EUROfusion

IAEA DEMO Programme Workshop

# Neutronics activities for European DEMO fusion reactor shielding and breeding blanket designs

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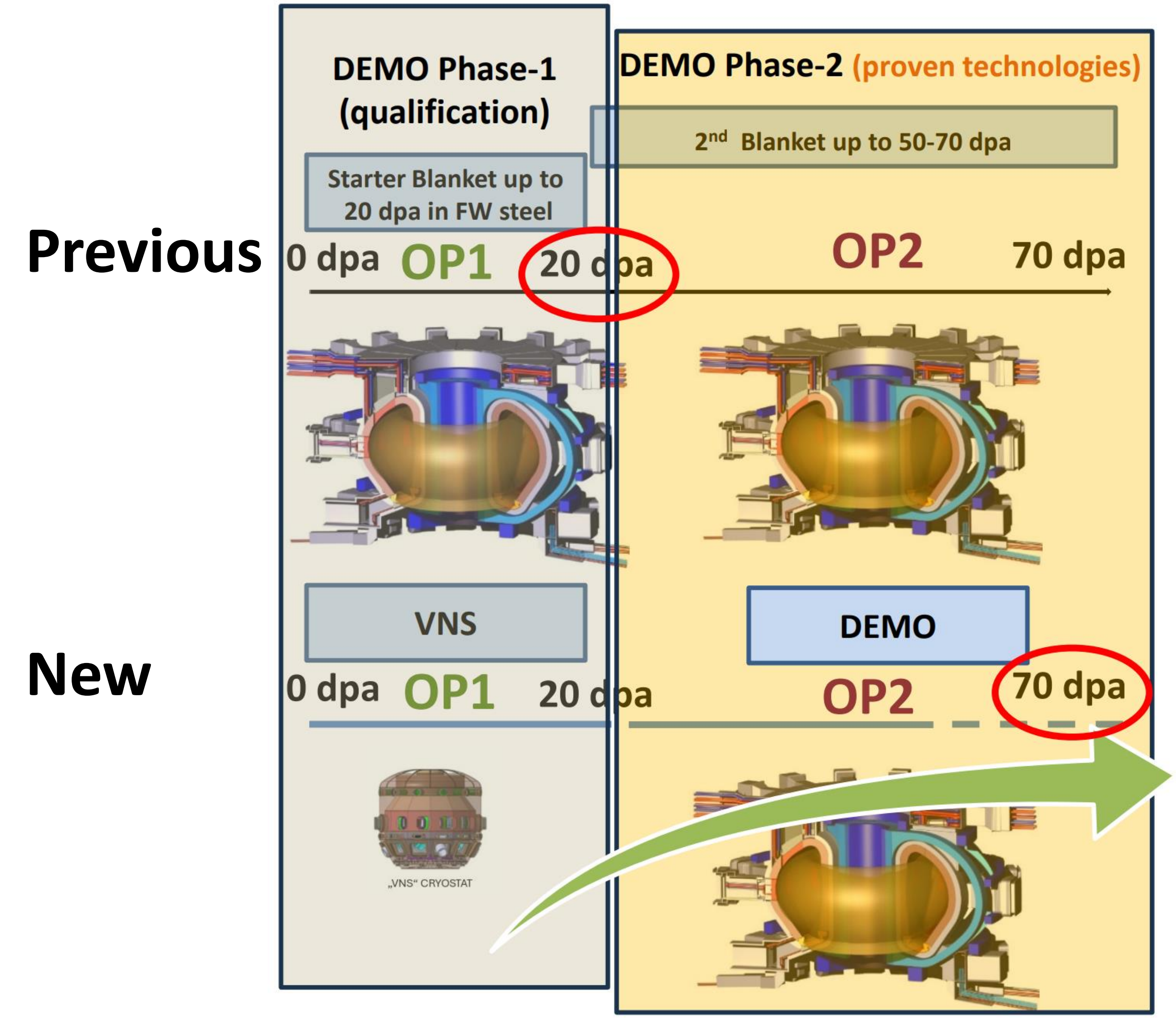
# Content

- Introduction
  - EU DEMO and VNS
- Neutronics Framework for DEMO Design
  - Methodology, tools, data
- Conceptual Shielding Efforts
  - Protection objectives
  - VNS experiences
  - DEMO tokamak examples
- DEMO Breeding Blanket Neutronics
  - BB concepts overview
  - TBR optimisation, uncertainties
- Conclusions

# Introduction (from G. Federici, Jan. 2025)




| DEMO phase -1 | DEMO | VNS |
|---|---|---|
| $P_f$ (MW) | 2000 | 30 |
| NWL (MW/m²) | 1 | 0.5 |
| fpy to reach 20 dpa | 2 | 4 |
| T (kg) burned to 20 dpa | 224 | 6.8 |

- VNS can decouple DEMO from ITER, validating more blanket concepts than ITER TBM and quicker and at higher fluences
- VNS would benefit from a lot of ITER industrial achievements (magnets, VV buildings, safety, etc.)
- VNS can replace OP1 phase in DEMO
- **VNS cannot replace OP2 phase in DEMO**, aimed at demonstrating self-sufficiency and production of electricity
- Motivate investor/governmental interest in the nearer term.
- Attractive involvement opportunity for industry.

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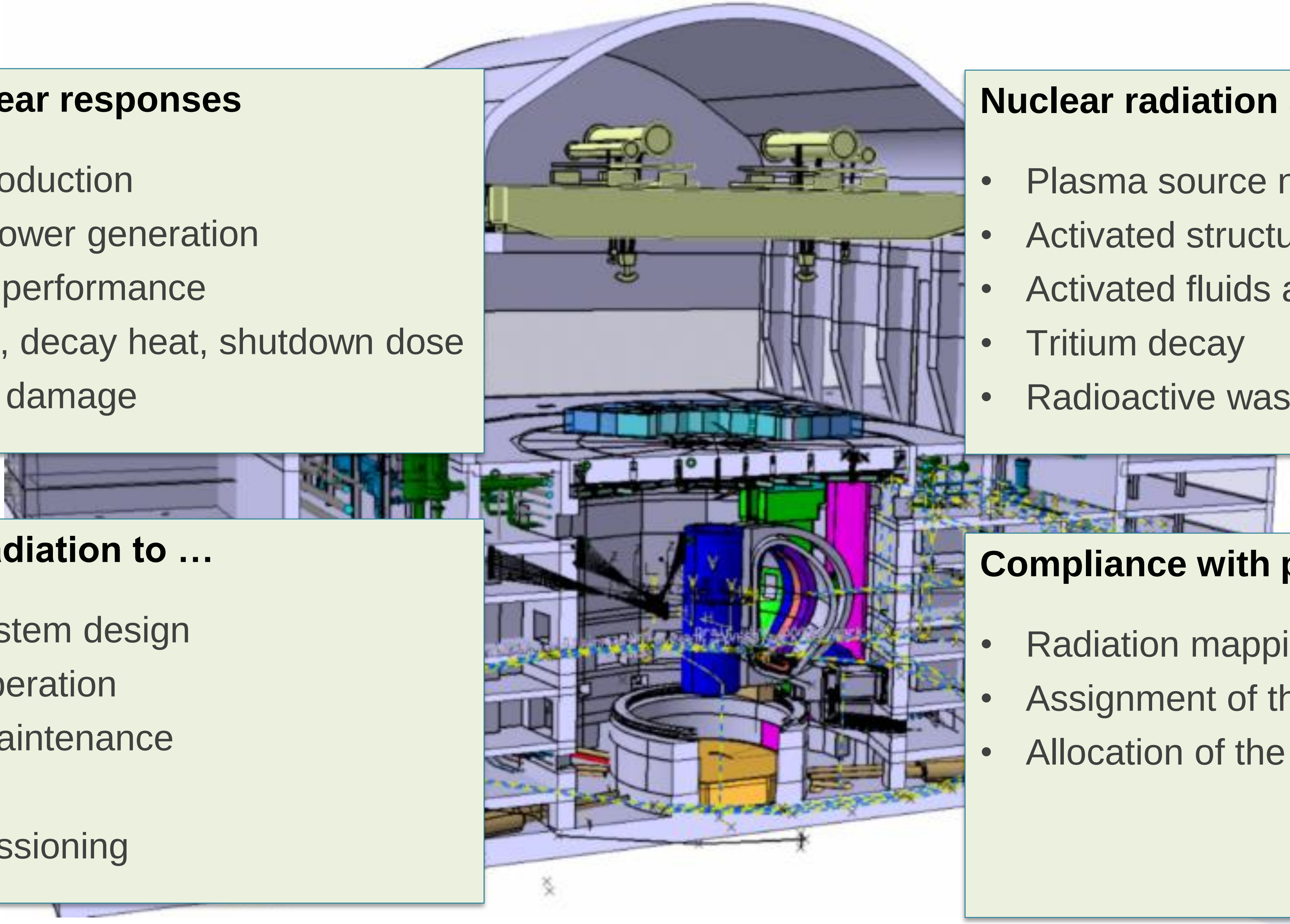
# Role of Neutronics in DEMO Design



**Global nuclear responses**

- Tritium production
- Heating/power generation
- Shielding performance
- Activation, decay heat, shutdown dose
- Radiation damage

**Nuclear radiation sources**

- Plasma source neutrons
- Activated structures
- Activated fluids and dust
- Tritium decay
- Radioactive wastes

**Impact of radiation to …**

- Global system design
- Facility operation
- Facility maintenance
- Licensing
- Decommissioning

**Compliance with project requirements**

- Radiation mapping
- Assignment of the radiological zones
- Allocation of the required protection

