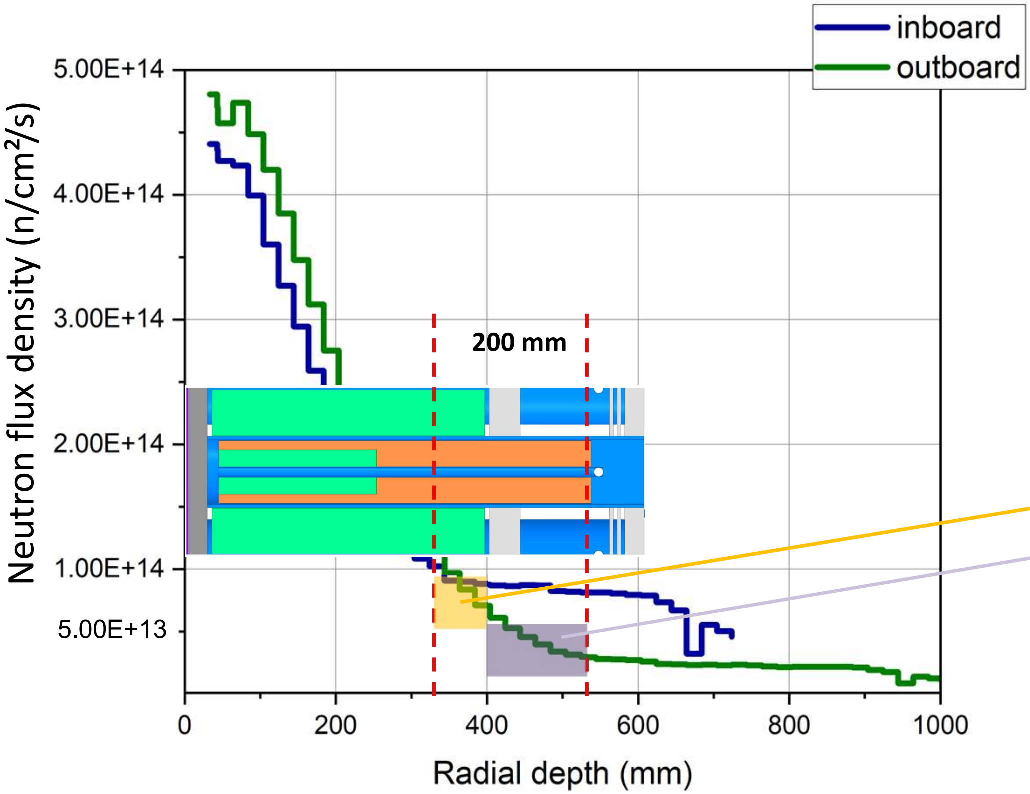
BLUME in Test Cell of IFMIF-DONES

Blue: Advanced ceramic breeder Li-pebbles
Green: Titanium beryllide
Magenta: Eurofer97 steel

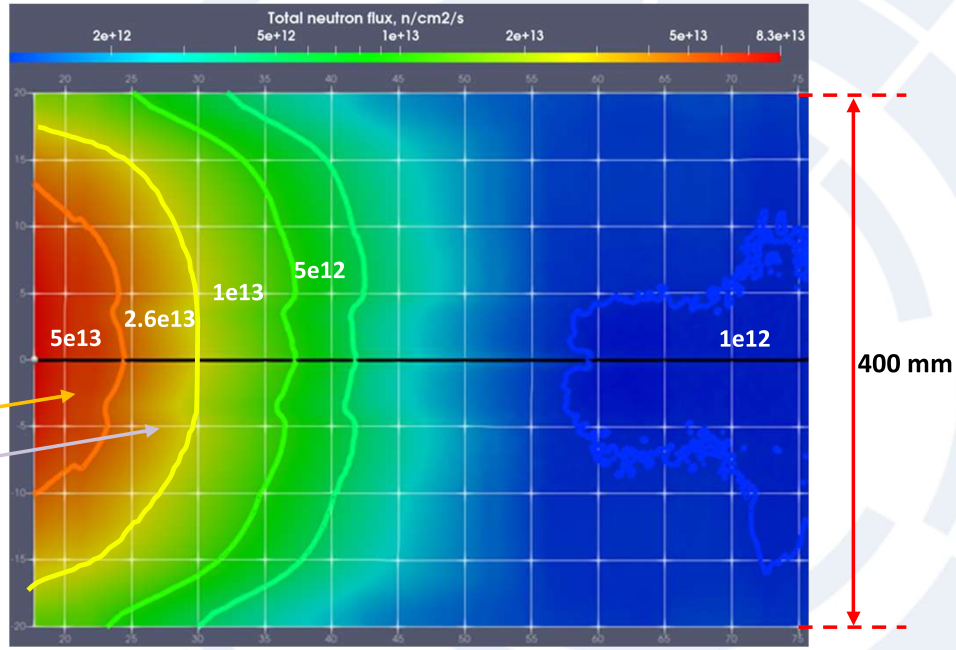


A-A cut-view

Comparison of neutron flux to DEMO



Neutron flux density of HCPB BB in EU-DEMO



Neutron footprint: 400 x 400 mm²

Neutron flux density of HCPB mockup in IFMIF-DONES

Testing goals of BLUME (Blanket functional materials module)

1 Heat Transfer Experiments

Goals	To address heat transfer in realistic fuel-breeder pin geometry
Measurements	Temperature (breeder, coolant, and purge), purge pressure drop, and post-test examination of the breeder structure and gap dimensions

2 Neutronics Prediction Validation (Tritium Generation, Nuclear Heating, Activation)

Goals	To verify neutronics predictions for tritium breeding, nuclear heating and activation
Measurements	Post-test examination for activation, tritium inventory, and neutron fluence

3 Tritium Behavior in Thermal and Flow Transients

Goals	To investigate the tritium inventory and permeation behavior during thermal and flow transients
Measurements	Measurements include temperature (breeder and coolant), coolant and purge tritium activity, and post-test examination for tritium inventory, cracking, or other changes in the solid breeder

