Parametric Neutronic Analysis of HCLL Blanket for DEMO

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Main objectives of the investigations

Three-dimensional neutronic calculations using MCNP code are performed for the DEMO-type reactor based on HCLL blanket

- *To reduce radial depth of the blanket as much as possible without reducing significantly its tritium breeding capability*
- *To assess shielding performance of the reactor with regards to radiation load to the TF-coil at the inboard reactor side and in particular to evaluate the shielding efficiency of different shielding materials*

The results of the analysis will be used for a second iteration of the blanket design.

The HCLL blanket concept is developed by CEA and FZK on the basis of model B parameters of the European Power Plant Conceptual Study (PPCS)

It is developed to share as much as possible the basic technology with the HCPB concept:

- Uses the same modular blanket arrangement
- Features the same radial steel structure
- HCLL blanket uses specific breeder unit inserts

Main features of HCLL Blanket Module

- Lithium Lead (eutectic) as a breeder/ neutron multiplier material - $T_{melt}=235^{0}C$
- Reduced activation steel Eurofer structure material
- Helium at high T as a coolant - Inlet/outlet T $300/500^{0}C$, 8 Mpa pressure
- All structures (FW, SPs and container) are actively cooled

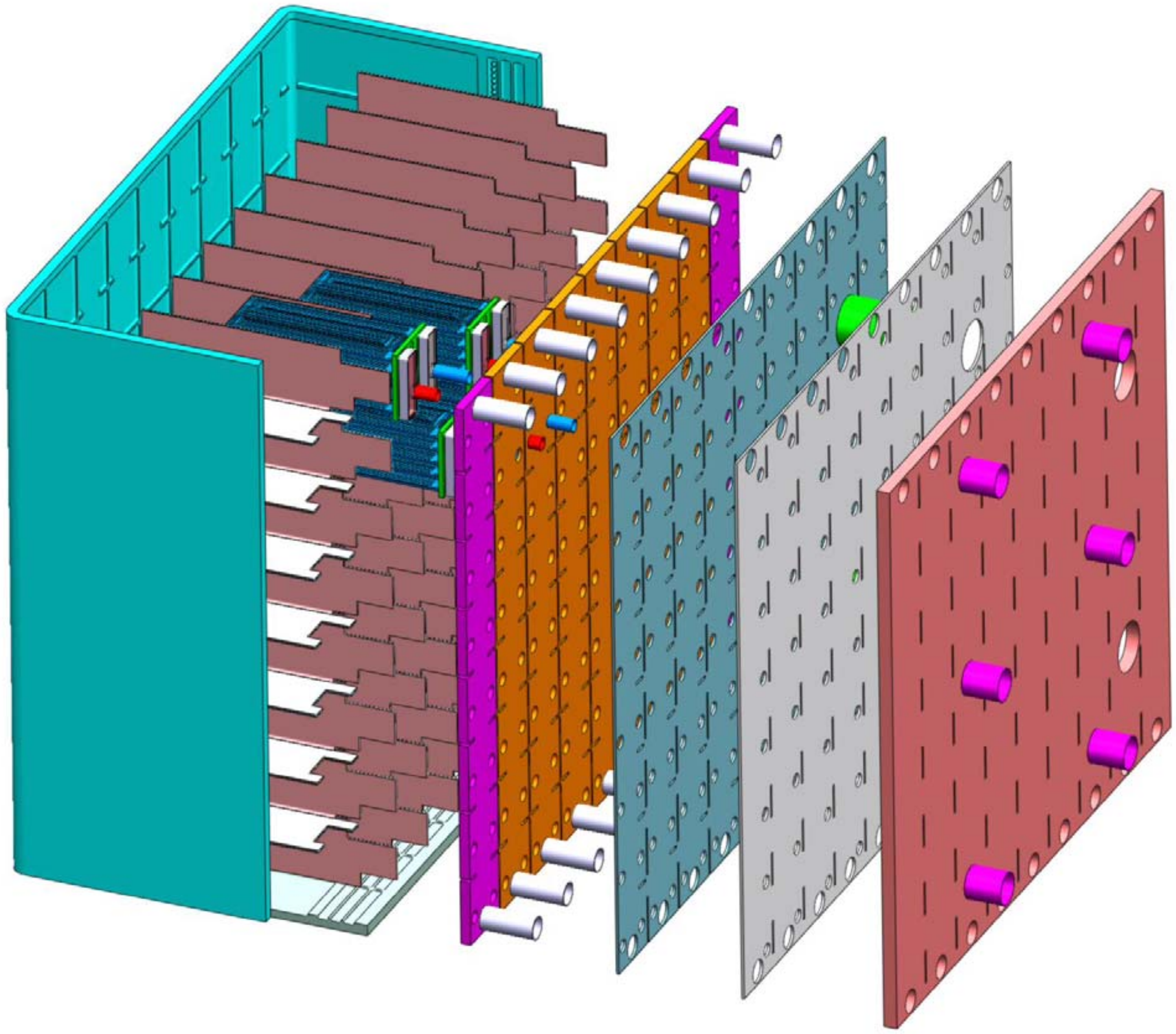
HCLL DEMO blanket module

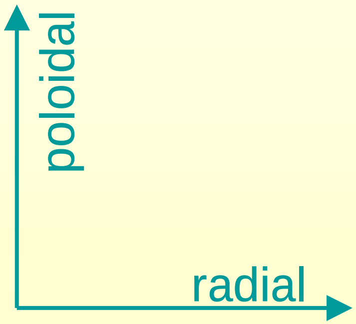
- Steel box reinforced by radial-poloidal and radial-toroidal stiffening plates (SPs) in order to withstand the He pressure in case of internal leak
- SPs subdivide the inside of the box in cells in which the breeder is slowly flowing
- The breeder material is cooled by the breeder cooling unit inserts
- Each breeder cooling unit consists of five horizontal cooling plates
- Breeder unit (BU) - the radial cells accommodating the cooling units and Pb-17Li

HCLL Steel Box Build

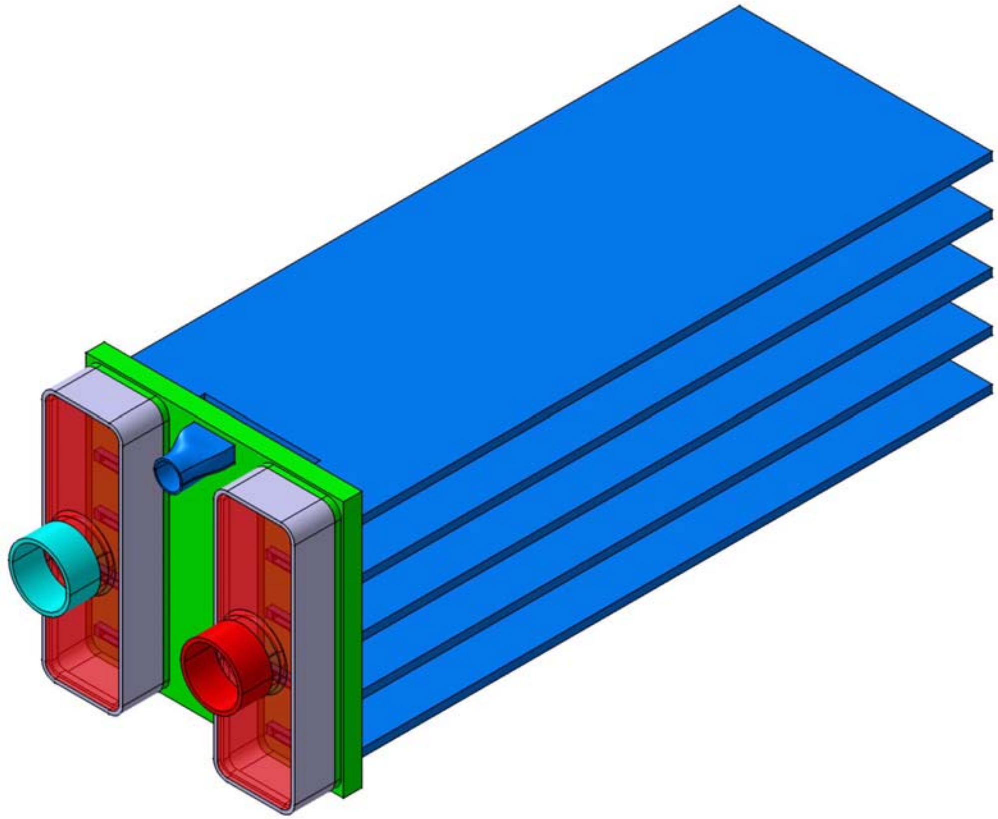
First wall (FW) & Side Wall (SW)	Toroidal cooling channels: (rad 14 x pol 15.6) mm^2, poloidal pitch between channels 21.6 mm Wall thickness: 25 mm (4/14/7 mm)
Top/bottom covers	Wall thickness: 30 mm (70% Steel + 30% He)
Horizontal Stiffening Plates (hSP)	Thickness 8 mm (He 31%, Steel 69%) Poloidal pitch between hSP: 208 mm
Vertical Stiffening Plates (vSP)	Thickness 8 mm (He 31%, Steel 69%) Toroidal pitch between vSP: 208.5 mm
Backplate (BP)	Radial thickness 182 mm He 57%, Steel 43%

