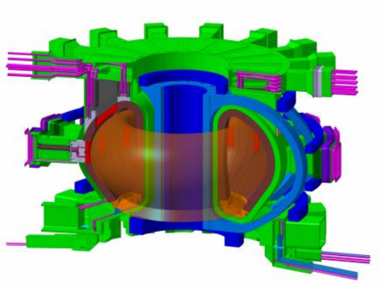

EUROfusion

Required, Achievable and Target TBR for the European DEMO

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KIT Karlsruhe Institute of Technology | EUROfusion | CCFE CULHAM CENTRE FOR FUSION ENERGY | ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

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Outline

- Introduction
- Tritium balance $\Rightarrow$ Required TBR
- Tritium breeding potential $\Rightarrow$ Achievable TBR
- TBR design target and margins
- TBR performance of driver blankets
- Summary & Conclusions

Introduction

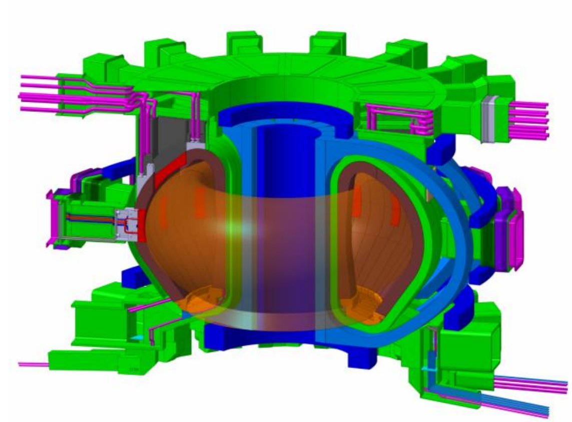
- **European Fusion Roadmap**
  - Development of **DEMO**nstration fusion power plant central element

⇒ *Conducted by **EUROfusion** Consortium in **Power Plant Physics and Technology (PPPT)** programme*

⇒ *<u>Objective:</u> To demonstrate **tritium** breeding capability, produce **net electricity**, provide **technologies** for commercial fusion power plant*

- **DEMO power plant**
  - D-T tokamak, fusion power ~ 2 GW → ~ 111 kg T per full power year (fpy)
  - No external sources available/conceivable to provide required T

⇒ ***DEMO must breed required tritium***
→ tritium self-sufficiency strict pre-condition!



Courtesy of EUROfusion/PPPT, PMU Garching, May 2019

Introduction

- **Tritium breeding requirement for DEMO**
  - Tritium Breeding Ratio (TBR) $\geq$ 1.0 to ensure one triton per D-T reaction is produced in breeding blankets and available for injection in plasma

    $\Rightarrow$ *To be demonstrated by appropriate neutronics calculations, validated as far as possible against integral experiments*
  - But: uncertainties margins to be added :
    - T loss budget of fuel cycle
    - Uncertainties in neutronics simulations for DEMO

  $\Rightarrow$ **TBR in excess of unity** to be demonstrated (by simulations)
    - How much excess ? → Defines required TBR_{req}
    - To be assessed for DEMO on the basis of neutronics & fuel cycle considerations

<u>This work:</u>

$\Rightarrow$ *Up-to-date assessment of TBR requirement for DEMO*

$\Rightarrow$ *Evaluation against TBR performance achievable for DEMO*

Tritium balance and required TBR

- **Basic requirement for T self-sufficiency: TBR ≥ 1.0**

  ⇒ *Defines net TBR which is to be achieved to enable continuous DEMO operation without external tritium supply*

- Actually: **TBR = 1.0 +** Δ_{FC} to be achieved

  Δ_{FC} = uncertainty margin due to T loss budget of Fuel Cycle (FC)

  – T decay, sequestration & trapping, build-up of T reserves to ensure DEMO operation in all conditions and, possibly, provide T start-up for another D-T power plant