4 Breeder/Structure Thermo-Mechanical Interactions

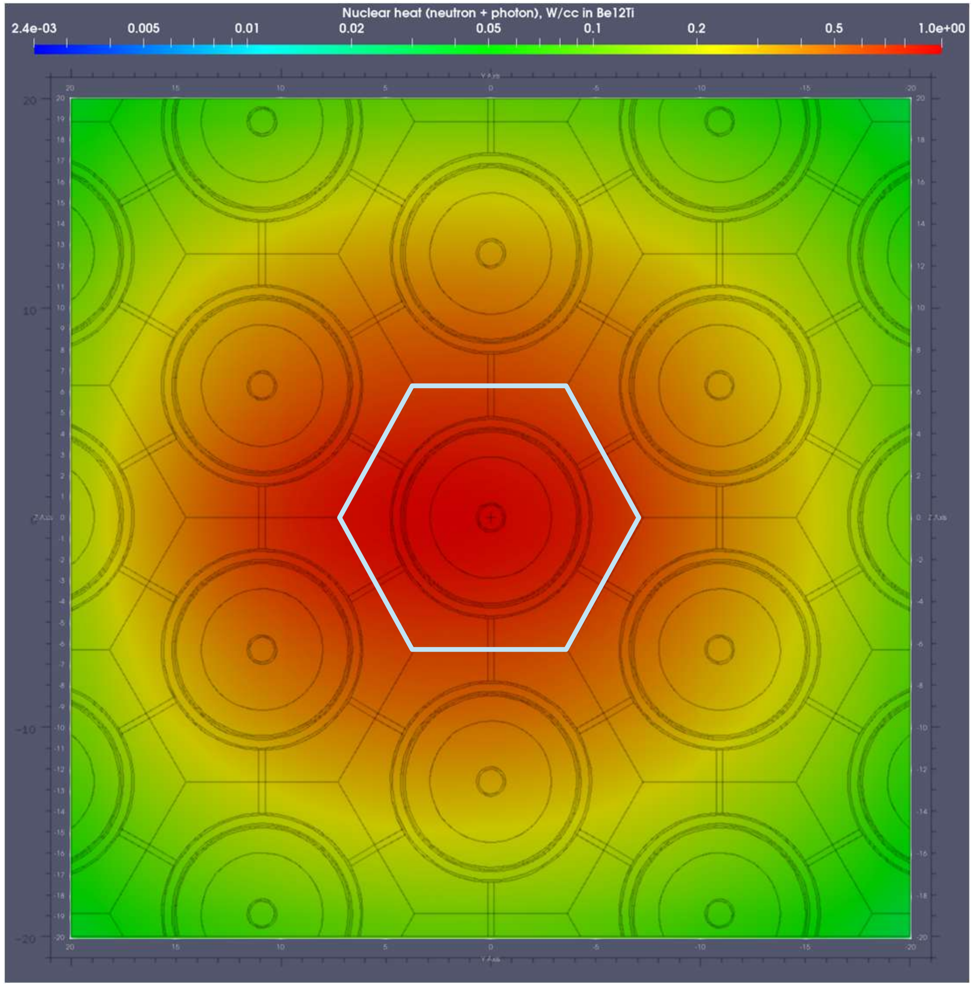
Goals	To study thermomechanical interactive effects on component behavior
Measurements	Temperature, stress, and post-test examination for gap size, cracking, sintering, settling, swelling, and other changes Stress and strain in the structure, cracking and redistribution in the breeder, and overall deformation and failure modes

Testing boundary conditions and target temperature

- Helium coolant at 3.5 bar pressure to share the same coolant supply with HFTM
- To ensure relevant temperature field of HCPB blanket

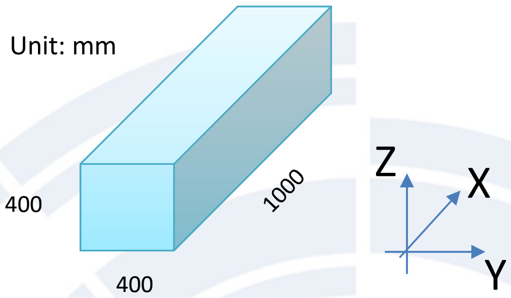
  - ✓ Coolant inlet temperature: 350 – 380 °C
  - ✓ Coolant outlet temperature: 500 – 520 °C
  - ✓ Eurofer temperature: 300 – 550 °C
  - ✓ Advanced ceramic breeder Li-pebble temperature: 400 – 920 °C
  - ✓ TiBe12 temperature: 350 – 1000 °C

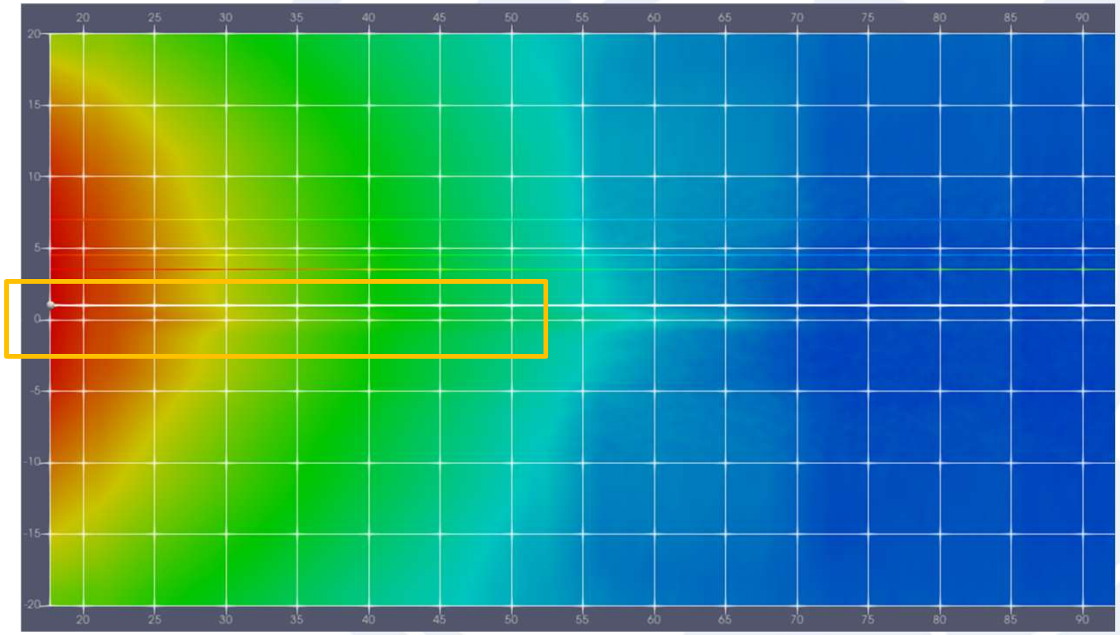
Nuclear heat map of initial design of BLUME