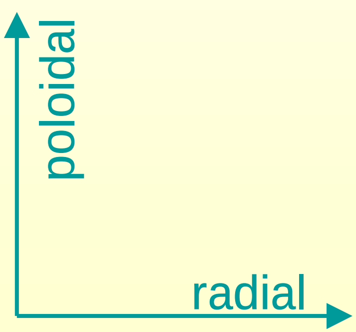
HCLL Breeder Blanket Module





HCLL Breeder Unit





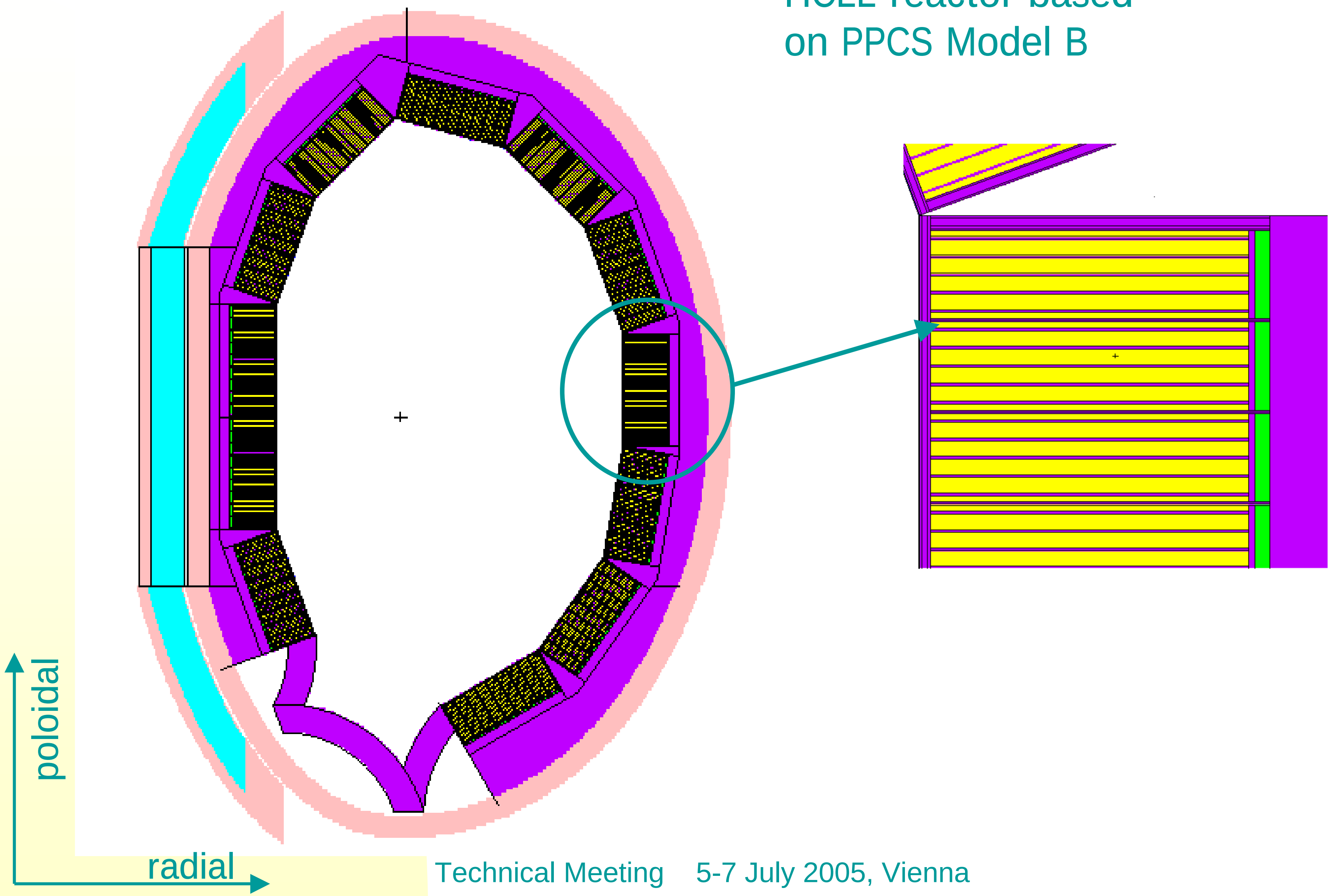
- HCLL module dimension: 200cm (toroidal) x 200 cm (poloidal)
- It consists of 81 BU (9 BU in both poloidal and toroidal directions)
- The reference module has a radial thickness of ≅100cm (75 cm is the breeder zone dimension, the BU total radial depth is 80 cm) and assumes 90% ^{6}Li enrichment

HCLL neutronics reactor model

- 9^0-sector MCNP power reactor model representing the modular structure of the blanket developed by FZK
- Devised by integrating HCLL blanket module into the neutronic model of a DEMO-type reactor based on the parameters of PPCS model B
- 3300 MW fusion power assumed for the model
- Proper simulation of the spatial distribution of the D-T source neutrons

MCNP torus sector model (9°)

HCLL reactor based
on PPCS Model B



METHOD OF CALCULATION

- Three-dimensional Monte Carlo transport code MCNP-4C
- FENDL-2.0 cross-section data to estimate the spatial/energy distribution of the neutron flux and the responses
- Tritium production -maximum relative error of 0.5%
- Parameters relevant to the TF-coil shielding- statistical error between 5 and 10%.

MAIN RESULTS

TRITIUM PRODUCTION

- TBR should be $\geq$1.10 in order to compensate the losses, to account for the presence of ports and penetrations in the blanket and to add an allowance for uncertainties in neutronic calculations of the TBR arising from methods approximations and errors in nuclear data.

Objectives of the analysis

To investigate the conditions for reducing the radial depth of the modules as much as possible without significantly reducing its tritium breeding capability.