# Tools and Data in DEMO Neutronics

Particle transport:
- European ***JEFF*** library
- ÎAEA ***FENDL*** library

Activation:
- ***TENDL***

Special purpose data

**Nuclear data**

**Plasma neutron source**

Plasma neutron source generation:
- ***TRANSGEN***

Geometry generation tools:
- ***CATIA***
- ***SpaceClaim***

Geometry conversion:
- ***McCAD, GEOUNED***

**Geometry modelling**

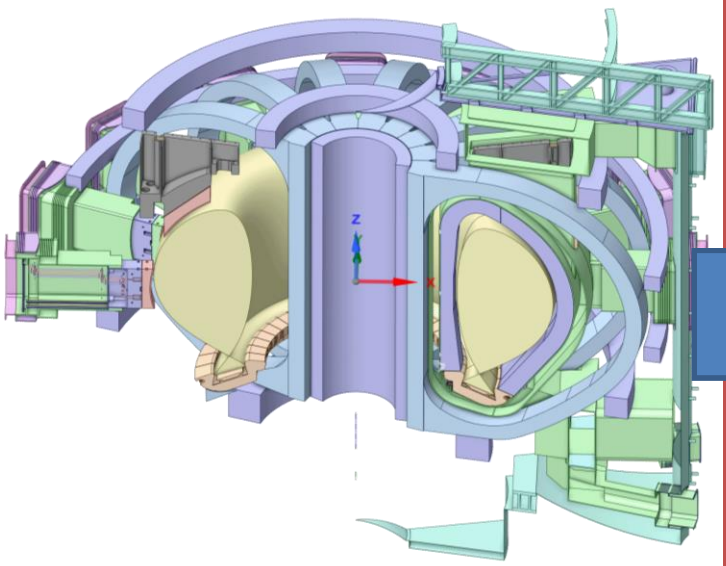
**Computer codes**

Particle transport:
- ***MCNP***
- ***TRIPOLI***
- ***OpenMC***

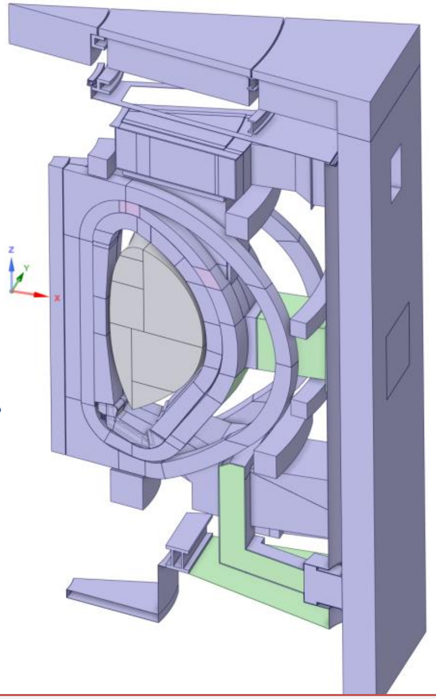
Shutdown dose rate:
- ***MCR2S, R2SUNED***
- ***AdvD1S, cR2S***

Activation/Inventory:
- ***FISPACT II, ACAB***

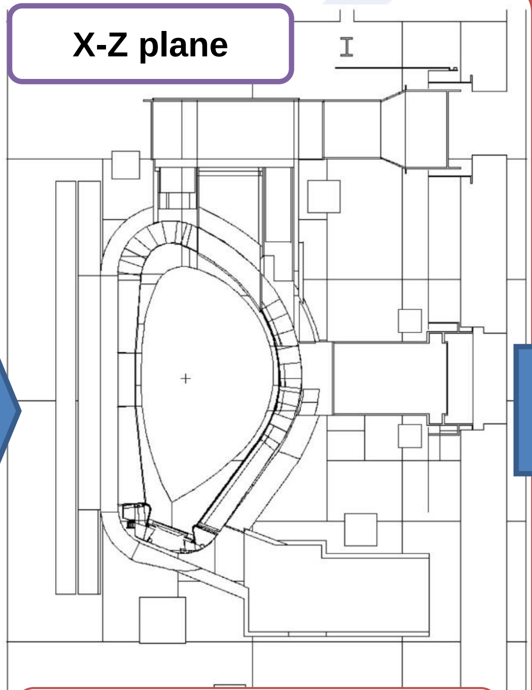
# Generic neutronics tokamak sector model



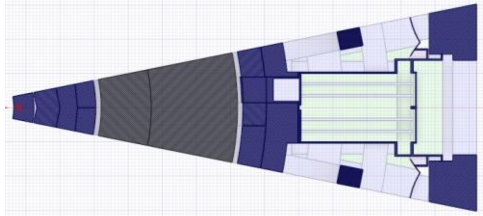
Engineering CAD



22.5° DEMO 2019
CAD generic model

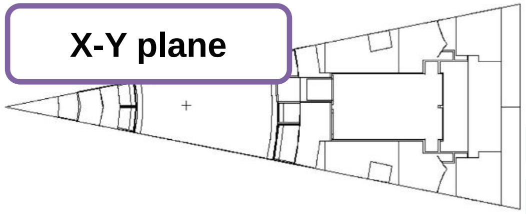


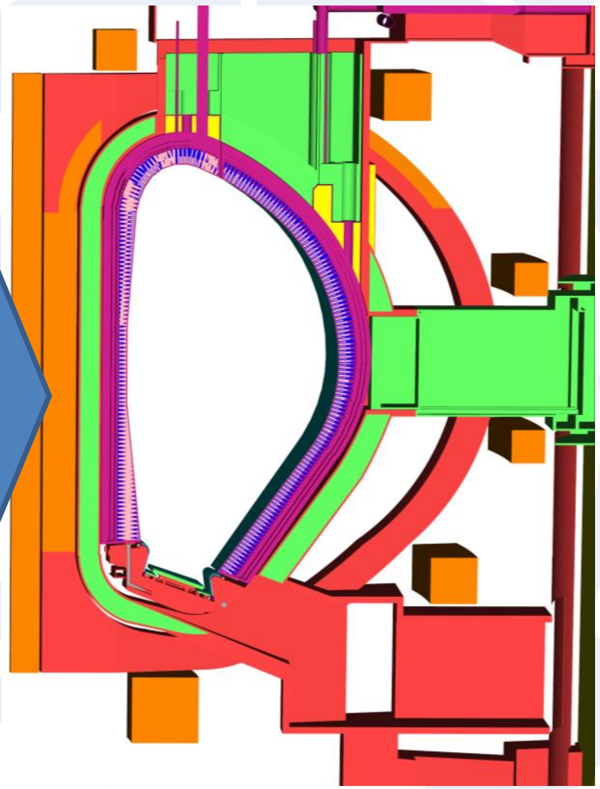
X-Z plane



22.5° DEMO 2019
Neutronics geometry model

X-Y plane





22.5° DEMO 2019
Neutronics generic model

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# Strategical approach for (tokamak) shielding objectives

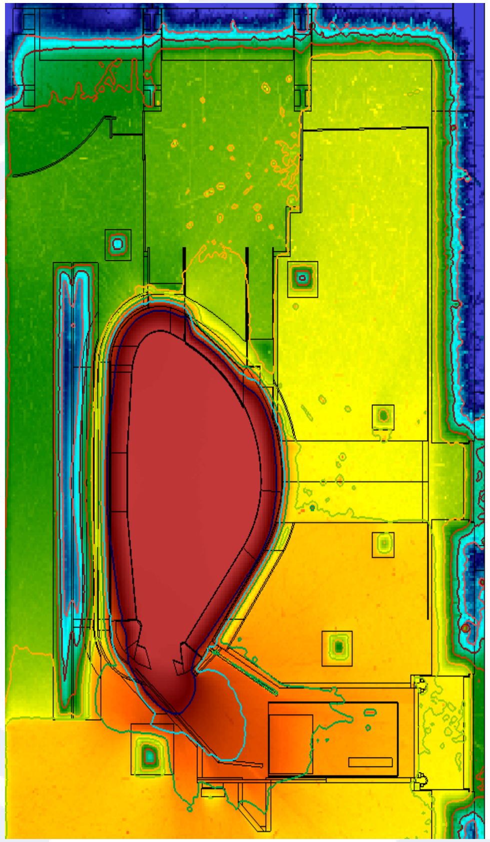
Status of protection requirements and priorities

Assessment of radiation mapping from plasma neutron source (other sources)

Identification of key configuration and design options

Study of advanced „baseline“ configuration: e.g. VV bulk shield & intercoil shields

Study of various options at port level



# DEMO Nuclear Shielding Requirements (and Targets)

| Component/ location | Requirement | Limit (target) |
|---|---|---|
| Port interspace | Shutdown dose rate 12 days after shutdown | ~500 µSv/h (target) |
| Port cells (occasional access) | | 100 µSv/h (target) |
| Maintenance hall above tokamak | | Tbd. |
| In-cryostat area, [7] | | 100 µSv/h (target) |
| Tokamak building areas beyond port cells requiring frequent access, [7] | Shutdown dose rate 1 day after shutdown | 10 µSv/h (target) |
| Critical electronic equipment | Neutron fluence during operation | 0.01 n/(cm²s) |
| Non-critical electronic equipment | | 100 n/(cm²s) |