Z axis

Y axis

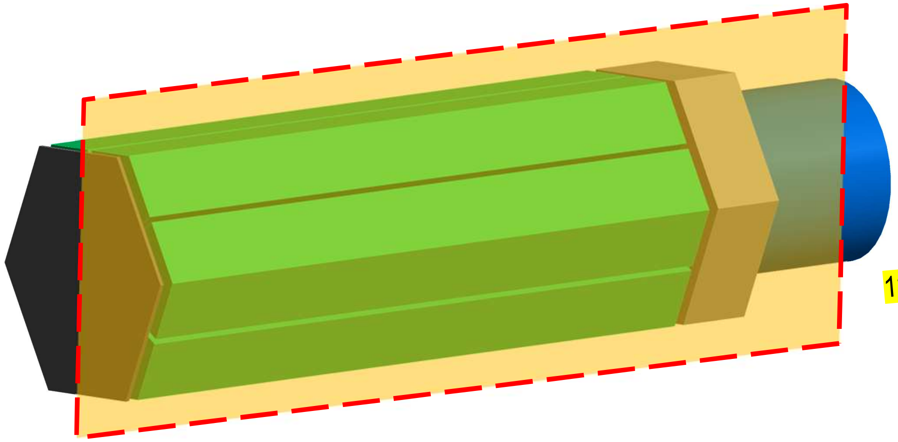


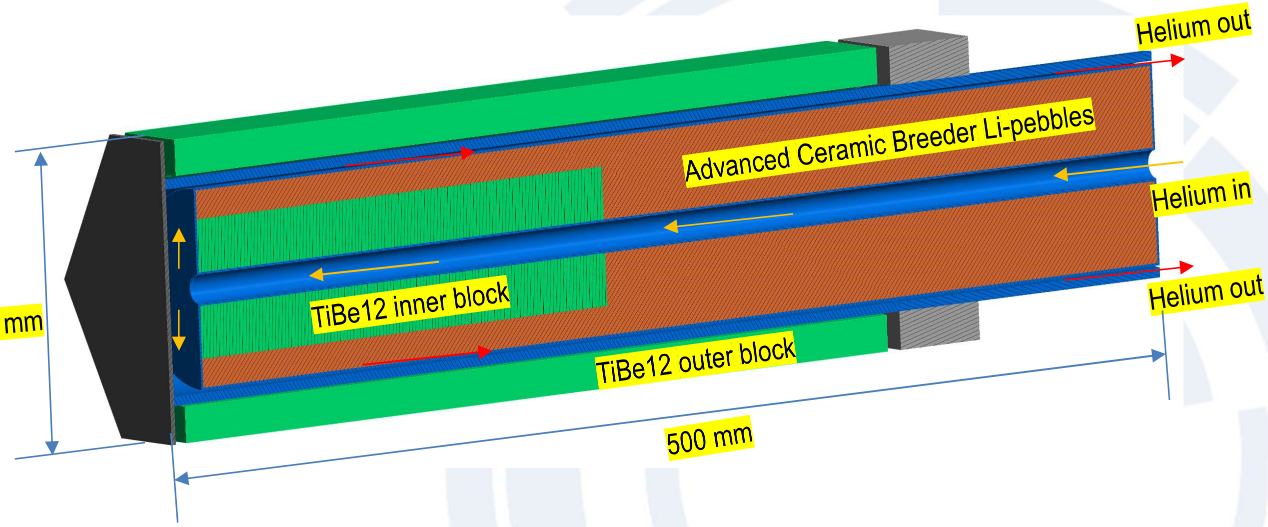


Z axis

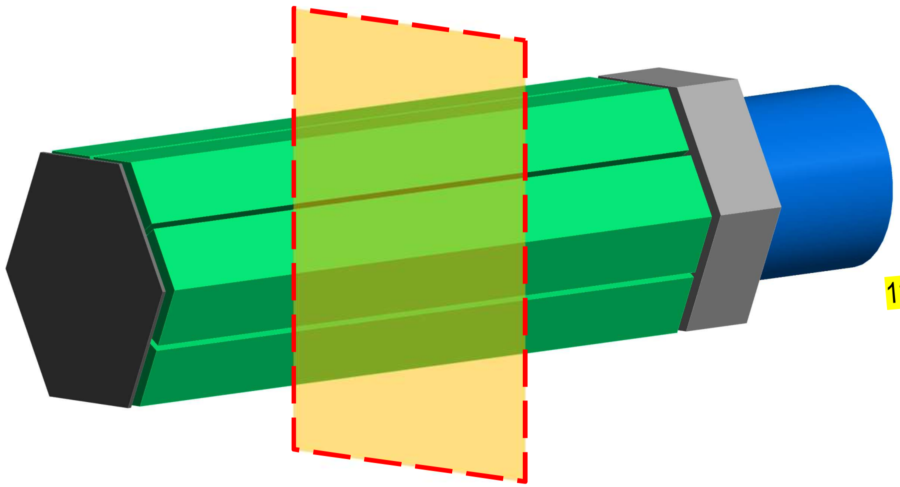
X axis

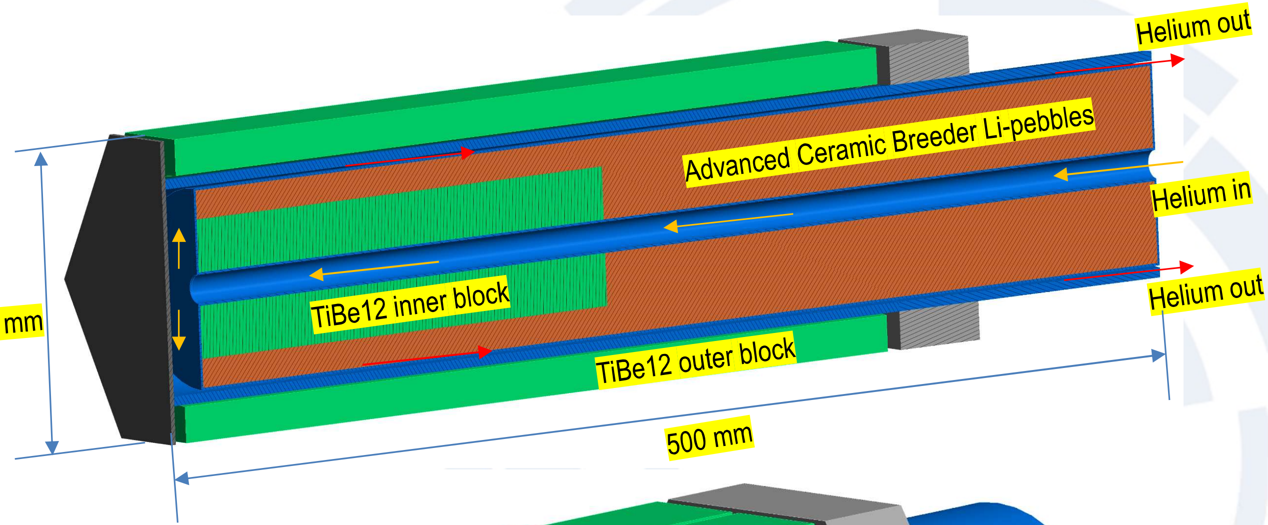
Initial design of BLUME (BLUME-1)



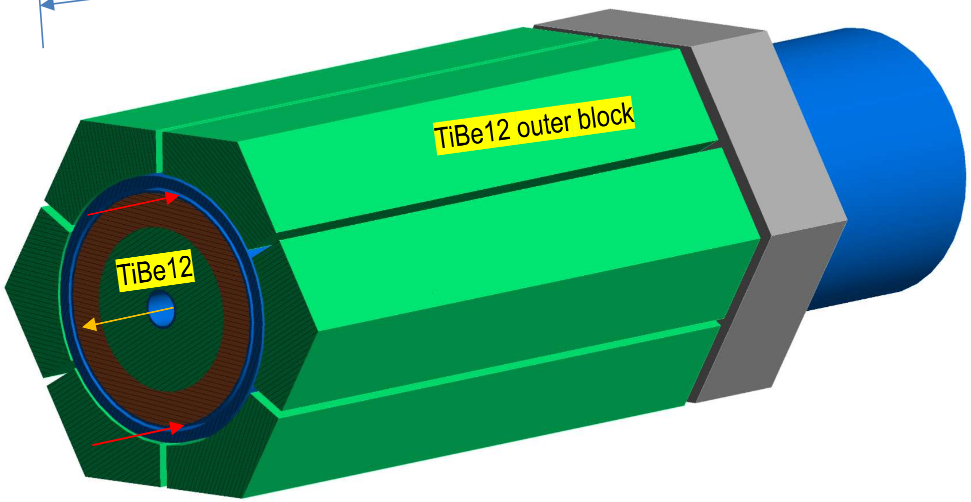


Initial design of BLUME (BLUME-1)

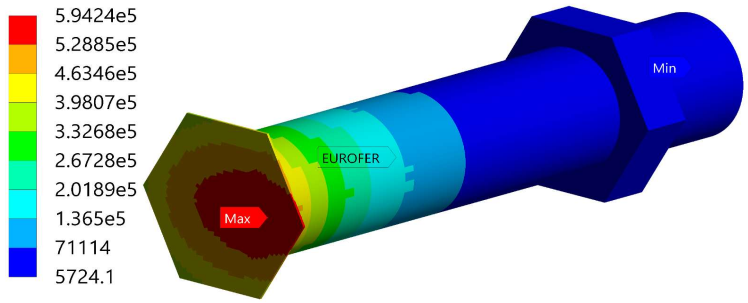




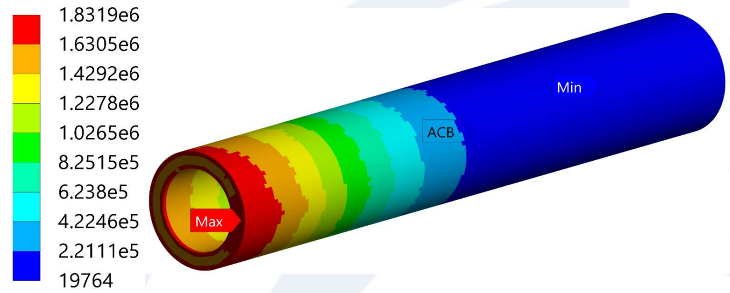
Materials	Total amount
ACB Li-pebbles, g	3009
TiBe12, g	6235
Eurofer, g	7880