- Two alternative Li-6 enrichments and three radial depth of the breeder zone are considered

Tritium Breeding Ratio

Radial depth of Breeder Unit, cm	90% Li-6 enrichment	60% Li-6 enrichment
75	1.226 (0.005)	1.152 (0.005)
60	1.183 (0.005)	1.095 (0.005)
55	1.148 (0.005)	1.065 (0.005)

Shielding capabilities of the HCLL DEMO reactor

In order to establish the shielding capabilities, it must be shown that the tolerable radiation loads to the super-conducting TF-coil as specified for ITER are not exceeded:

- the fast neutron fluence to the superconductor
- the peak nuclear heating in the winding pack
- the radiation damage to the copper stabilizer
- the radiation dose absorbed by the Epoxy insulator

Investigated configurations

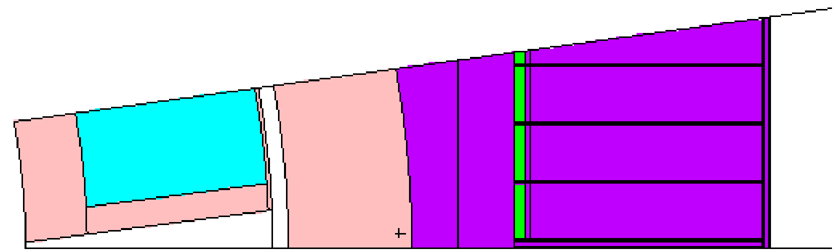
Two shield/Vacuum Vessel configurations are assumed in our analyses:

- WC composite (tungsten curbide composed of 50% W and 50% C) as a shield behind central inboard modules and Vacuum Vessel of SS 316-LN cryogenic steel (VV_{REF})
- Eurofer shield behind central inboard modules and Vacuum Vessel ITER FDR design (VV_{ITER}). It consists of 30 cm thick shielding mixture of borated steel (60%) and water (40%) sandwiched between two SS-316 steel plates with thickness of 5 cm each.
- The thickness of the vacuum vessel at the inboard side is 40 cm.

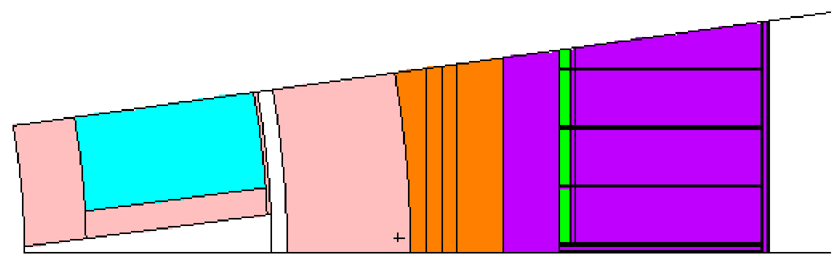
In-vessel shield thickness

- To keep the total radial thickness of 100 cm (thickness of the reference modules), a 15 cm and 20 cm thick shield behind blanket modules of 60 cm and 55 cm breeder zone radial length is added.
- This additional shield is either Eurofer or WC composite depending on the chosen shielding composition between the central inboard modules and vacuum vessel.
- In the location of the inboard mid-plane the shield thickness totals 15 cm, 30 cm and 35 cm for the blanket with breeder zone depth of 75 cm, 60 cm and 55 cm respectfully
- The total thickness of the blanket/shield system in the inboard side amounts to 115 cm.

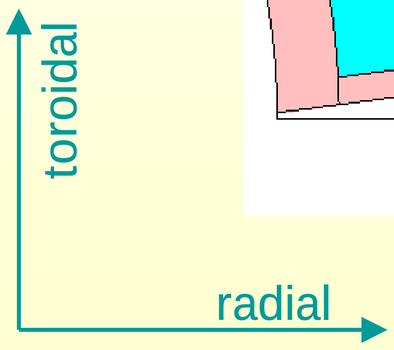
MCNP torus sector model (9°)