- *Previous assumption for DEMO(*):*

$$\Delta_{FC} = 0.05 \rightarrow TBR_{req} \geq 1.05$$

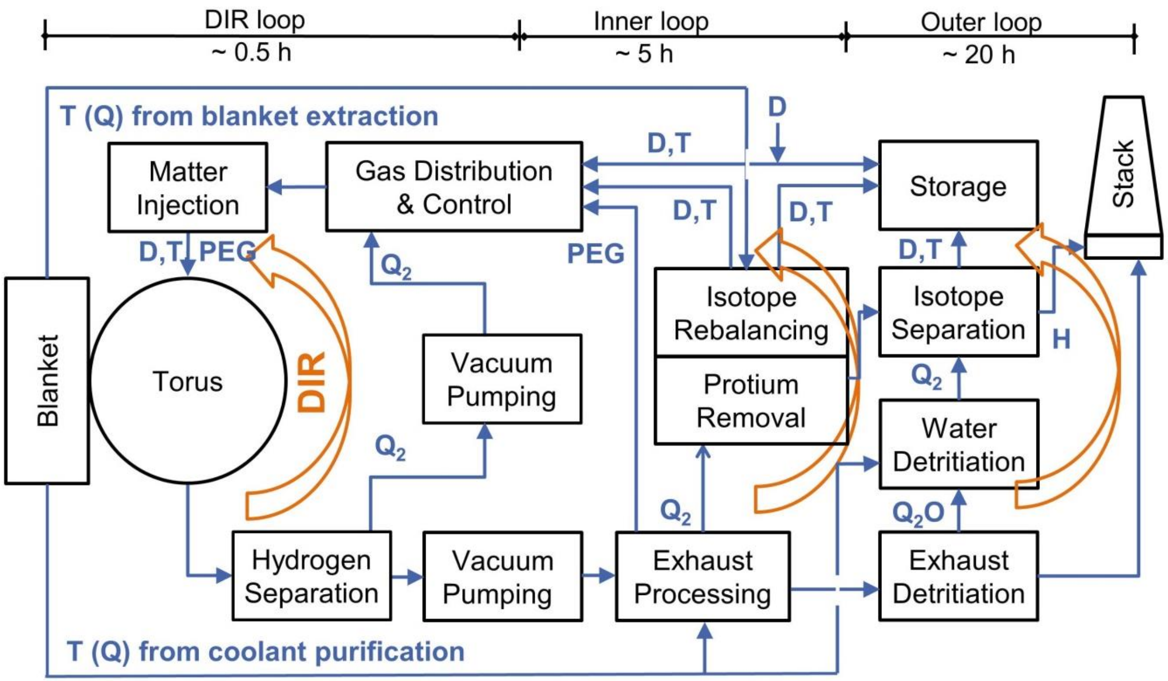
  – Based on "pre-DEMO" studies without further justification or supporting analysis

(*) *U. Fischer, C. Bachmann, I. Palermo, P. Pereslavtsev, R. Villari, Neutronics Requirements for a DEMO Fusion Power Plant, FED 98–99 (2015) 2134–2137*

Tritium balance and required TBR

- **European DEMO (PPPT)**

  Advanced Fuel Cycle concept based on Direct Internal Recycling (DIR)(*)



⇒ Continuous processes in inner tritium loop with direct recycling of plasma exhaust gas to the fueling system, i.e. no separation of the D-T fuel constituents.

⇒ **Significantly reduced D-T cycle times and tritium inventories**, can relax the TBR requirements for same performance.

(*) C. Day, T. Giegerich, The Direct Internal Recycling concept to simplify the fuel cycle of a fusion power plant, FED 88(2013), 616-620

Tritium balance and required TBR

- **Advanced FC simulations exploring DEMO design space (*)**
  - Dedicated fuel cycle model for variety of potential DEMO timelines subjected to randomized selection process
  - Takes into account DIR fuel cycle and varies a rich set of FC parameters and load factors
  - **Includes the requirement DEMO must produce sufficient tritium for starting another FPP during its lifetime**

⇒ TBR and load factor are dominant parameters affecting reactor doubling time t_D ; no significant effect on T start up inventory m_{start}.

⇒ DIR Fuel Cycle results in reduction of m_{start} by factor 3.

⇒ **Recommended minimum requirements for DIR fraction (≥0.6), target load factor (≥0.2) and TBR (≥ 1.05)**

- Close to current assumptions for DEMO: DIR fraction = 0.8, target availability = 0.3, and TBR≥ 1.05 (→ m_{start}= 5.6 kg, T_D = 12.9y)

(*) *M. Coleman, Y. Hörstensmeyer, F. Cismondi, DEMO tritium fuel cycle: performance, parameter explorations, and design space constraints, Fusion Eng. Des. 141 (2019) 79–90*

Tritium balance and required TBR

Based on these findings, assuming that the DIR fraction and availability target are met, the TBR required for DEMO is set to:

$$\mathbf{TBR_{req} \geq 1.05} \qquad \text{– as previously specified !}$$

<u>Notes:</u>

(1) TBR_{req} defines the amount of tritium to be provided to the Fuel Cycle from the breeding blanket system.