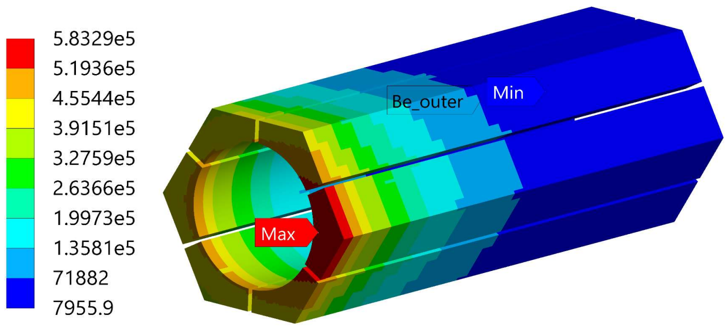
Neutronics analysis: power density [W/m³]



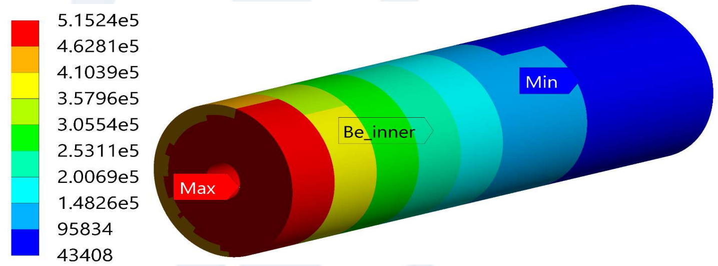
Eurofer



Advanced Ceramic Breeder Li-Pebbles



TiBe12 outer block



TiBe12 inner block

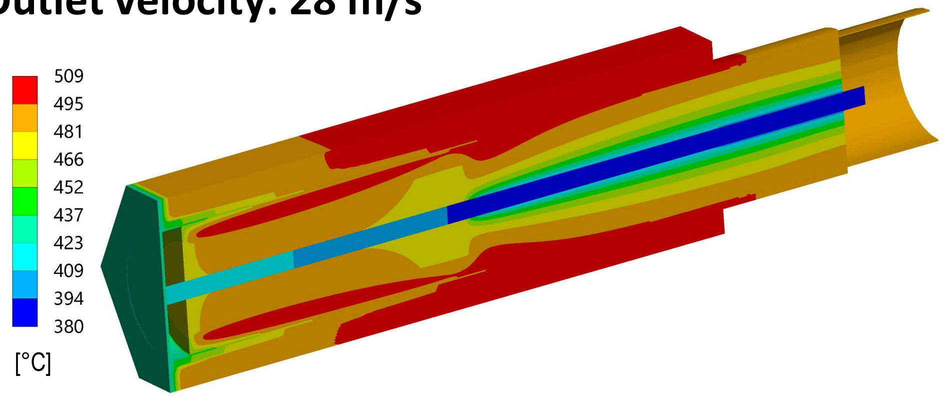
9-degree inclination of deuteron beam causes asymmetry in nuclear heating

Total power: 1044 W

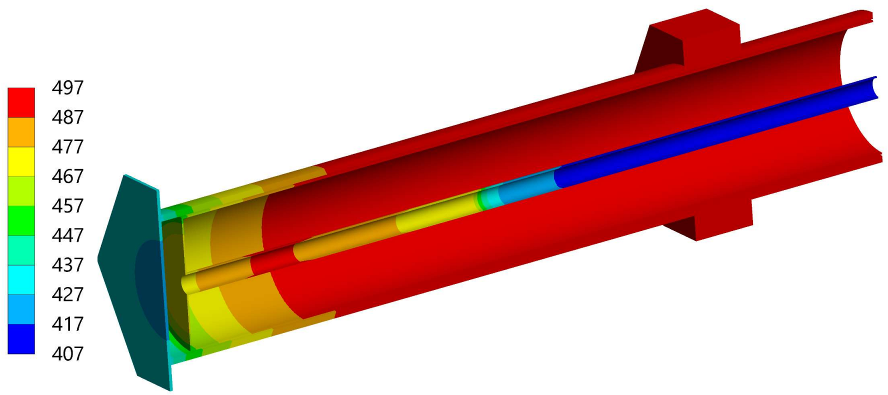
Parameter	DEMO HCPB BB	BLUME-1
Tritium production [per pin]	3.3 mg/day	0.34 mg/day

Thermal analysis: temperature field [°C]

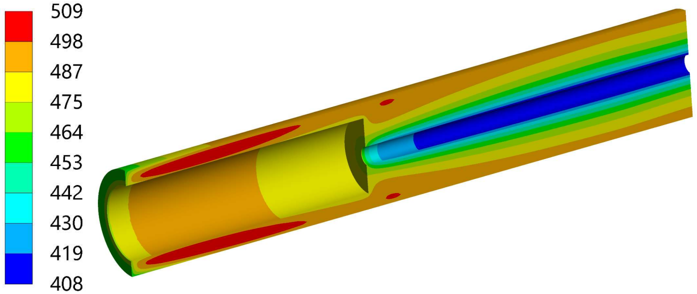
Tin = 380 °C, mass flow rate: 1.7 g/s
Inlet velocity: 57 m/s
Outlet velocity: 28 m/s