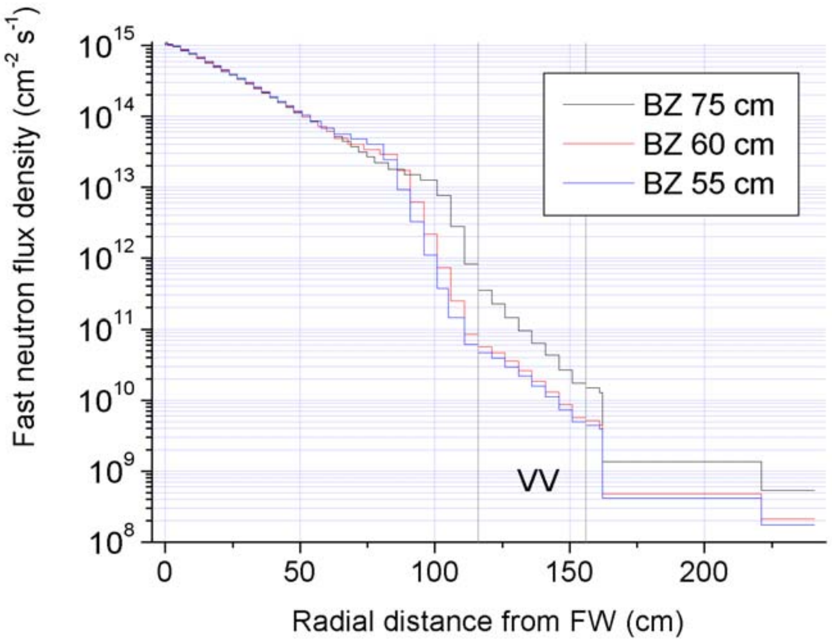
Central inboard module-reference case BZ depth 75 cm



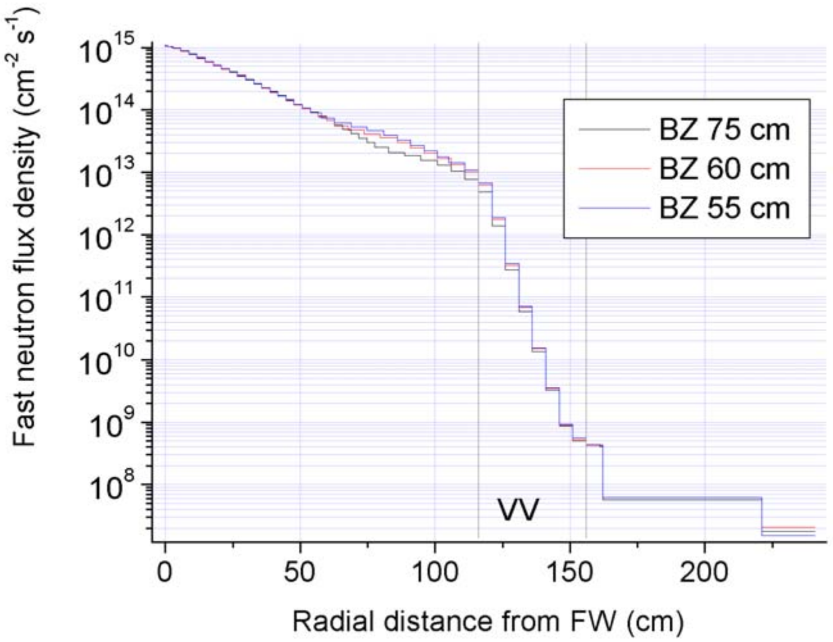
BZ depth 60 cm



Radial profile of fast neutron flux



WC shield / VV-REF



Eurofer shield / VV-ITER

RADIATION LOADS TO THE INBOARD TF-COIL (20 FULL POWER YEARS OPERATION) FOR WC SHIELD AND VV_{REF}

RESPONSE	Design limits	75 cm BZ 15 cm WC	60 cm BZ 30 cm WC	55 cm BZ 35 cm WC
Integral radiation dose in the insulator (Epoxy) [Gy]	$5.0x10^{6}$	$7.2x10^{7}$	$6.9x10^{6}$	$3.2x10^{6}$
Peak fast neutron fluence in Nb_3Sn super conductor [cm^{-2}]	$5.0x10^{18}$	$4.6x10^{18}$	$4.0x10^{17}$	$1.8x10^{17}$
Peak displacement damage to Cu stabilizer [dpa]	$2.5x10^{-4}$	$2.3x10^{-3}$	$1.8x10^{-4}$	$8.0x10^{-5}$
Peak nuclear heating in winding pack [$W.cm^{-3}$]	$1.0x10^{-3}$	$6.6x10^{-4}$	$6.3x10^{-5}$	$3.0x10^{-5}$