## Investment protection

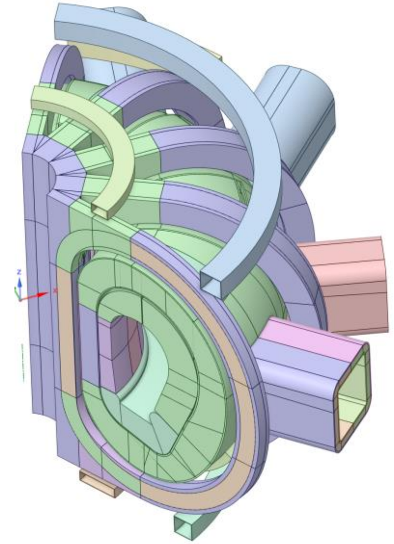
- Ageing and damage limits

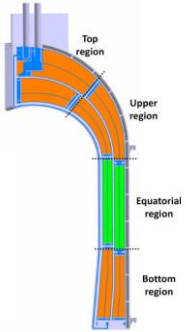
## Radiological protection

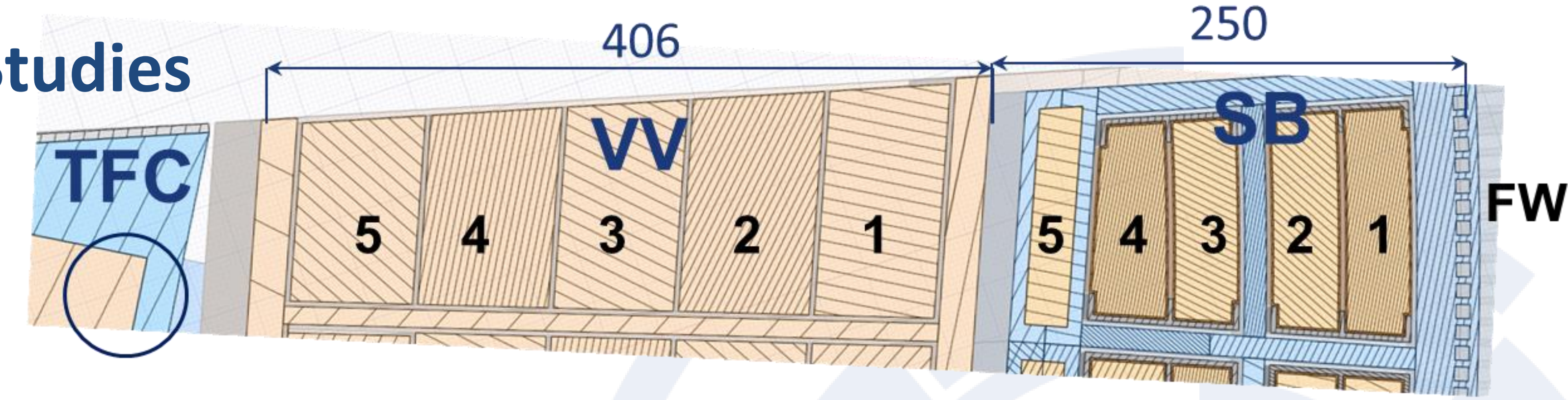
- Exposure rate constraints/targets

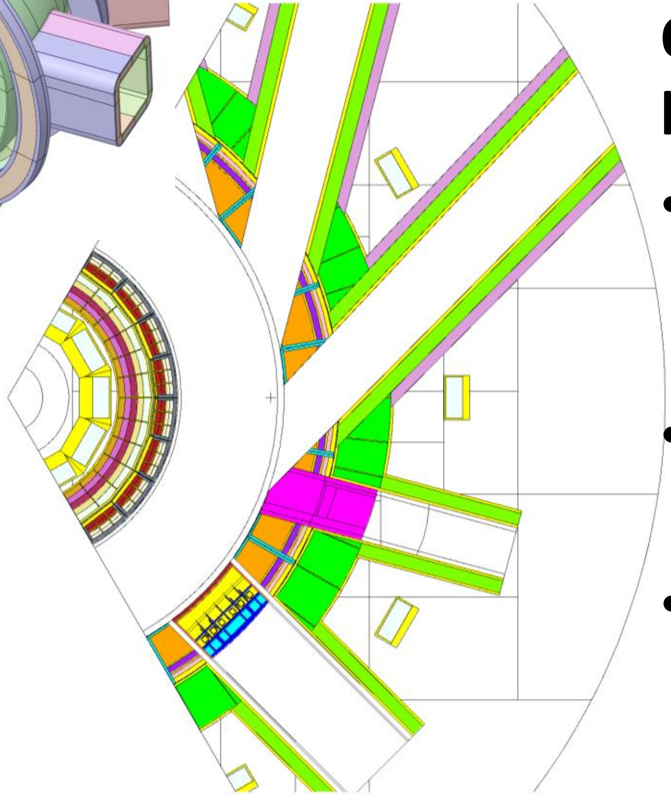
| Component/ location | Requirement | Limit (target) |
|---|---|---|
| Starter blanket FW | Displacement damage to Eurofer | 20 dpa |
| 2nd blanket FW | | 50 dpa |
| Divertor cassette body (@ 180°C), [8] | | 6 dpa |
| Divertor PFCs, [9] | Displacement damage to CuCrZr | 10 dpa, possibly up to 20 dpa |
| VV | Displacement damage | 2.75 dpa |
| | Nuclear heating, [10] | 0.5-1 W/cm³ (target) |
| | Activation, [2] | Minimize (target) |
| Cutting/re-welding location in IVC cooling pipes | Helium production | 1 appm |
| Superconductors, [11], [12] | Total neutron fluence to epoxy insulator | $10^{22}$/m² |
| | Fast neutron fluence to the Nb3Sn | $10^{22}$/m² |
| | Neutron fluence to Cu stabilizer between TFC warm ups | $1\text{-}2 \cdot 10^{21}$/m² |
| | Nuclear heating in winding pack | 50 W/m³ |

# VNS Inboard Shielding Studies





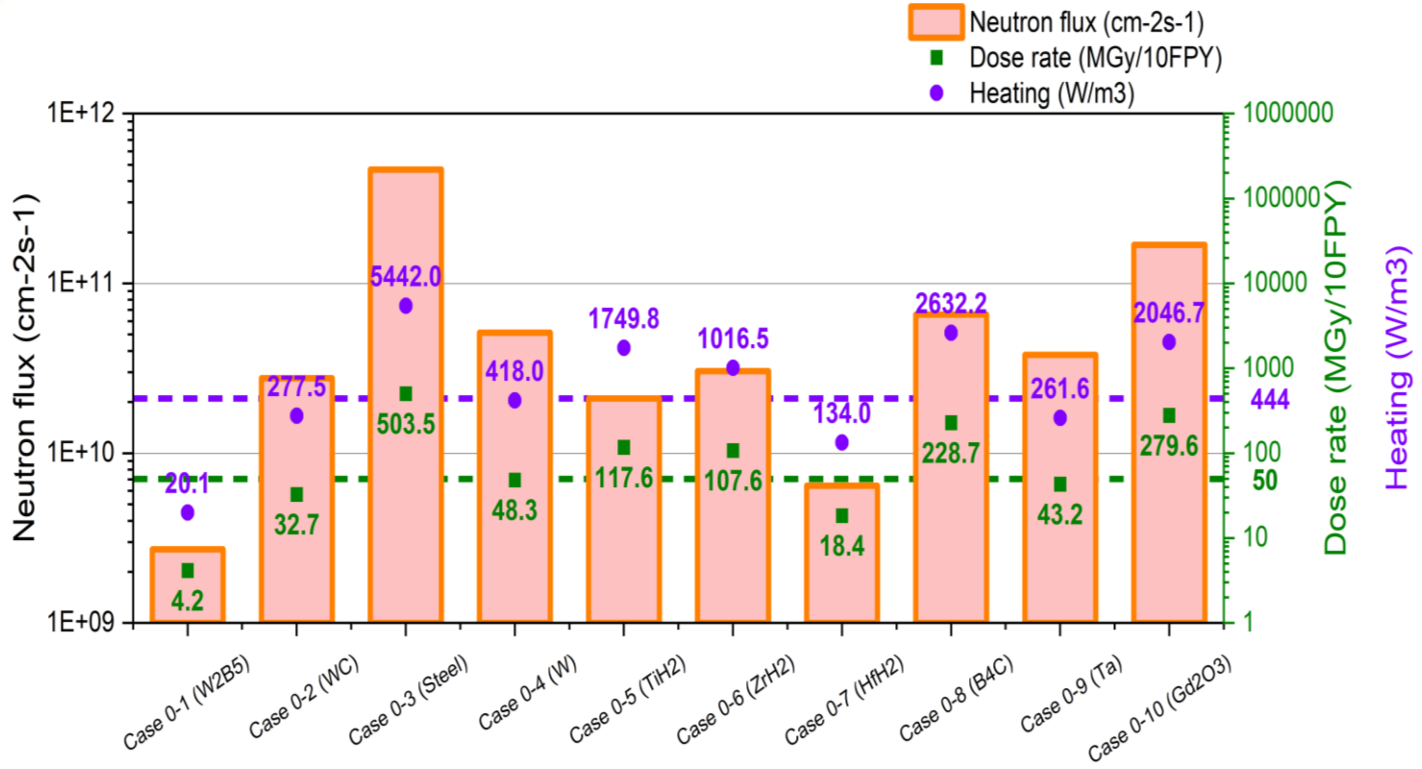



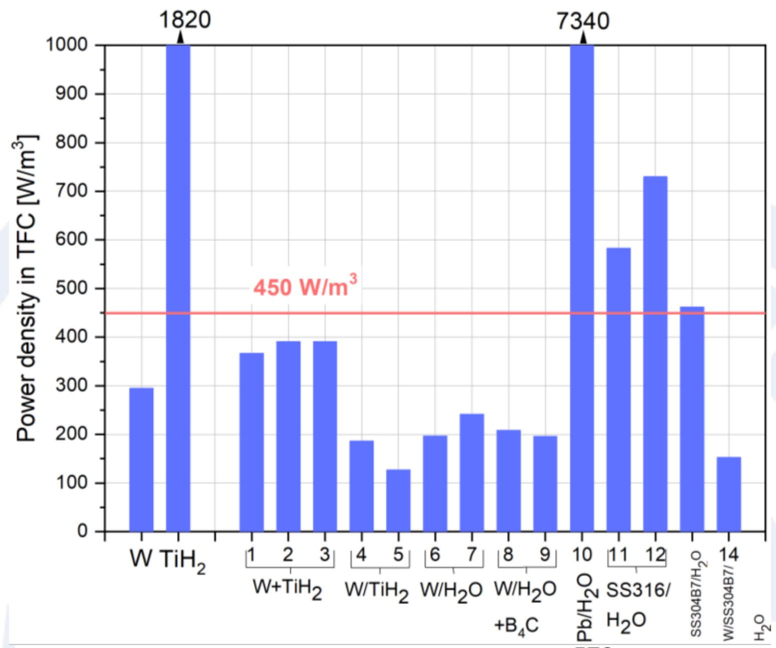
**Objective: protection of TFC with limited IB radial build**