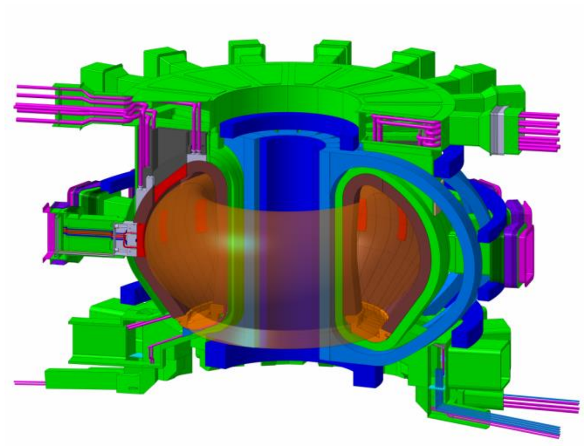
(2) Requirement can be relaxed if DEMO must not feed another power plant (provision of Tritium start-up inventory)

- ***<u>Very recent PPPT strategical change</u>: "DEMO shall aim to provide a considerable fraction of the tritium required for the start-up of another fusion plant"***

⇒ ***Consequences on quantification of TBR requirement to be analysed by FC simulations, reduction to 1.02 – 1.03 possible***

⇒ Requirement to neutronics: To be demonstrated, if and how requirement can be fulfilled

Tritium breeding potential of DEMO



- DEMO conceived as Component Test Facility (CTF) with driver blankets
  - Helium Cooled Pebble Bed (HCPB) blanket
  - Water Cooled Lithium Lead (WCLL) blanket
  - RAFM steel Eurofer structural material

- PPPT strategical approach: DEMO baseline configuration equipped with HCPB or WCLL blanket must fulfil TBR requirement
  - To be proven by neutronics simulations → ***calculated TBR***
  - Achievable TBR_a subject to neutronics design evaluation and optimization
  - Calculation of TBR_a involves several sources of uncertainties that need to be taken into account to make sure the calculated TBR_a is reliable.

TBR calculation approach in PPPT

- **Calculation of global TBR:**
  - Monte Carlo (MC) particle transport simulation with validated MC codes and nuclear data, using suitable 3-D torus sector model, as prescribed in PPPT neutronics guidelines
  - Torus sector model (22.5°/11.25°) derived from CAD model of DEMO baseline tailored to neutronics needs.
  - Conversion to MC simulation model with suitable conversion software (McCad)
  - Integration of HCPB or WCLL blanket modules/segments for full DEMO model.

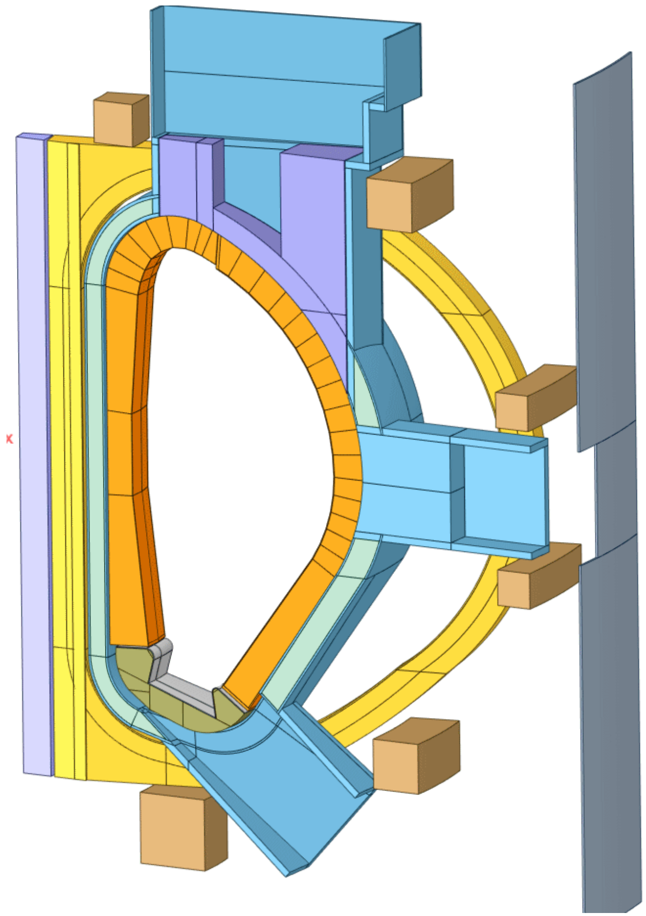
  ⇒ *Blanket model to be consistent with engineering design and satisfy neutronics requirements including sufficient details (heterogeneities!)*
  - Model does not include blanket cut-outs, ports, penetrations, etc., as required for the installation of auxiliary systems, plasma heating and control, diagnostics and fueling, or use of limiters.