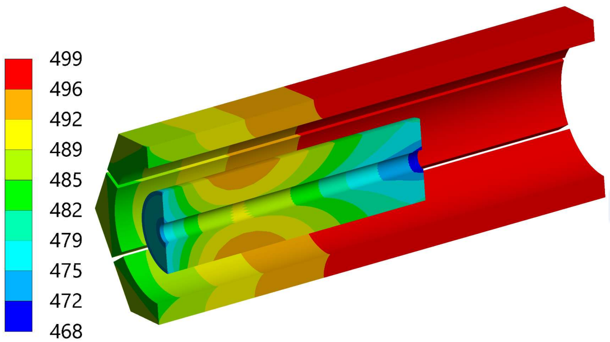
All materials



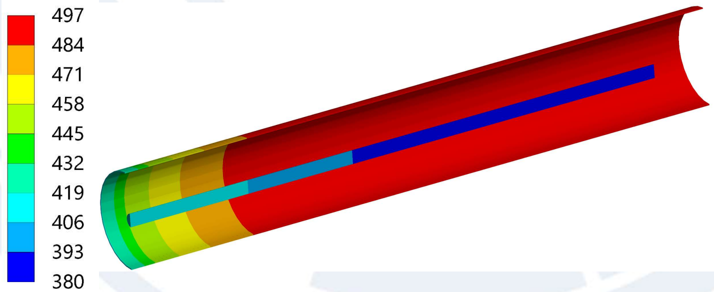
Eurofer



Li-pebbles



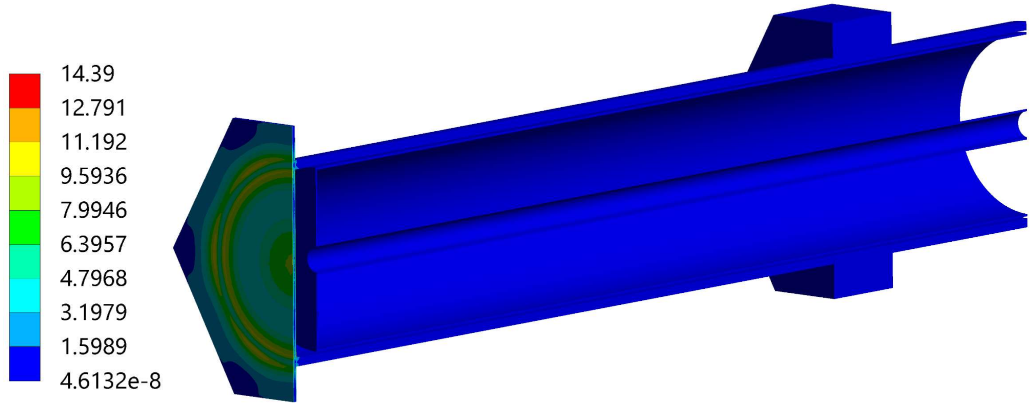
TiBe12



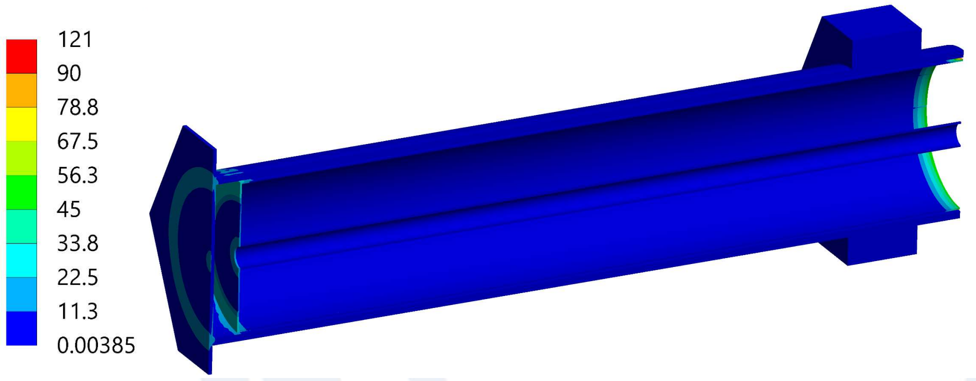
Coolant

Structural analysis: Von-Mises Stress field [MPa]

Coolant-wetted surfaces: 3.5 bar pressure
Body: temperature field
Fixed at rear surfaces of BLUME



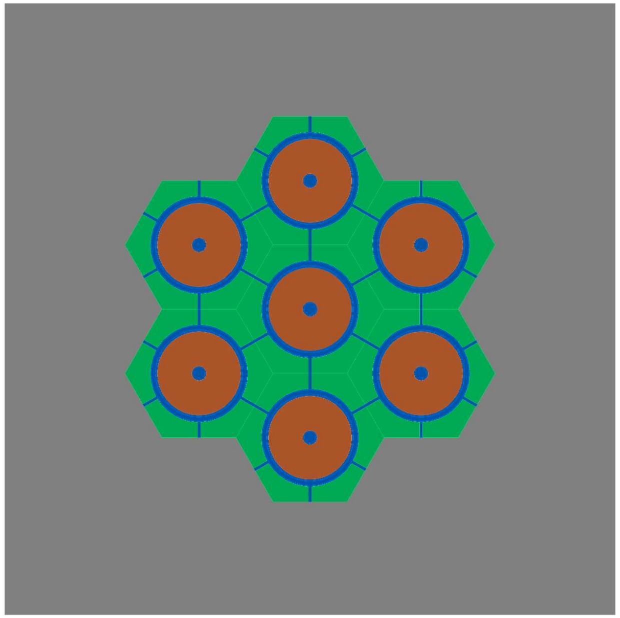
Stress with pressure load

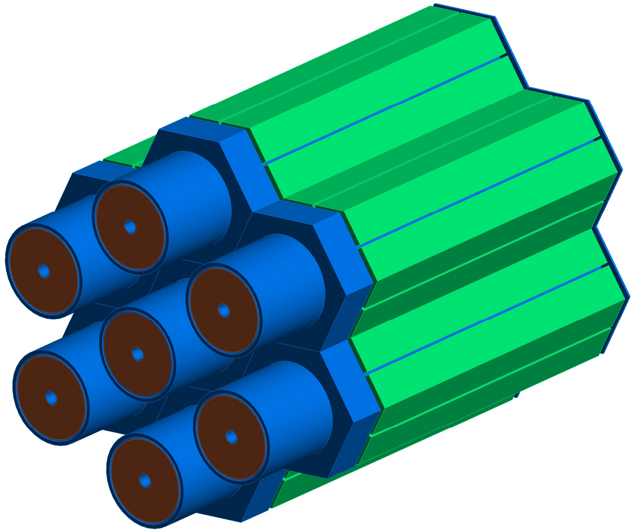


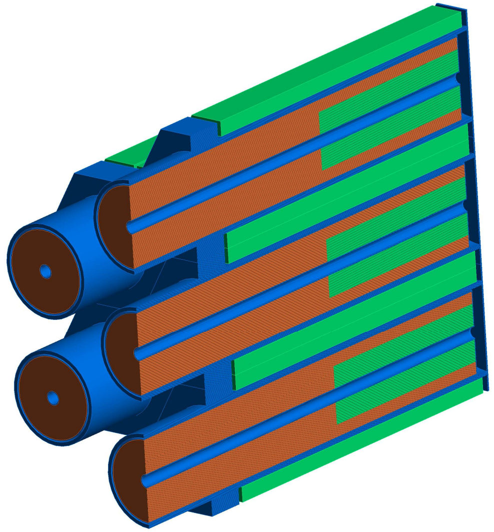
Stress with pressure and temperature field

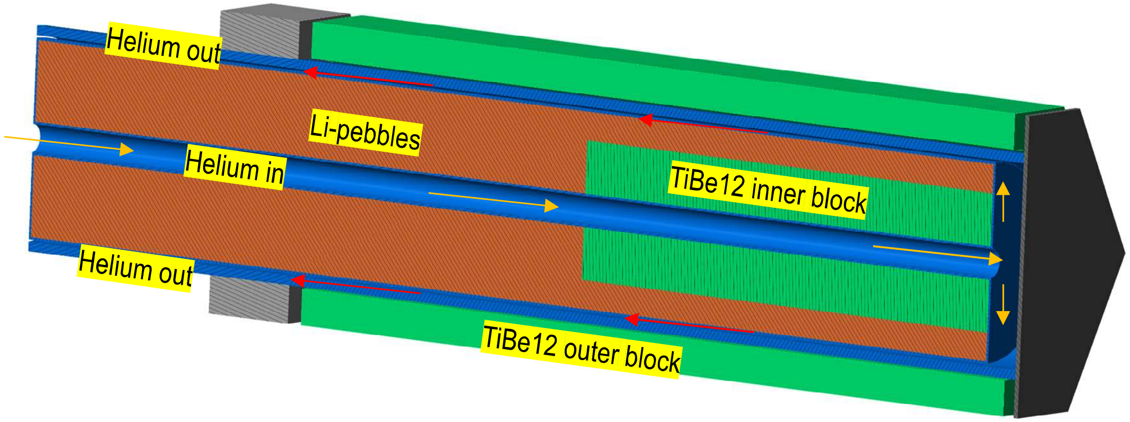
Structure is robust enough to withstand the pressure and thermal stresses.