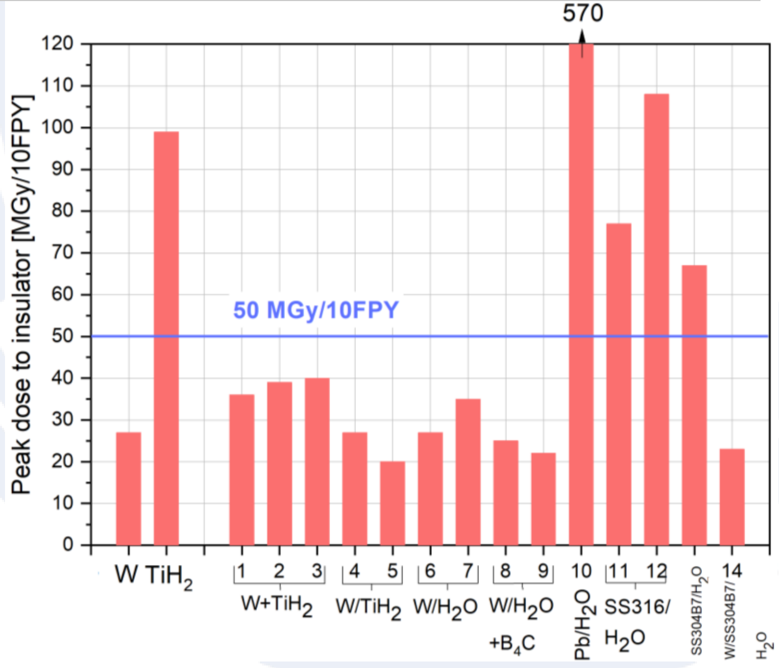
- VNS shielding concept
  - Shield Blanket, shield material compartments
  - Vacuum Vessel with in-wall shield containers
- Mapping of nuclear responses across radial build
- Assessment of promising shield material combinations

$W_2B_5$ (Tungsten Diboride)
WC (Tungsten Carbide)
SS (Stainless Steel)
W (Tungsten)
$TiH_2$ (Titanium Hydride)
$ZrH_2$ (Zirconium Hydride)
$HfH_2$ (Hafnium Hydride)
$B_4C$ (Boron Carbide)
Ta (Tantalum)
$GdO_3$ (Gadolinium Oxide)

# VNS Inboard Shielding Studies



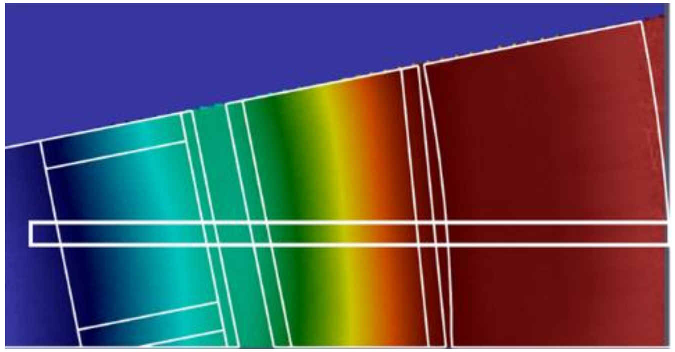




## Selection of promising options

- W-based materials provide best generic options
- Use of SS304B7 to replace SS316

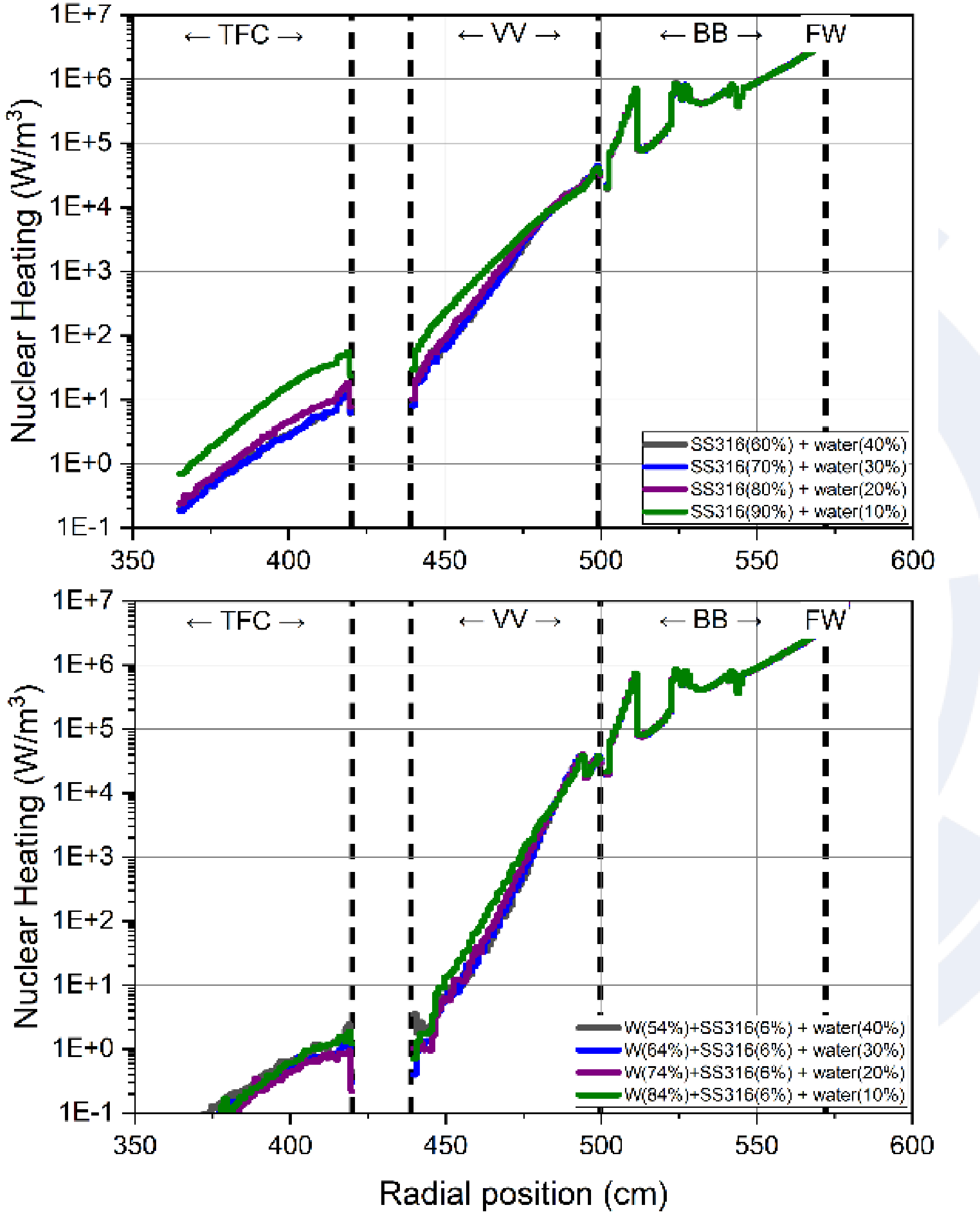
- TFC protection is feasible with sufficient margins.

# DEMO Inboard Shielding Studies



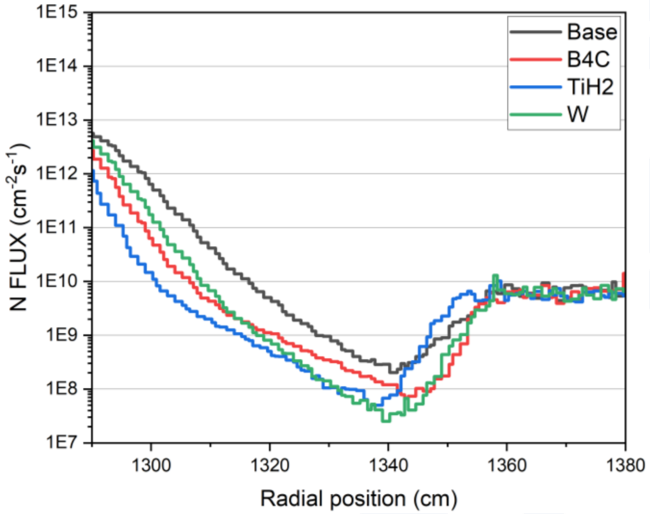
Radial profiles of nuclear responses

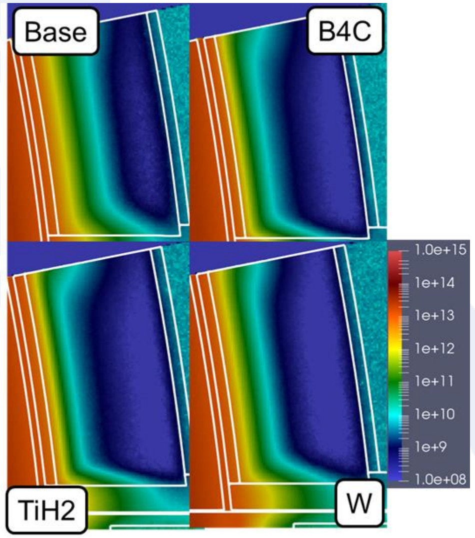
- Adopting lessons learnt from VNS studies
  - Confirm radial build and VV thickness, check margins.
  - Note: Breeding Blanket with modest attenuation!
  - Note: neutron spectrum moderation different at VV entry!
- Shield options
  - Steel/water, with additional SS304B7: convenient choice for moderate demands.
  - W/$TiH_2$ slabs at highly loaded locations
  - Water cooled breeding blanket provide additional margin.



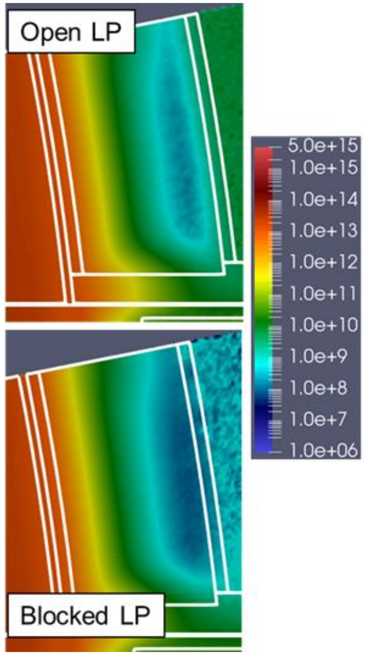
# DEMO Outboard Shielding Troubles …

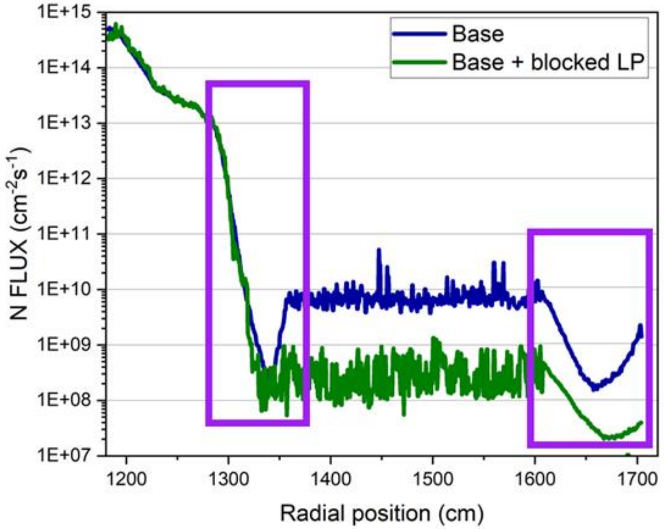
- No continuous flux attenuation!
  - Neutron streaming through penetrations and ports.
  - Lower pumping port leakage (without proper shielding) spoil ex-vessel shielding efforts.