  ⇒ *Effects to be investigated with additional ("extra") analyses using dedicated model (ideally 360°, with all systems integrated) → running PPPT activity*

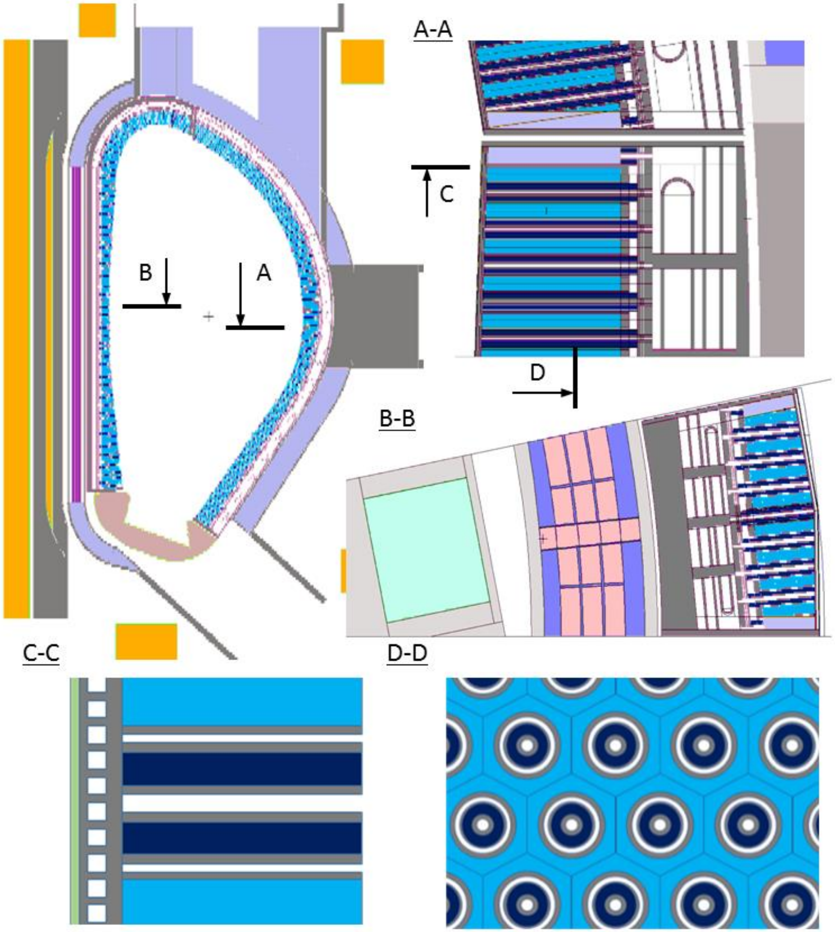
TBR calculation approach in PPPT

MCNP simulation model generated for HCPB DEMO

CAD model DEMO baseline 2017



Generated MCNP model (2D cuts)



TBR calculation approach in PPPT

- TBR calculation must demonstrate: $\mathbf{TBR_a \geq TBR_{req}}$
- Calculated TBR is for ideal case of Torus Sector (TS) with no non-breeding systems installed (except divertor).

$\Rightarrow$ **PPPT pragmatic approach:**

- Calculate TBR for ideal case (TS only with breeding blankets)
- Assess and optimize TBR against a specified target value $\mathbf{TBR_{target}}$

$$\mathbf{TBR_{target} = TBR_{req} + \Delta_{DM} = TBR_{req} + \Delta_{US} + \Delta_{CM}}$$

Δ_{CM} : DM accounting for incomplete Computational Model (CM) due absence of non-breeding systems TBR calculations

Δ_{US} : DM accounting for all other Uncertainty Sources (US) involved in TBR calculation (e. g. nuclear data, Li burn-up, design/modelling uncertainties).

TBR design target and margins for DEMO

- **TBR design target for DEMO** previously set to $\mathbf{TBR_{target} \geq 1.10}$(*)
  - ⇒ *Used in PPPT for evaluation and optimization of breeding blanket*

⇒ Re-consideration with objective to provide update of $\mathbf{TBR_{target}}$ applicable for current DEMO, baseline 2017, with driver blankets.

$$\mathbf{TBR_{target} = TBR_{req} + \Delta_{US} + \Delta_{CM}}$$

<u>Discussion of TBR margins</u>

- Δ_{CM}: Accounts for incompleteness of applied model (no auxiliary non-breeding systems, limiters, ports , except divertor port, taken into account)
  - Previously assigned 5% based on then poor knowledge of number and dimensions of blanket openings/ports assumed for DEMO
  - ⇒ *Limitation for first wall area not covered by breeding blankets: ~3 to 5%.*
  - ⇒ ***<u>Recommendation (then):</u>*** *Increase margin in case a larger non-breeding area is required for DEMO*

(*) U. Fischer, C. Bachmann, I. Palermo, P. Pereslavtsev, R. Villari, Neutronics Requirements for a DEMO Fusion Power Plant, FED 98–99 (2015) 2134–2137