Design of 7 pins BLUME (BLUME-7)



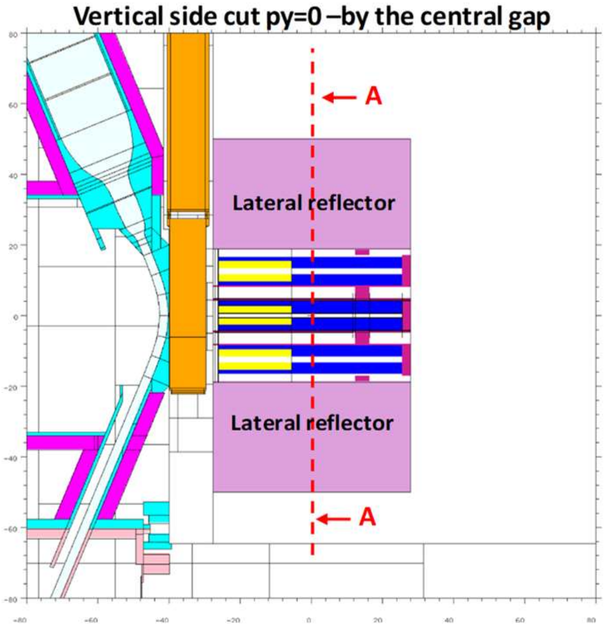


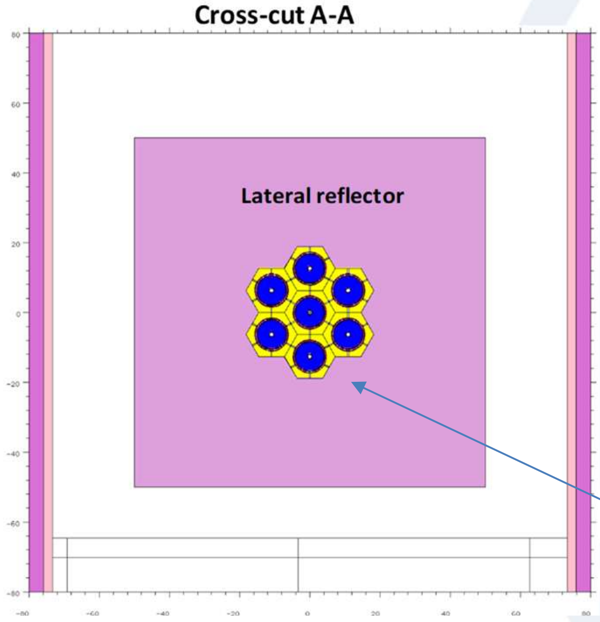




Neutronics analysis of BLUME-7

- More advanced model (2024) → 7 fuel-breeder pin
- Neutronics model

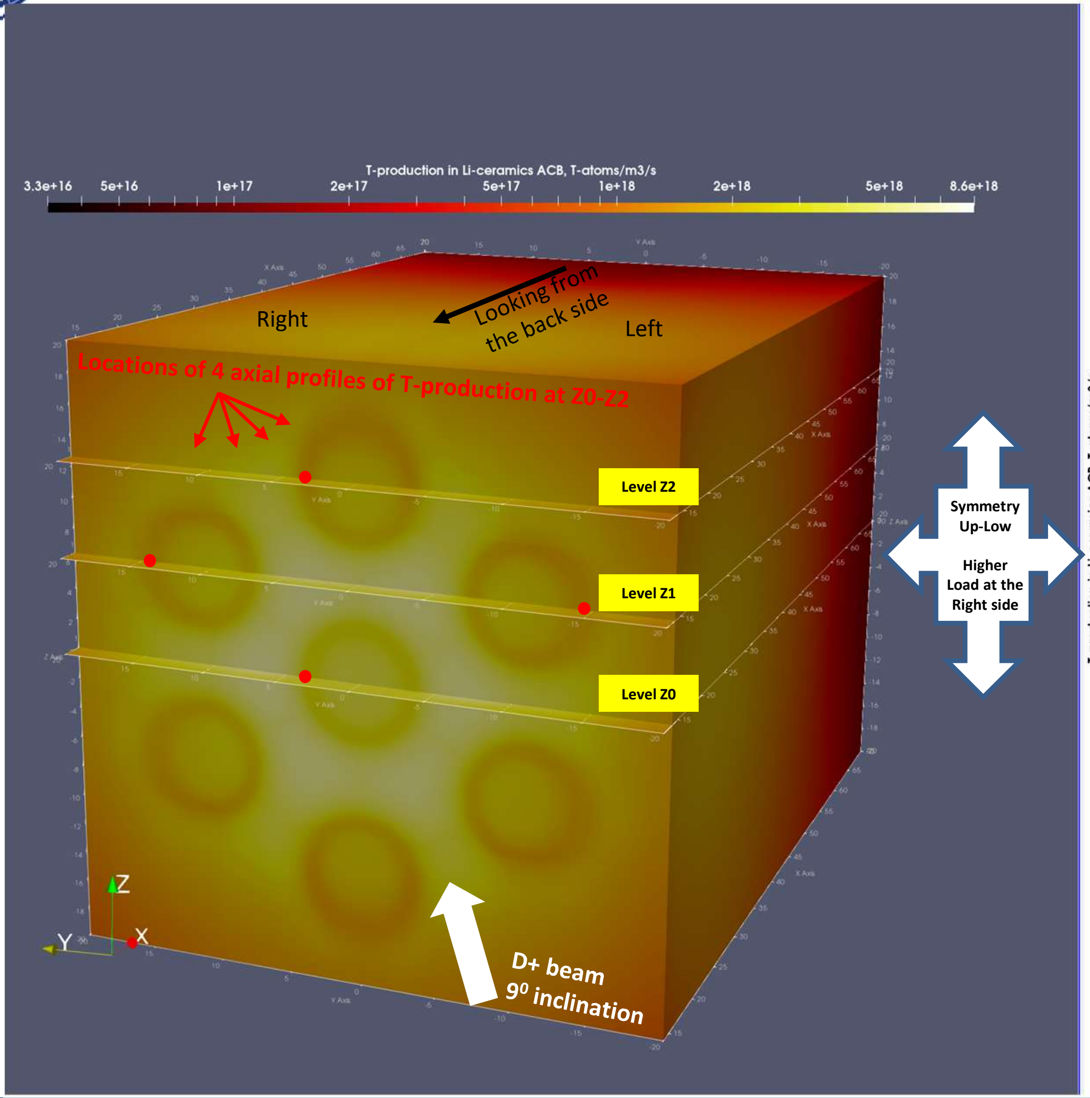


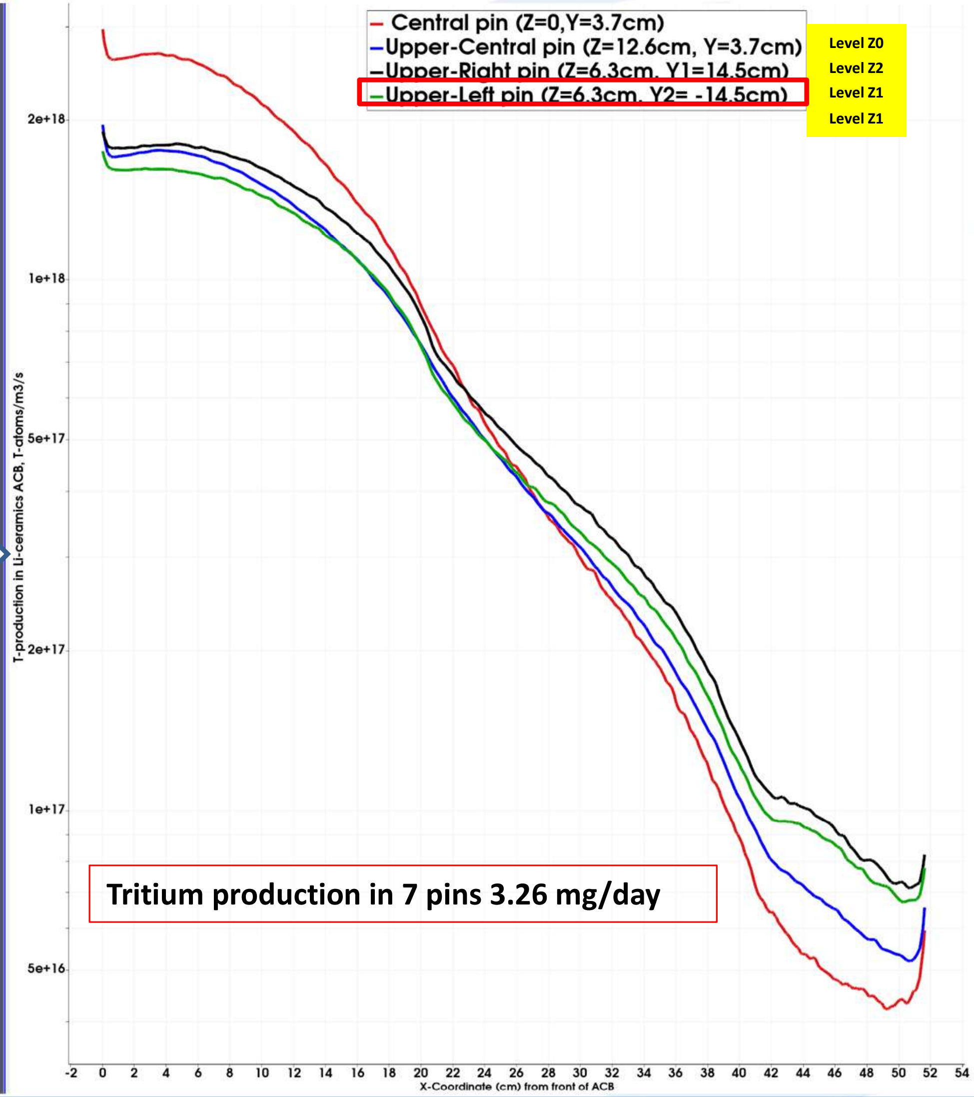


Calculated and compared :
1) Neutron fluxes
2) Nuclear heat for the different materials
3) T-production in Li-ceramics ACB
4) Neutron damage (DPA/FPY)