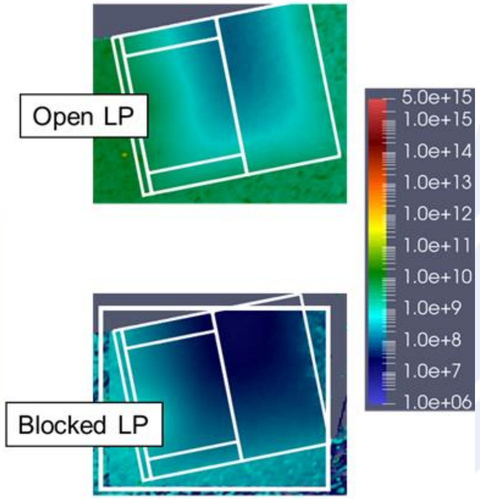




- Isolation of bulk shield performances
  - … by blocked lower port.
  - Neutron flux drops by factor 10…100
  - Bulk shield performance sufficient, but …
- **Shield weaknesses need to be addressed for any ex-vessel radiation shielding objectives**




N flux radial profile – HCPB base + blocked LP



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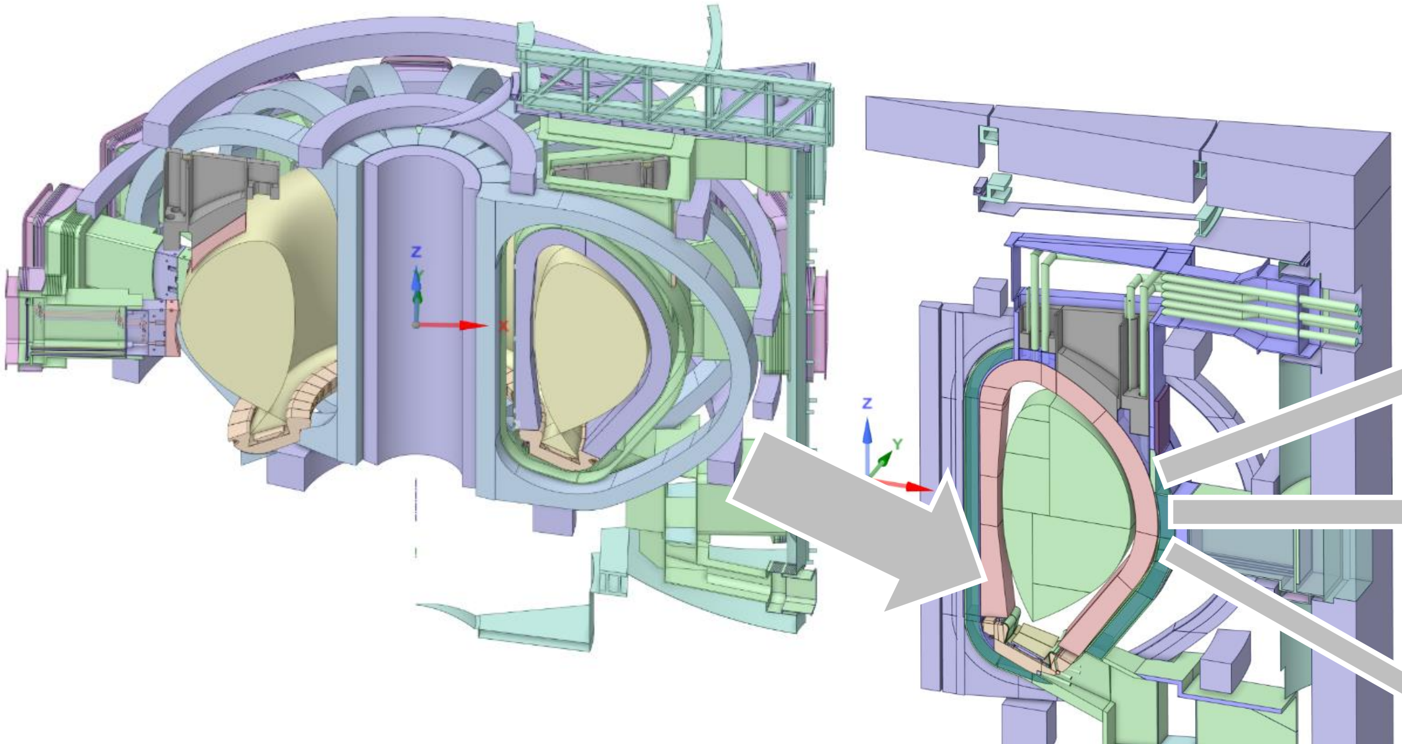
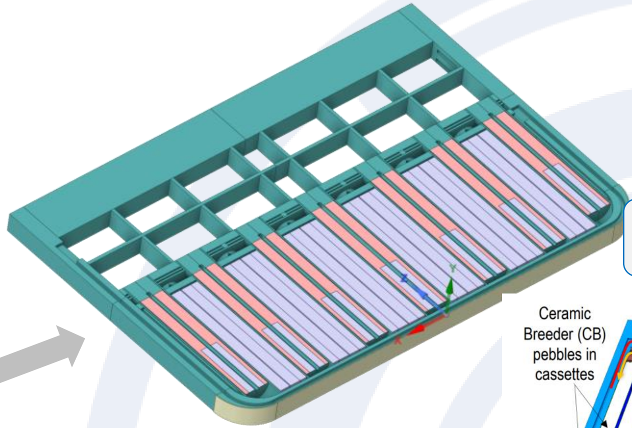
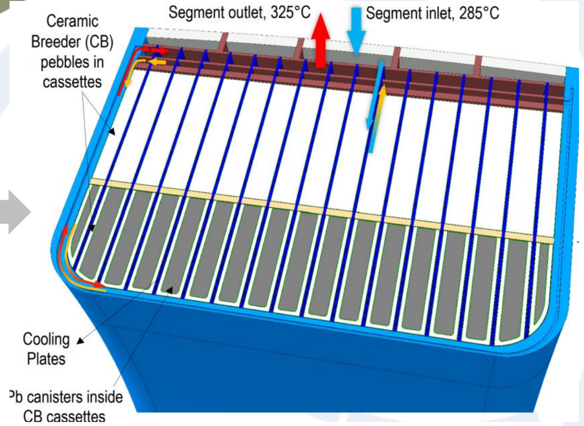
# DEMO Breeding Blanket Concepts

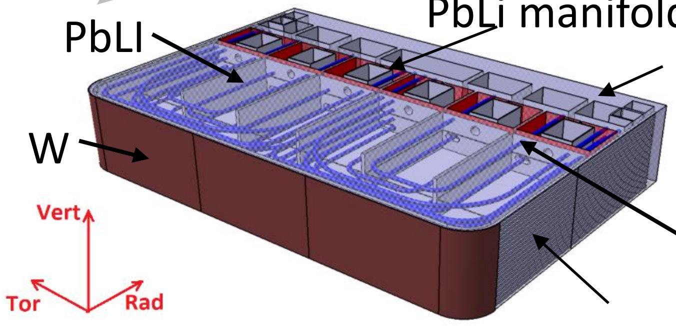


HCPB blanket



WLCB blanket




WCLL blanket

**DEMO baseline (2017-2019)**

- New baseline 2024: DEMO LAR

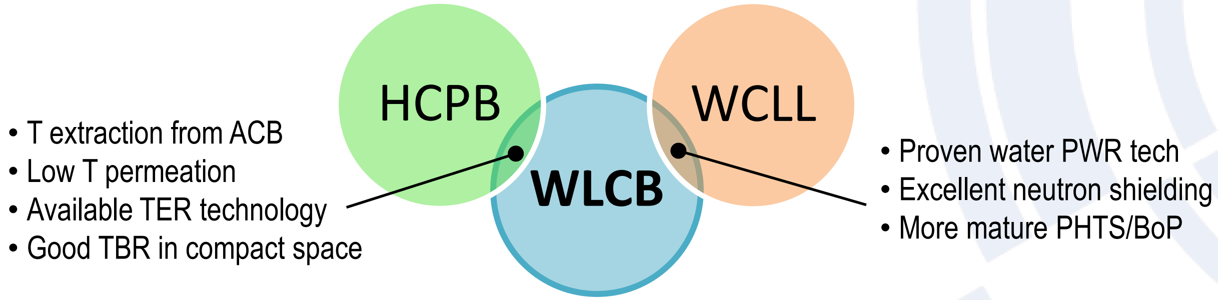
- Breeder blanket space evelope is the same for all DEMO concepts.
- Baseline configuration and machine architecture applicable for implementation of specific BB designs.