TBR design target and margins for DEMO

Δ_{CM} (cont'd)

- DEMO 2017: Various systems considered which are deemed necessary for integration (heating systems, current drive and control, diagnostics, …)

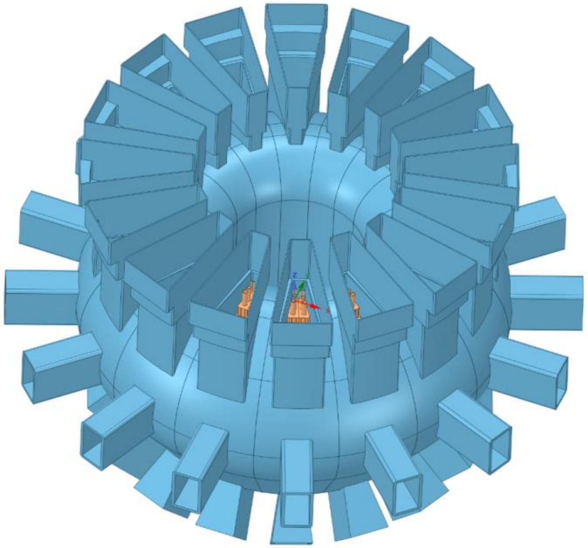
Current assumption:

System	Surface area [m^2]	Limiters	Surface area [m^2]
3 neutral beam (NB) ducts, ~1.3 m^2 each	4	4 equatorial, ~3 m^2 each	12
4 Electron-cyclotron (EC) launchers, ~4 m^2 each	16	4 inboard, ~2.5 m^2 each	10
5 diagnostic plugs, ~4 m^2 each	20	4 lower mid-plane, ~3 m^2 each	12
8 upper port plugs, ~1 m^2 each	8	8 upper port, ~4.5 m^2 each	36
Total	48		70

- DEMO first wall area = 1473 m^2

  $\Rightarrow$ (48 + 70) m^2 /1473 m^2 = 8% of first wall covered with non breeding elements

TBR design target and margins for DEMO



Δ_{CM} (cont'd)

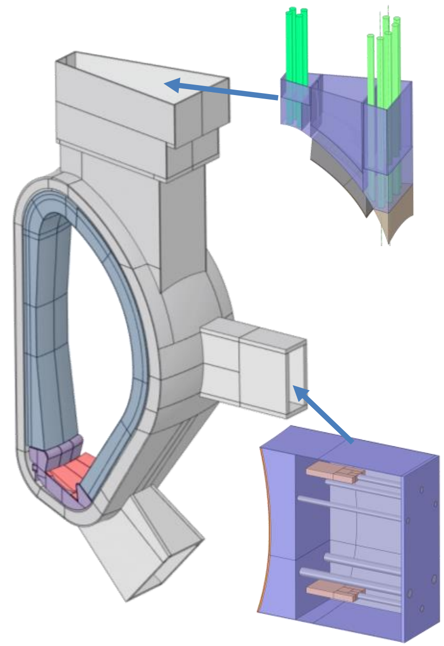
- Integration of non breeding systems in 360° DEMO model underway to provide better estimate for Δ_{CM}
- Preliminary assessment based on correction factor (CF) approximation method for reduced FW coverage(*)
- CF = 1473 m^2/(1473 m^2 - 118 m^2) = 1.087

$$\Rightarrow \Delta_{CM} \sim 9\ \% \ \rightarrow \mathbf{TBR_{target} \sim 1.14}$$

⇒ However, still large uncertainty associated with Δ_{CM} (systems to be integrated, combined effect on TBR in 360° DEMO configuration)

⇒ Therefore conservative specification: $\mathbf{TBR_{target} \sim 1.15}$

- Δ_{CM} dominant contributor to Δ_{DM} : Strong need for accurate assessment !



(*)Checked with test calculation for 16 equatorial steel port plugs in 360° model: Very good agreement !