The model includes Pb or C reflectors surrounding the BLUME mockup

T-production in Li-ceramics ACB in BLUME-7 model with Pb reflector



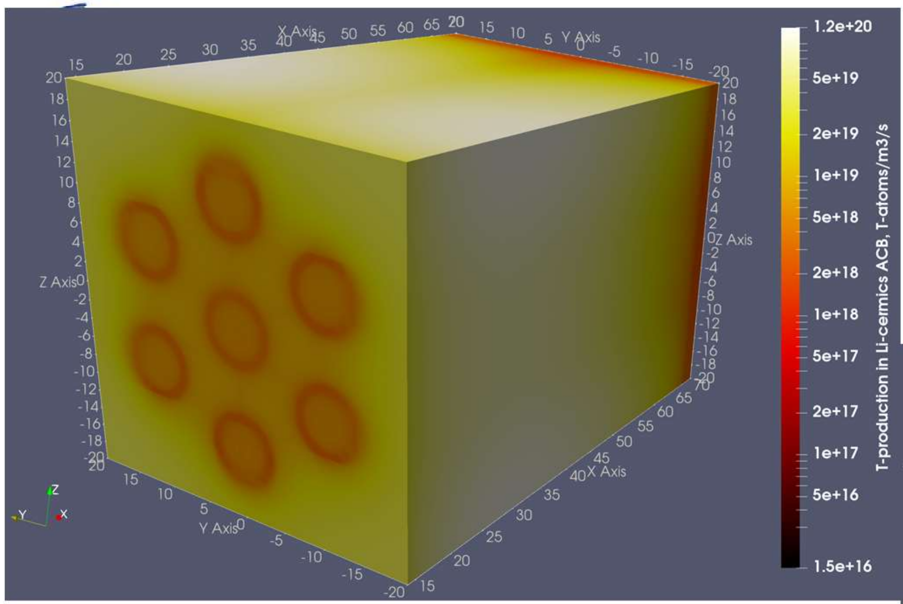


T-production in Li-ceramics ACB

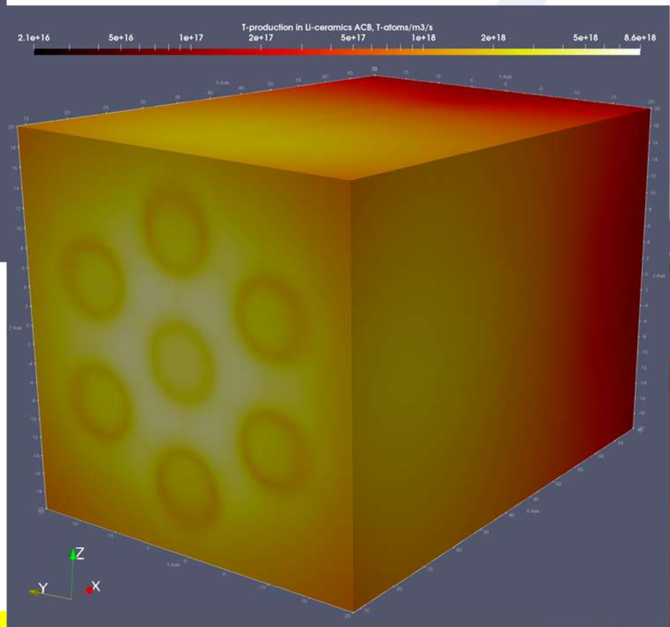
1. Max. T-production in ACB = 7e18 T-atoms/m3/s

2. Max. T-production in ACB = 3e18 T-atoms/m3/s

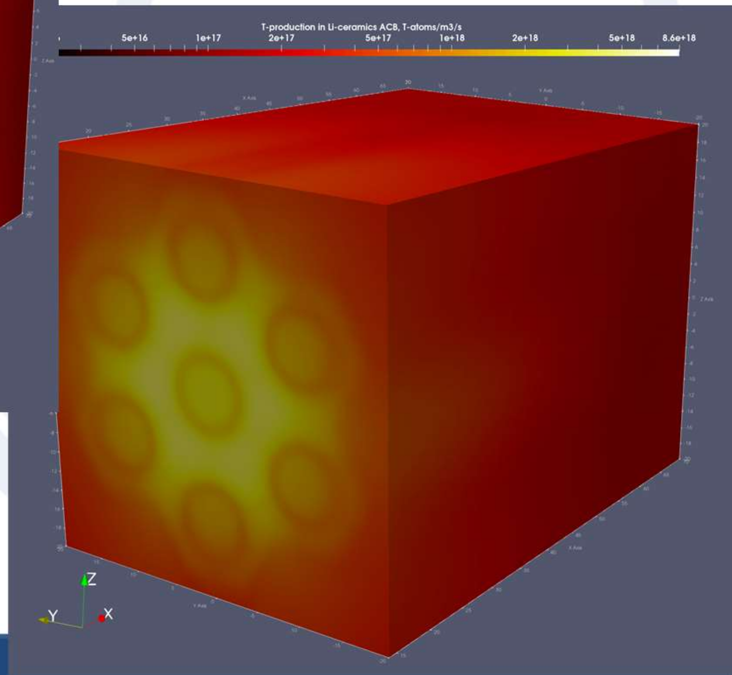
3. Max. T-production in ACB = 2e18 T-atoms/m3/s