# DEMO Breeding Blanket Concepts

**Three blanket concepts are currently developed in the European DEMO fusion programme**

I. Based on a **liquid breeder** technology: **WCLL** (Water Cooled Liquid Lead)
- *PbLi eutectic is used as a neutron multiplier and tritium breeder ($^6$Li enrichment 90%)*
- *Water (155 bar) is used as a coolant*

II. Based on a **solid breeder** technology: **HCPB** (Helium Cooled Pebble Bed) concept.
- *Solid breeder ceramic ($Li_4SiO_4$ + 35%mol. $Li_2TiO_3$, $^6$Li enrichment 60%)*
- *$Be_{12}Ti$ manufactured as blocks is used as neutron multiplier.*
- *He gas (2 bar) is used as a coolant and purge gas*




III. Based on a **hybrid** technology: **WLCB** (Water cooled Liquid lead Ceramic Breeder) concept.
- *Water (155 bar) is used as a coolant*
- *Liquid lead as a neutron multiplier*
- *Solid ceramic ($Li_4SiO_4$ + 35%mol. $Li_2TiO_3$, $^6$Li enrichment 90%)*

# Blanket Neutronics Objectives

**Tritium self-sufficiency capability:**

- Required Tritium Breeding Ratio (TBR) (accounting for uncertainties in neutronics assessment)
- $TBR_{target} = TBR_{required} + \Delta_{uncertainties}$; 1.15 = 1.05 + 0.10

**Power handling capabilities**: power deposition and nuclear heat mapping

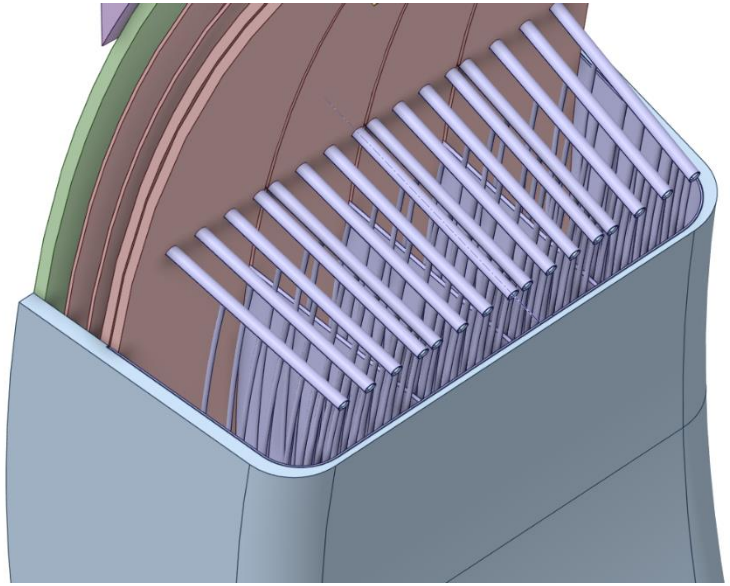
- Global power deposition (energy multiplication factor)
- Mesh data of nuclear heat densities for downstream analyses

**Shielding capabilities**: radial profiles for flux densities, nuclear heat density, and dpa

- VV: lifetime dpa accumulation, nuclear heating (target)
- TFC: nuclear heating in winding pack, absorbed dose to insulator
- Estimation of bulk shield performance of BB&VV system for ex-vessel shielding objectives

# Breeding Blanket Performance

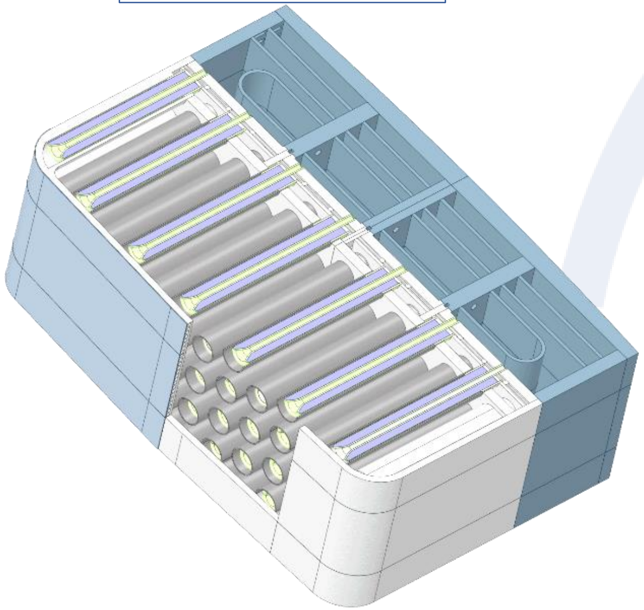
**WCLL-db**



**TBR=1.15**

- Tritium self-sufficiency:  possible
- Nuclear performances:   not optimal
- Shielding performance: good
- Improvements:
  - *Geometry optimization difficult*
  - *New materials not possible*

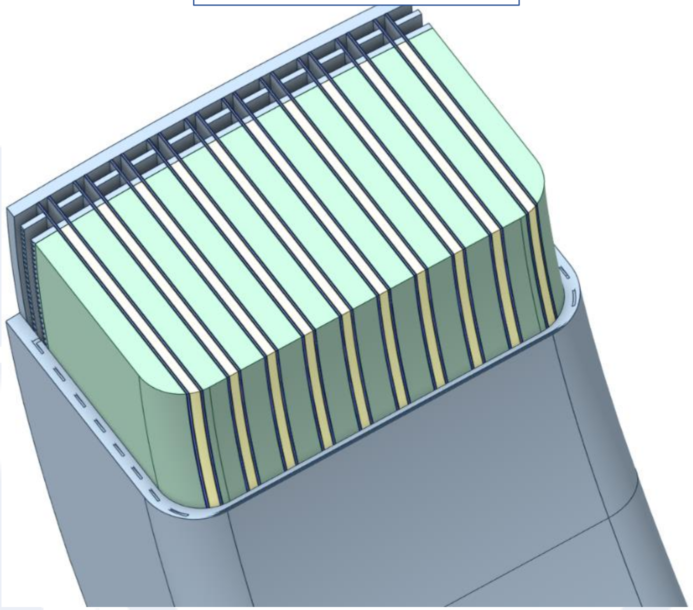
**HCPB**



**TBR=1.17**

- Tritium self-sufficiency:  yes
- Nuclear performances : very good
- Shielding performance: weak
- Improvements:
  - *Geometry optimization*

**WLCB**



**TBR=1.14**

- Tritium self-sufficiency:  likely
- Nuclear performances : not optimal
- Shielding performances: good
- Improvements:
  - *Geometry optimization*
  - *New breeder ($Li_8ZrO_6$ or $Li_8PbO_6$)*
  - *Gas coolant (He or $CO_2$)*

# TBR Uncertainties: Nuclear Data Uncertainties

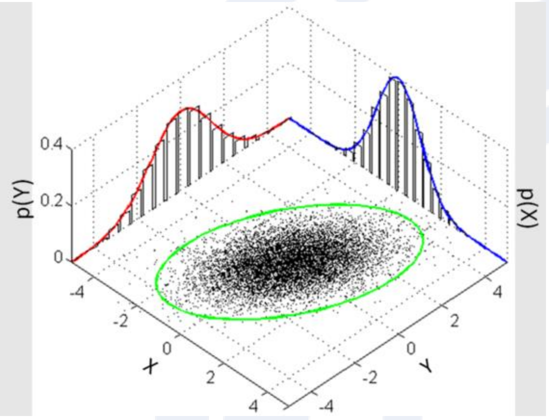
**Propagating basic nuclear data uncertainties to TBR**

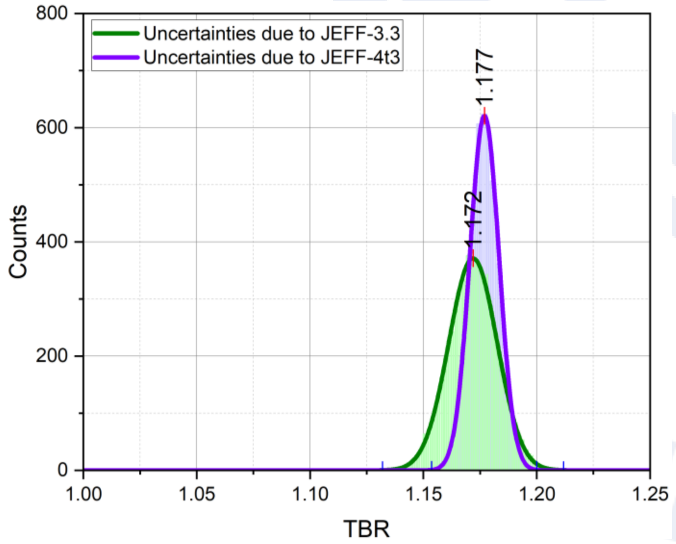
- Originating from data evaluation procedure and model defects.
- Distributions given as covariance matrices.

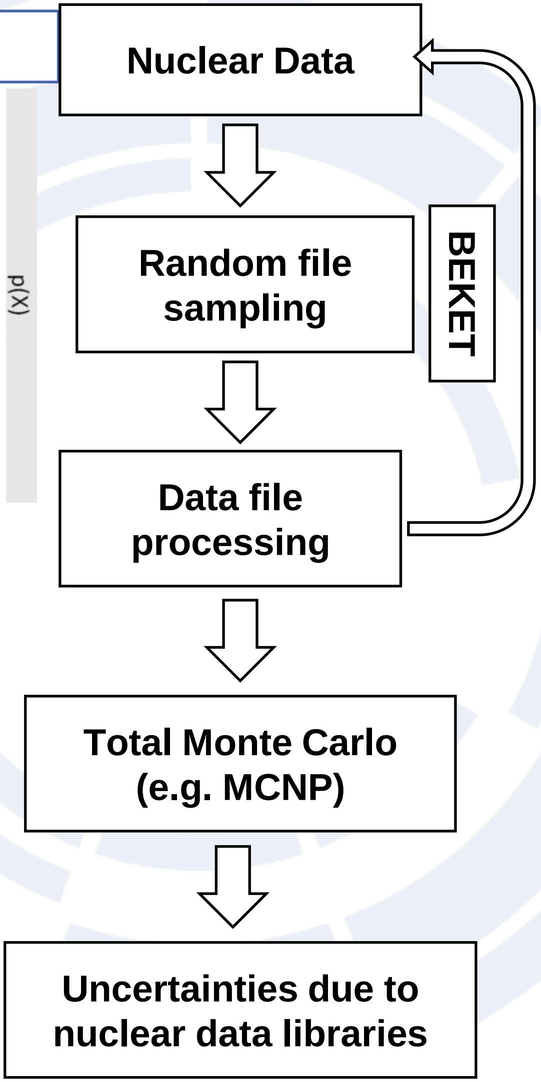
- Random nuclear data sampling
  - Total 139,500 random files
- Total Monte Carlo methods
  - Use randomly selected random libraries for each simulation
  - Each case utilized **10000 simulations**

| Nuclear data library | TBR | 2σ deviation |
| --- | --- | --- |
| JEFF-3.3 | 1.172 | 2.13 (%) |
| JEFF-4t3 | 1.177 | 1.28 (%) |