TBR design target and margins for DEMO

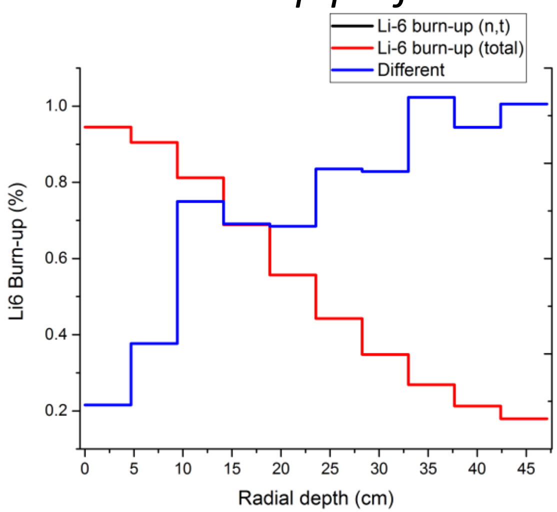
- Δ_{US}: Involves the following sources of uncertainty: nuclear data uncertainties, statistical uncertainties of MC calculation, uncertainties due to modelling and design assumptions, Li burn-up effect

Burn-up effect

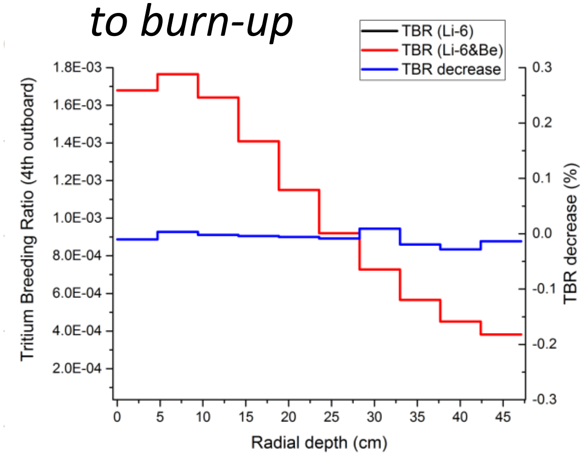
- Entirely negligible for WCLL blanket (Pb-Li circulation for T extraction, high ^{6}Li enrichment of 90 at%)
- Very modest for HCPB blanket with Li_4SiO_4 breeder and typical ^{6}Li enrichment of 40 at%: provisional assessment shows TBR reduction by ~0.13% per fpy

⇒ ***TBR reduction of 0.2 % and 0.6 % for DEMO first and second operation phases (1.57 and 4.43 fpy, respectively)***

Local burn-up profile



Local TBR reduction due to burn-up



TBR design target and margins for DEMO

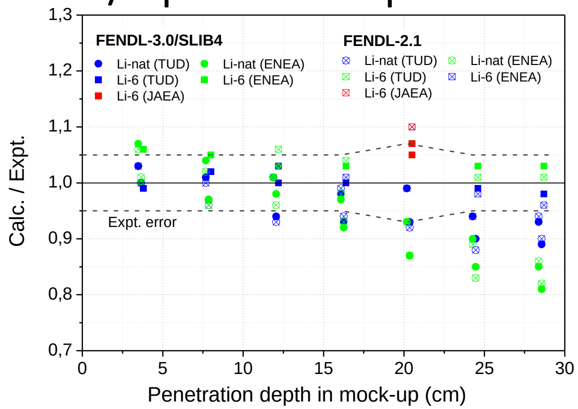
Nuclear data uncertainties Δ_{US} (cont'd)

- May have significant effect on TBR depending on blanket concept and materials
- HCPB blanket in DEMO: MC based uncertainty analysis shows TBR uncertainty of ± 3.2 % with JEFF-3.2 nuclear data(*)
- No such analyses available for WCLL blanket in DEMO; however, judgement that TBR uncertainty is very low due to low uncertainties of relevant Pb, Li cross-section data
  - Confirmed by integral experiment on HCLL mock-up blanket showing TBR uncertainties, due to nuclear data uncertainties, around ± 1- 2 % (**)
  - Measured T production rates predicted within 2 to 3% with reasonable fluctuations of C/E (calculation/experiment) around unity(**)

⇒ ***No extra uncertainty margin to be assigned to a TBR calculation of Pb_Li based blankets***

HCLL mock-up @FNG

C/E profile of T production



(*) E. Nunnenmann, U. Fischer, R. Stieglitz, Sensitivity and uncertainty analysis for the TBR of a DEMO fusion reactor with HCPB blanket, EPJ Web of Conferences 146, 09025 (2017)

(**) P. Batistoni et al., Neutronics experiments for uncertainty assessment of tritium breeding in HCPB and HCLL blanket mock-ups, Nuclear Fusion 52, 083014 (2012)

TBR design target and margins for DEMO

Nuclear data uncertainties Δ_{US} (cont'd)

- Integral experiment on HCPB breeding blanket mock-up, conducted previously @ Frascati Neutron Generator (FNG)(*)