RADIATION LOADS TO THE INBOARD TF-COIL (20 FULL POWER YEARS OPERATION) FOR EUROFER SHIELD AND VV_{ITER}

RESPONSE	Design limits	75 cm BZ 15 cm Eurofer	60 cm BZ 30 cm Eurofer	55 cm BZ 35 cm Eurofer	55 cm BZ 35 cm Eurofer+ 5 cm WC
Integral radiation dose in the insulator (Epoxy) [Gy]	5.0×10^{6}	6.9×10^{6}	9.9×10^{6}	1.1×10^{7}	3.6×10^{6}
Peak fast neutron fluence in Nb_3Sn super conductor [cm^{-2}]	5.0×10^{18}	3.6×10^{17}	2.6×10^{17}	2.8×10^{17}	6.6×10^{16}
Peak displacement damage to Cu stabilizer [dpa]	2.5×10^{-4}	1.2×10^{-4}	9.5×10^{-5}	1.1×10^{-4}	2.3×10^{-5}
Peak nuclear heating in winding pack [$W.cm^{-3}$]	1.0×10^{-3}	6.0×10^{-5}	1.0×10^{-4}	1.1×10^{-4}	3.5×10^{-5}

The design limit can be met for the following blanket/shield/vacuum vessel configurations:

- Blanket with 55 cm radial length of the breeder zone using 35 cm thick WC shield at the inboard mid-plane and VV_{REF}
- Blanket with 55 cm radial length of the breeder zone using two-component shield between the central inboard modules and vacuum vessel composed of Eurofer with thickness of 30 cm followed by 5 cm thick WC shield and ITER FDR design of the vacuum vessel

Analysis

- More than 80% of the integral radiation dose absorbed by the Epoxy and 90% of the total nuclear heating in the winding pack are due to the photon absorption for all cases regarded.
- The most crucial quantity regarding the design limit is the integral absorbed dose in Epoxy which in most cases exceeds the limit.

VV_{REF} / WC shield configuration

- The absorbed dose and nuclear heating due to gamma absorption decrease with WC thickness increasing
- Only the 35 cm thick WC shield ensures the absorbed dose below the design limit

VV_{ITER} / Eurofer shield configuration

- With Eurofer thickness increasing the gamma-dose and gamma-heating increase due to the steel acting as photon emitter
- The gamma radiation should be decreased. This can be achieved by replacing a part of the steel, at the inboard mid-plane, adjacent to the vacuum vessel, by efficient gamma-radiation absorber, such as WC.
- Two-component shield behind the central inboard modules is applied in the analysis of a blanket of 55 cm radial length, consisting of 30 cm thick Eurofer followed by 5 cm thick WC shield
- The obtained decrease of the gamma radiation absorbed dose and heating with about a factor of three ensures fulfilling the requirement of the specified limit for the integrated absorbed dose in Epoxy

CONCLUSIONS

Tritium breeding self-sufficiency can be obtained

- *assuming 90% ^{6}Li enrichment and a breeder zone radial thickness reduced to 55 cm*
- *or with a ^{6}Li enrichment of 60% and a breeder zone radial depth of 75 cm, the blanket with breeder zone radial length of 60 cm being close to ensure the required TBR.*

SHIELDING EFFICIENCY

- *The blanket with radial length of 55 cm shows the best performance by fulfilling the goal of the parametric study to meet the target TBR at reduced radial length and in terms of radiation load on TF-coils below the design limit. The design limits can be met utilizing shield/vacuum vessel configuration of WC and VV_{REF} or two-component shield of Eurofer and WC and VV_{ITER}.*