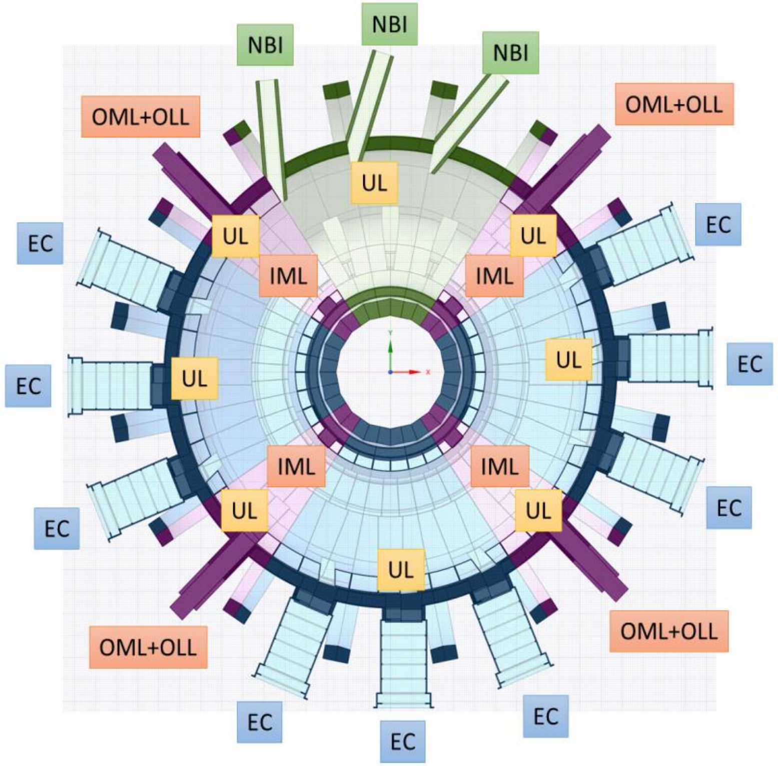
Probability density function

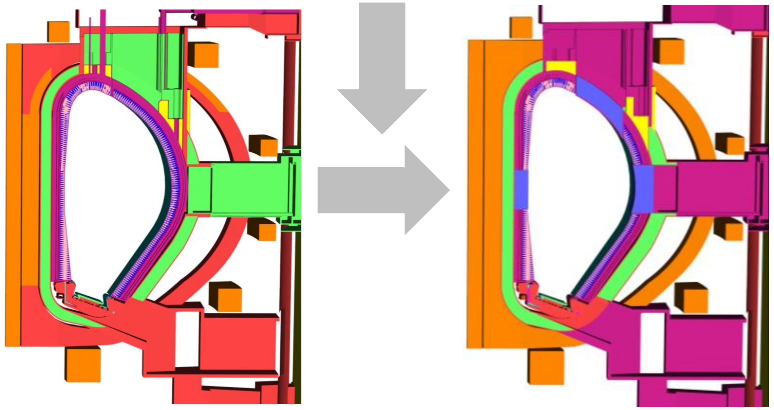


# TBR Uncertainties: Design Integration and Modelling Approach

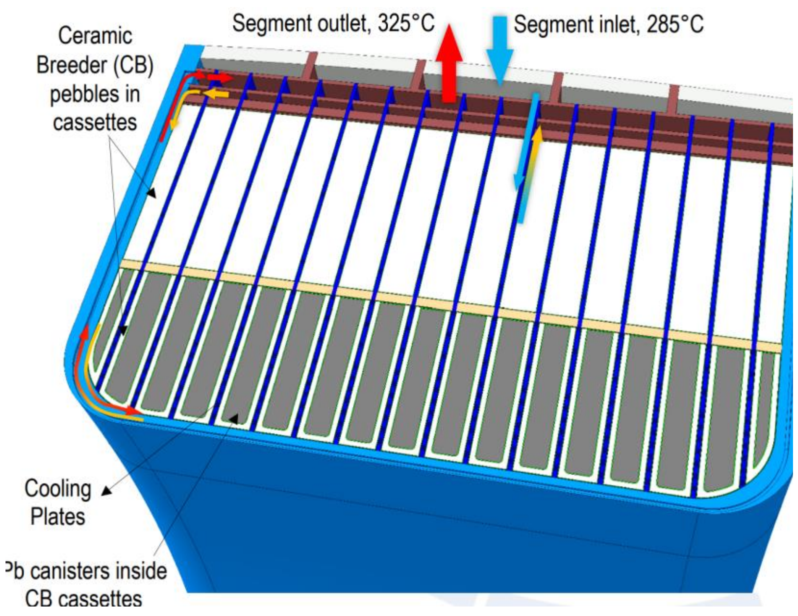


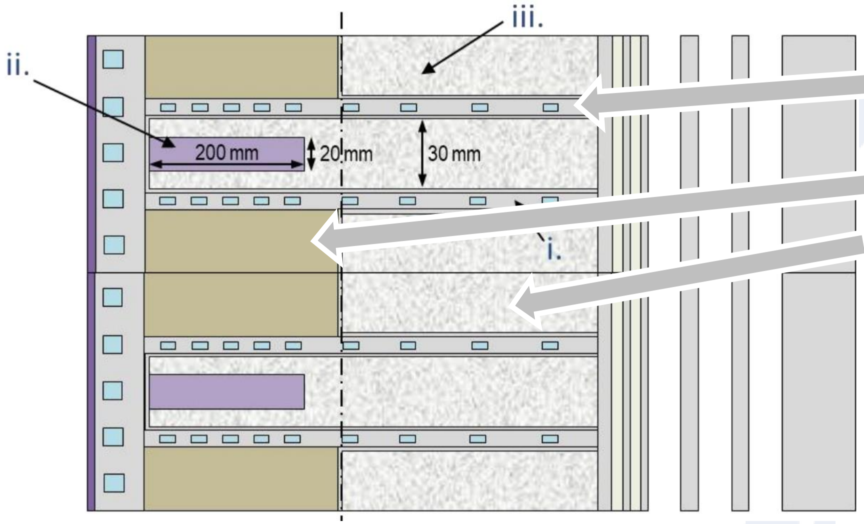



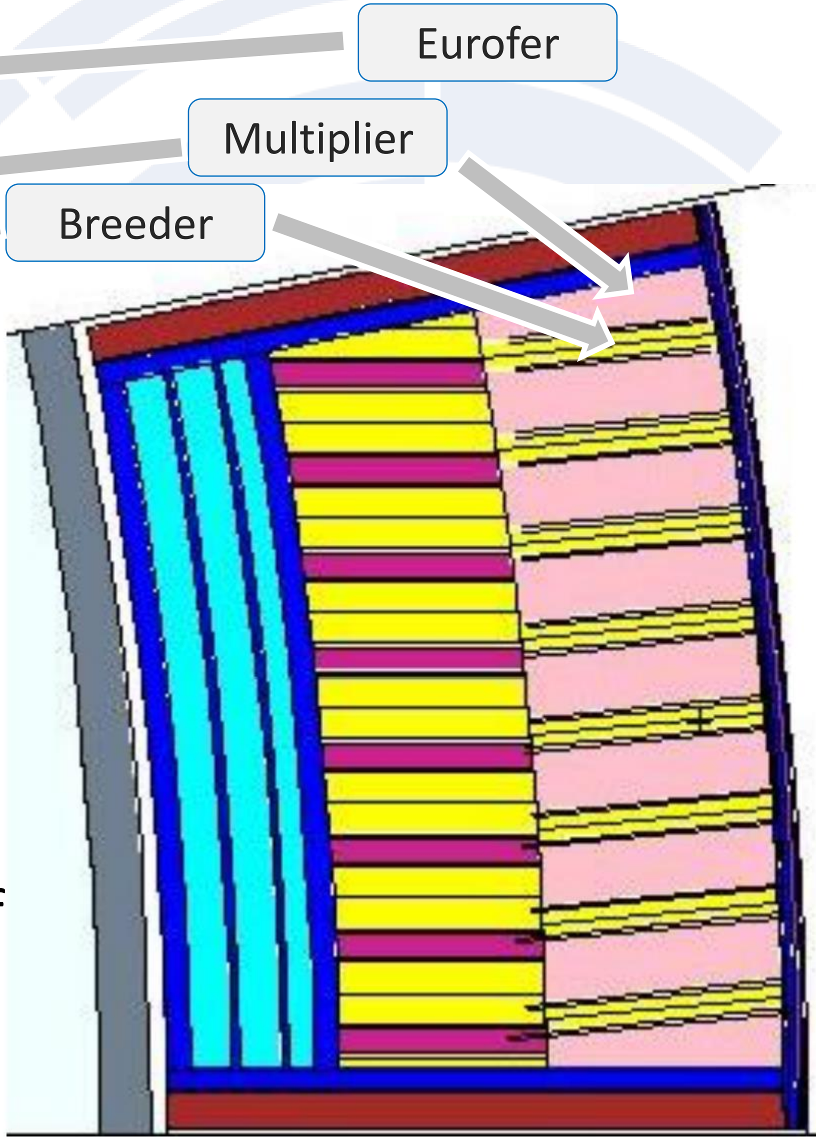
- TBR assessment taking account of realistic blanket coverage
  - In-vessel components (IVC): Port allocation and limiter system distribution assumed and implemented in 360° torus model.
  - Relative TBR loss per IVC integration.
- Design Integration: ΔTBR 9…11%
- Heterogeneous model approach: ΔTBR ca. 1-2%

| | Homogeneous HCPB | | Homogeneous WCLL | | Heterogeneous HCPB | | Heterogeneous WCLL | | Heterogeneous WLCB | |
|---|---|---|---|---|---|---|---|---|---|---|
| | δTBR single IVC | δTBR 360° Tokamak | δTBR single IVC | δTBR 360° Tokamak | δTBR single IVC | δTBR 360° Tokamak | δTBR single IVC | δTBR 360° Tokamak | δTBR single IVC | δTBR 360° Tokamak |
| **EC** | 0.272 | 2.448 | 0.261 | 2.350 | 0.218 | 1.966 | 0.266 | 2.397 | 0.185 | 1.661 |
| **NBI** | 0.160 | 0.480 | 0.240 | 0.720 | 0.218 | 0.655 | 0.266 | 0.799 | 0.185 | 0.554 |
| **UL** | 0.612 | 4.896 | 0.499 | 3.990 | 0.517 | 4.135 | 0.440 | 3.522 | 0.503 | 4.022 |
| **IML** | | | | | 0.192 | 0.767 | 0.212 | 0.848 | 0.165 | 0.662 |
| **OML** | 0.773 | 3.092 | 0.803 | 3.210 | 0.373 | 1.492 | 0.386 | 1.544 | 0.299 | 1.196 |
| **OLL** | | | | | 0.373 | 1.492 | 0.386 | 1.544 | 0.299 | 1.196 |
| **Total in tokamak** | | **10.916** | | **10.270** | | ***10.507*** | | ***10.653*** | | ***9.292*** |