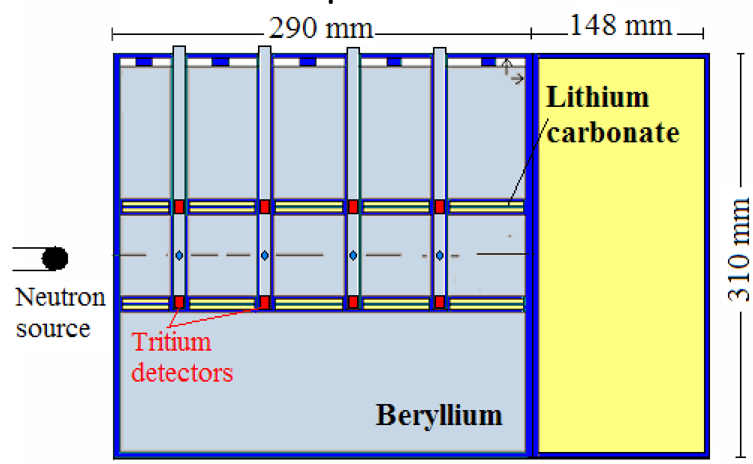
⇒ Systematic underestimation of measured tritium production in the order of 5 to 10%

⇒ Translates into underestimation of TBR calculated for HCPB blanket in DEMO

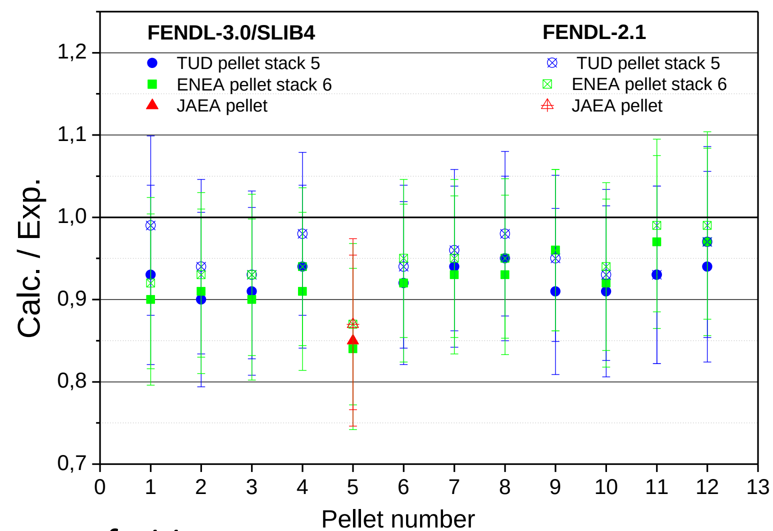
⇒ HCPB design calculations conservative: no extra uncertainty must be added to calculated TBR!

⇒ ***Based on results of available benchmark experiments (HCPB & HCLL) it is concluded that no extra uncertainty margin is to be assigned to a TBR calculation for DEMO***

HCPB mock-up



C/E profile of T production



(*) *P. Batistoni et al., Neutronics experiments for uncertainty assessment of tritium breeding in HCPB and HCLL blanket mock-ups, Nuclear Fusion 52, 083014 (2012)*

TBR design target and margins for DEMO

- As result of the previous discussions we judge the Δ_{US} margin to the TBR, compared to $\Delta_{CM,}$ as not significant.
- Δ_{US} is thus not considered when assessing the TBR for DEMO.
- Although there are still many uncertainties regarding the integration of non-breeding systems, limiters, etc. in DEMO, the Δ_{CM} margin is assumed to be at a level of ~0.1.
- As a consequence, the **TBR design target for DEMO** is set to:

$$\mathbf{TBR_{target} = TBR_{req} + \Delta_{CM} = 1.15}$$

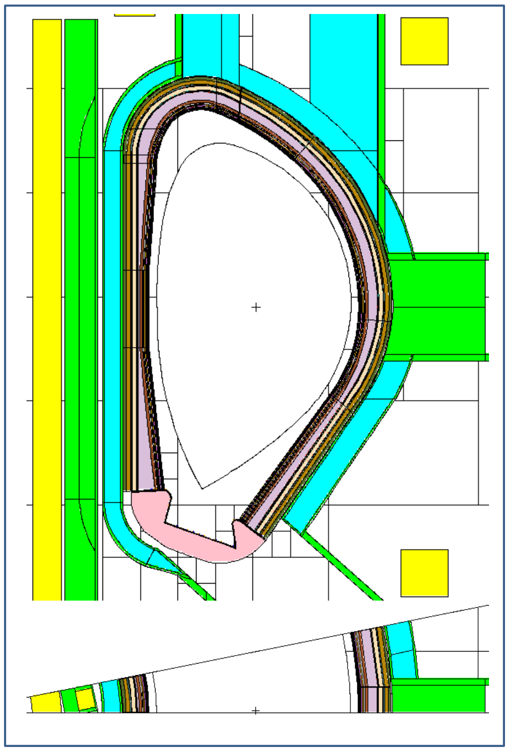
⇒ *To be re-evaluated once quantitative FC assessment is available for the case that DEMO must provide only "**a considerable fraction of the tritium required for the start-up of another fusion plant" → reduction to 1.12 – 1.13 possible.***

- It is recalled that this target value is set for a TBR calculated by a MC transport simulation with a "full BB TS" model (i. e. with no auxiliary systems, limiters, extra ports, etc.) and an appropriate representation of the blanket consistent with the engineering blanket design and in accordance with the neutronic requirements.