1. With graphite-reflectors

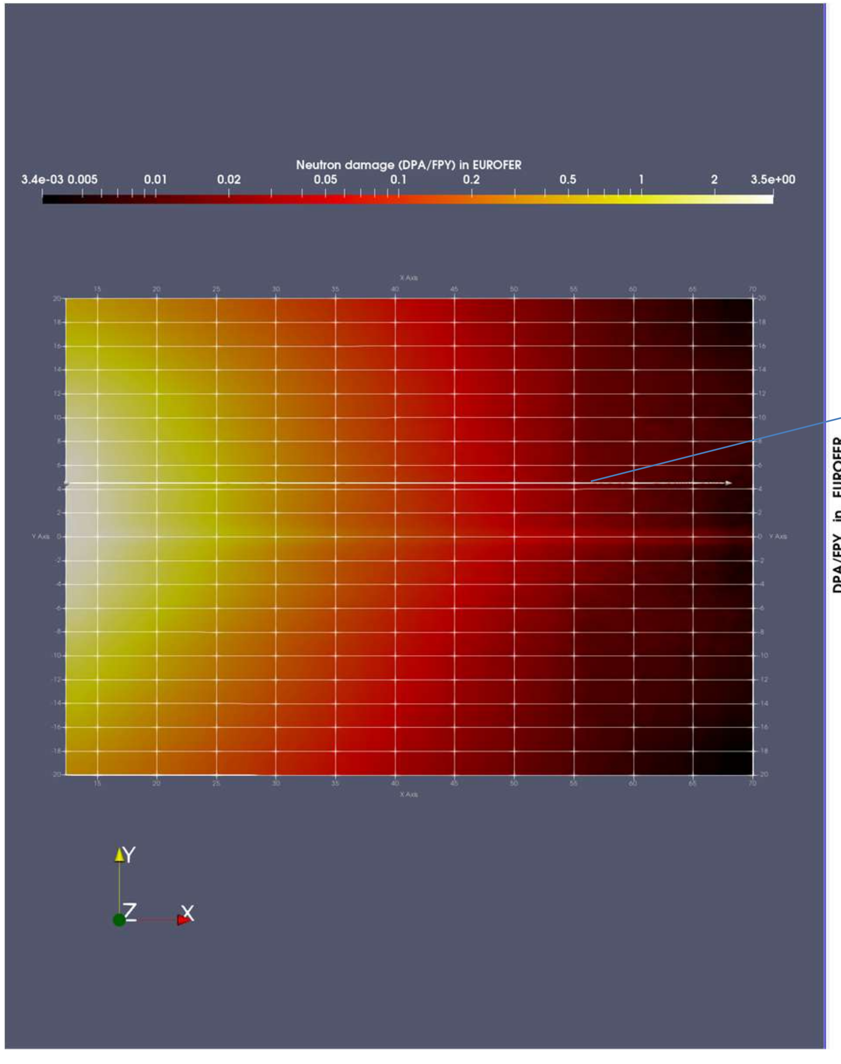


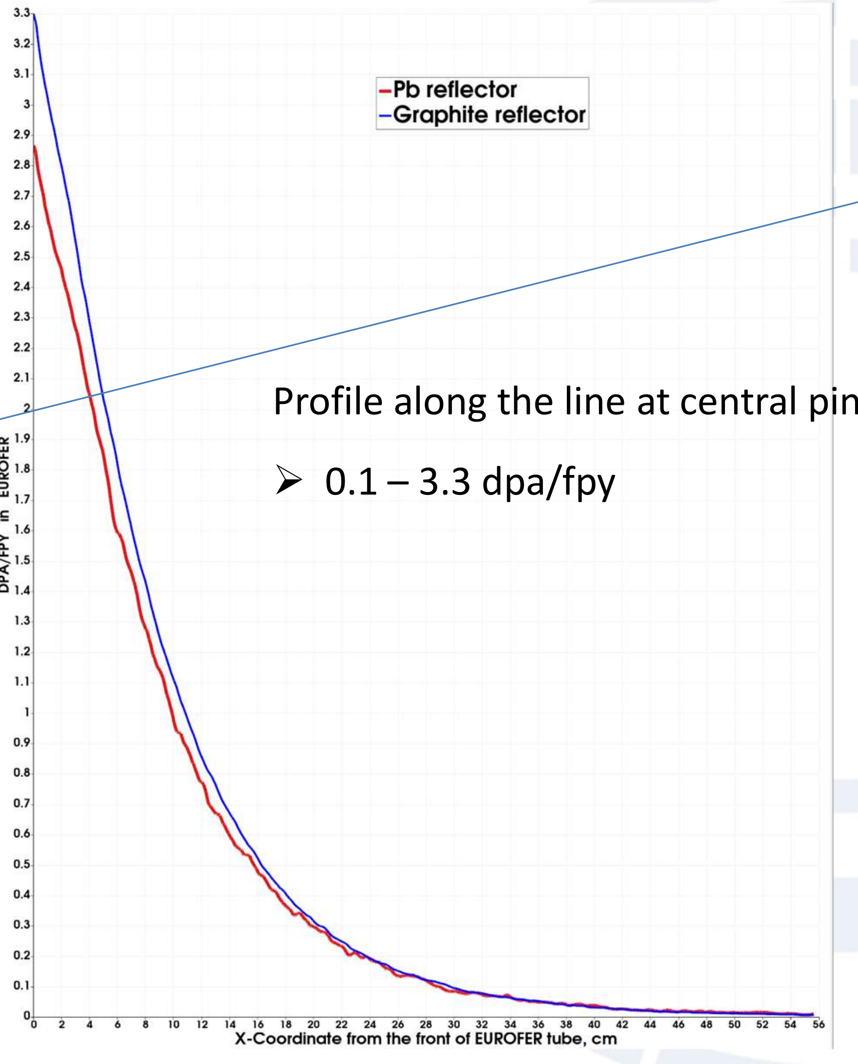
2. With lead-reflectors

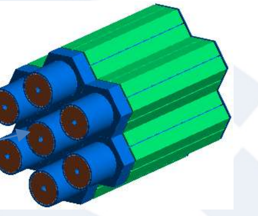


3. Without any reflectors around BLUME-7

Neutron damage (DPA/FPY) in EUROFER of BLUME-7 model







Profile along the line at central pin

- 0.1 – 3.3 dpa/fpy

Comparison with DEMO HCPB BB

Parameter	DEMO HCPB BB	BLUME-1	BLUME-7
Tritium production [per pin]	3.3 mg/day	0.34 mg/day	0.52 mg/day 3.26 mg/day in 7 pins
Temp. range of Eurofer	300 – 550 °C	407 – 497 °C	421 – 547 °C
Temp. range of ACB Li-pebble	400 – 920 °C	408 – 509 °C	421 – 557 °C
Temp. range of TiBe12	350 – 1000 °C	468 – 499 °C	525 – 550 °C
Temp. range of coolant	350 – 520 °C	380 – 497 °C	380 – 540 °C

Conclusions

➢ **Summary:**

- Key validation needs of HCPB BB presented
- Testing goals of BLUME are presented
- Preliminary design of BLUME is proposed

➢ **Outlook:**

- Interface with Test Cell of IFMIF-DONES will be established
- Measurement requirement of different test goals will be defined
- Ancillary systems requirement for BLUME will be defined

Values of EUROfusion

Thank you for your attention!