# TBR Optimization Studies (WLCB)



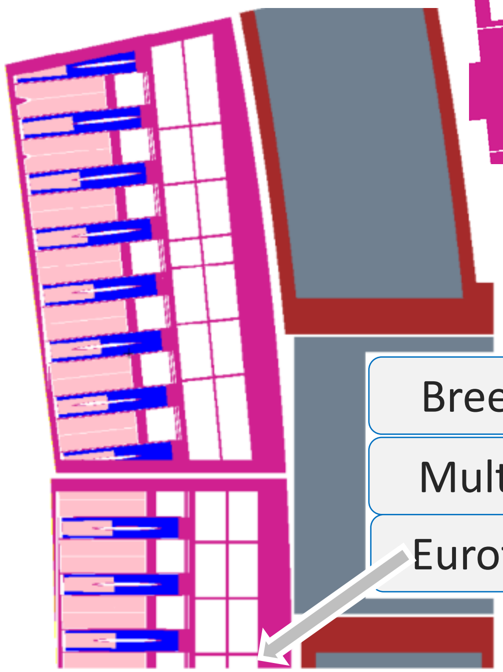



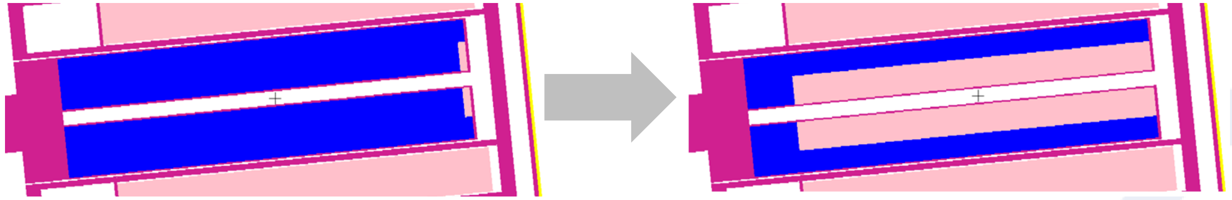

- Geometrical optimisation (breeder, multiplier, structure, coolant)
- Material optimisation (new breeder ceramics, reduction of Beryllide, …)
- Achieving margin beyond $TBR_{required}$

# TBR Optimization Studies (WLCB)

| Design option | Rationale | ΔTBR |
|---|---|---|
| Substitution of front ACB with OLP | Higher Li-density | +0.04 |
| Modification of the cooling plates | Higher water content | <+0.01 |
| Lower density (porous) of front Pb | Lower effective Pb density | -0.02-0.04 |
| Front unit layout (Pb layer thickness) | Optimized Breeder/Multiplier | +0.02 |
| Application of optimized front unit to rear zone | Optimized Breeder/Multiplier | +0.01 |
| Use of ACB in the rear zone without n-multiplier | Avoid Beryllide | -0.01 |
| Use of Pb, C and ZrH2 in the rear zone instead of beryllide | Avoid Beryllide | -0.01-0.03 |
| Use of 100% OLP in the rear zone and mixture of 50% ACB + 50% OLP in the front | Optimized breeding capacity | +0.02 |
| Cooling plate thickness from 5 mm to 7-8 mm | Thermohydraulic demands | -0.01-0.02 |
| FW modifications with additional 1 cm layer ACB | Enhancing front breeding | +0.015 |
| Toroidal stiffener 2 cm steel | Mechanical stiffening | -0.015 |

# TBR Optimization Studies (HCPB)

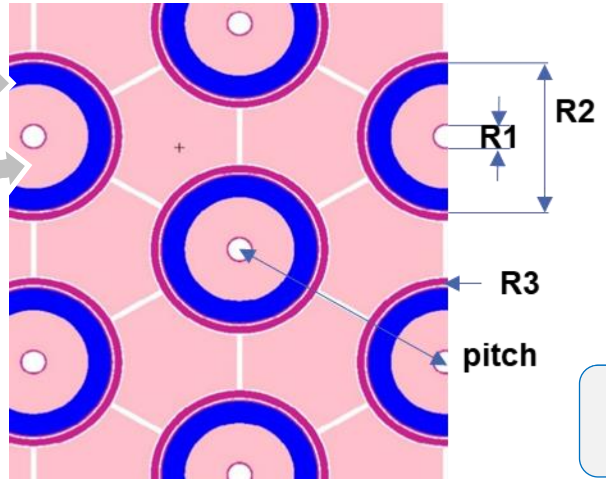


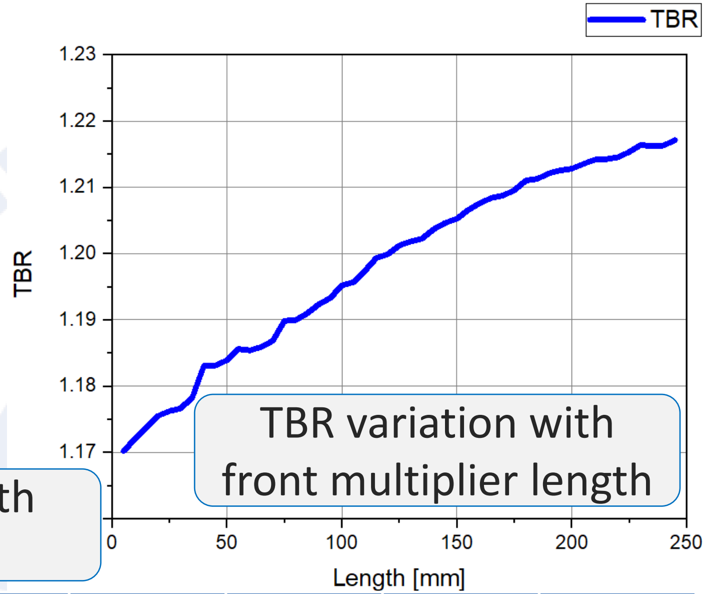


Breeder

Multiplier

Eurofer



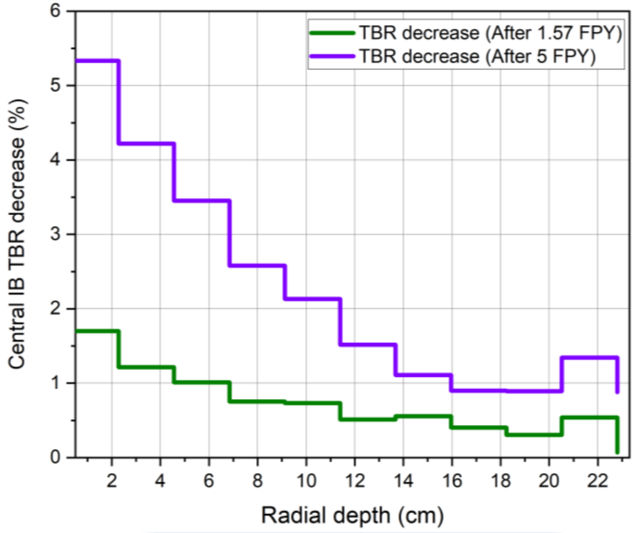




TBR variation with front multiplier length

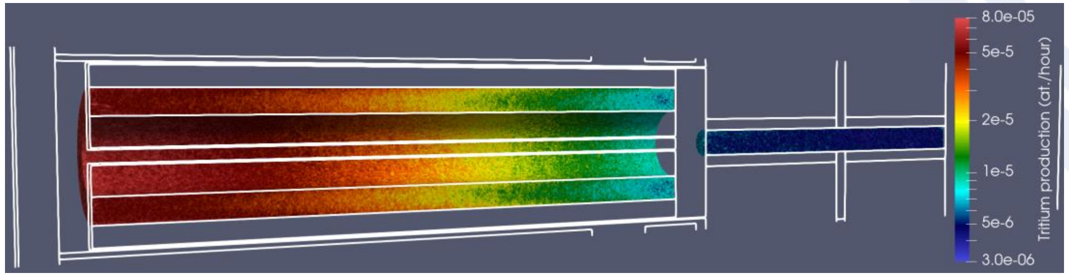
TBR variation with pitch distance

| Pitch(mm) | 130 | 128 | 126 | 124 | 122 | 120 |
|---|---|---|---|---|---|---|
| TBR | 1.133 | 1.160 | 1.172 | 1.184 | 1.194 | 1.204 |

TBR reduction due to $^{6}$Li burnup




Tritium generation density along breeder pin



# Content

- Introduction
  - EU DEMO and VNS
- Neutronics Framework for DEMO Design
  - Methodology, tools, data
- Conceptual Shielding Efforts
  - Protection objectives
  - VNS experiences
  - DEMO tokamak examples
- DEMO Breeding Blanket Neutronics
  - BB concepts overview
  - TBR optimisation, uncertainties
- **Conclusions**

# Summary and conclusions

- Neutronics studies are extensively deployed throughout DEMO (and VNS) conceptual design activities.
- Radiological protection requirements are (partially) design drivers.
  - Protection of TFC (nuclear heating, absorbed dose): Inboard shielding with sufficient margins by advanced shield materials
  - Ex-vessel radiation: bulk shield performances are reasonable, but dedicated effort required to cover neutron leakage pathways
- Breeding Blanket objectives are crucial for DEMO and  realization of fusion power plants
  - Near-term blanket concepts are developed (HCPB, WCLL, WLCB).
  - TBR targets are set to compensate for neutronics modelling and nuclear data uncertainties.
  - TBR optimization studies provide insight into attractive design variants.
- DEMO conceptual architecture and critical system designs need to provide sufficient margins for achieving protection and nuclear performance objectives.

## FAIRNESS

Transparency

Collaboration

Loyalty

## OPENNESS

Open doors

Open hearts

Open minds

Open ears

## COMMITMENT

Ownership

Critical thinking

Determination

Respect

## DIVERSITY

Cooperation

Equal opportunities

Inclusion