TBR performance of HCPB and WCLL DEMO

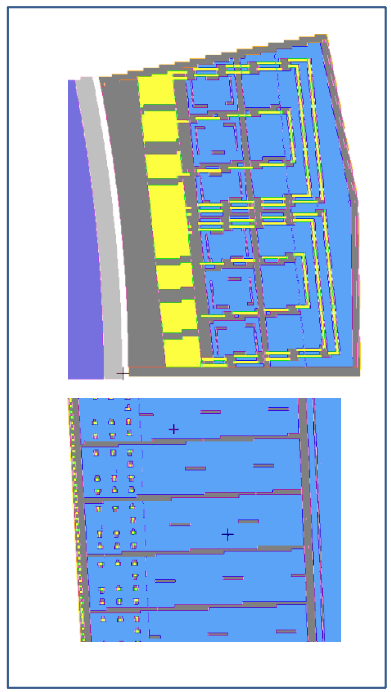
WCLL driver blanket – SMS (Single Module Segmentation) design, DEMO 2017 baseline

Torus sector model with radial layers (MCNP)



TBR = 1.12

Full heterogeneous torus sector model (MCNP)

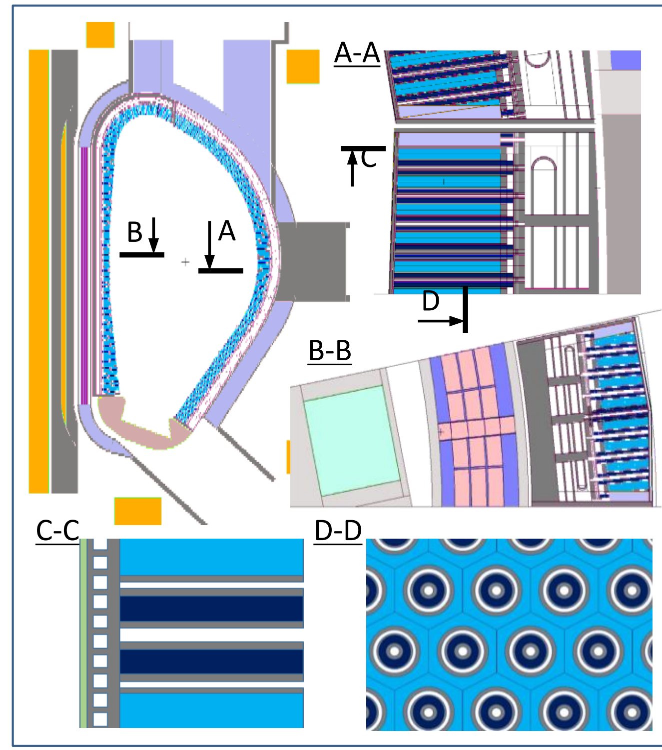


TBR = 1.10

?

HCPB driver blanket – SMS design, fission like fuel pins, $Be_{12}Ti$ neutron multiplier, DEMO 2017 baseline

Full heterogeneous torus sector model (MCNP)



TBR = 1.20

Summary & Conclusions

TBR requirements for DEMO reviewed and updated

- <u>Required TBR (Fuel Cycle) set to:</u>
  - **TBR_{req} = 1.05 assuming DEMO must provide tritium start-up inventory for another fusion power plant (FPP)**
  - ***Requirement can be relaxed if DEMO must only provide "considerable fraction of the tritium required for the start-up of another FPP" → to be analysed by FC simulations & quantified***

- <u>TBR design target (neutronics) set to:</u>
  - **TBR_{target} = 1.15 assuming DEMO must provide tritium start-up inventory for another FPP**
  - ***Relaxed requirement if DEMO must only provide "considerable fraction of the tritium required for the start-up of another FPP" → to be quantified***

- <u>Achievable TBR for DEMO ~ 1.10 (WCLL) to 1.20 (HCPB)</u>
  - **Design improvements required for WCLL driver blanket: TBR = 1.12 -1.13 seems feasible, TBR = 1.15 difficult to achieve (DEMO 2017 baseline)**
  - **HCPB driver blanket with $Be_{12}Ti$ neutron multiplier can easily satisfy T breeding requirements (DEMO 2017 baseline) and provide additional margins.**