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Neutronic Performance Issues of the Breeding Blanket Options for the European DEMO Fusion Power Plant

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Outline

- Background
- Breeder blanket concepts for DEMO
- Neutronic characteristics of blanket concepts
- Requirements for breeding and shielding
- Methodological approach for DEMO nuclear analyses
- Tritium breeding potential
- Shielding performance issues
- Conclusions

Background

- European Fusion Roadmap
  - *Realization of fusion as energy source for electricity by 2050 (Fusion Power Plant to providing electricity to the grid)*
- "Horizon 2020" research framework programme
  - *Conceptual design of a fusion power demonstration plant (DEMO)*
  - *Power Plant Physics and Technology (PPPT) Project organized within the EUROfusion Consortium for the Development of Fusion Energy* [(1)]
- DEMO power plant
  - *Relies on technically mature breeder blanket providing Tritium for self-sufficiency and producing heat for conversion into electricity*
  - *Four different design concepts are under investigation for DEMO* [(2)]

  ⇒ ***Evaluation of nuclear performance for assessing potential and suitability for DEMO at an early development phase***

[(1)] G. Federici, Keynote 2

[(2)] L. V. Boccaccini, Oral 1A

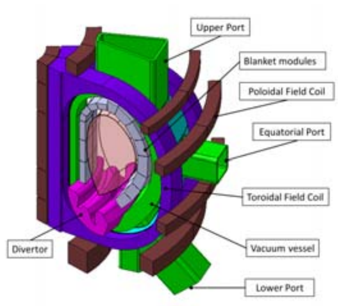
Breeder Blanket Concepts for DEMO

Common Design Features

“DEMO 2014” configuration

- 16 Toroidal Field Coils (TFC)
  ⇒ *Torus sectors of 22.5 ° with 3 outboard and 2 inboard segments*
- Multi Module Segmentation (MMS) scheme for blanket arrangement and maintenance
- Back Supporting Structure (BBS) acting as mechanical support and hosting main manifolds
- Vacuum vessel with integrated shielding function for protection of TFC over plant lifetime (6 full power years)
- Available radial space for blanket modules: 80 cm inboard, 130 cm outboard.
- Designed for peak values of Neutron Wall Loading (NWL): 1.15 MW/m^2 (inboard), 1.35 MW/m^2 (outboard)

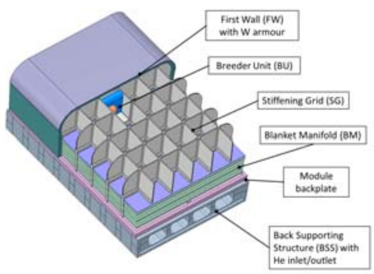
Major radius (m)	9.0
Minor radius (m)	2.25
Plasma elongation	1.56
Plasma triangularity	0.33
Plasma peaking factor	1.7
Fusion power (MW)	1572
Net electric power (MW)	500
Average NWL (MW/m^2)	1.07



Helium Cooled Pebble Bed (“HCPB”) Blanket

- **HCPB 2014 MMS blanket design:**
  6 blanket modules both at inboard and outboard.
- **Blanket module:** Steel box made of Eurofer with U-shaped First Wall (FW), stiffening grid (SG) with breeder units (BU), a box manifold with a back wall, two caps at the top and the bottom, and integrated BSS.
- **Li_4SiO_4 ceramics** as breeder with ^{6}Li enriched to 60 at% and **Beryllium** as neutron multiplier.
  ⇒ *Filled in the form of pebble beds in the space between the cooling/stiffening plates.*
- **Coolant:** High pressure (8 MPa) He gas for cooling of BU, FW, and box structure.

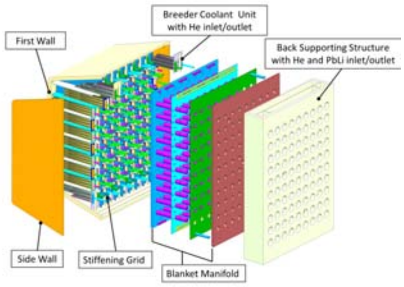
HCPB breeder blanket module



Helium Cooled Lithium Lead ("HCLL") Blanket

- **HCLL MMS blanket design:**
  7 blanket modules inboard, 8 outboard.
- **Blanket module:** Eurofer steel box with stiffening grid similar to HCPB box design
  - ⇒ *Open space filled with PbLi eutectic alloy for Tritium breeding*
  - ⇒ *Insertion of Coolant Units for cooling of PbLi*
  - ⇒ *Complex manifold scheme for circulation of PbLi (T extraction) and He gas (coolant)*
- **Pb-15.8Li** eutectic alloy as breeder (90 at% ^{6}Li enrichment) and neutron multiplier.
- **Coolant:** High pressure (8 MPa) He gas for cooling of the breeder and the structure.

HCLL breeder blanket module

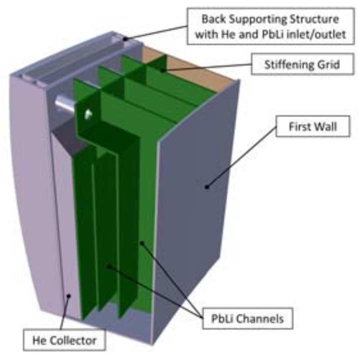


J. Aubert et al, P2.034, *Status on DEMO Helium Cooled Lithium Lead Breeding Blanket Thermo- Mechanical Analyses*

Dual Coolant Lithium Lead ("DCLL") Blanket

- **DCLL MMS blanket design:**
  7 blanket modules inboard, 8 outboard
- **Blanket module:** Eurofer steel box with large sized coolant channels with thin flow channel inserts and attached BSS with integrated manifolds for He and PbLi.
- **Pb-15.8Li** eutectic alloy as breeder (90 at% ^{6}Li enrichment) and neutron multiplier.
- **Coolant:** High pressure (8 MPa) He gas for cooling of the Eurofer structure including FW, PbLi for the breeder zone.

DCLL breeder blanket module



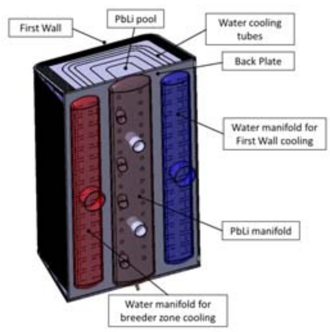
I. Palermo et al, P3.051, *Neutronic Analyses of the Preliminary Design of a DCLL Blanket for the EUROfusion DEMO Power Plant*

Water Cooled Lithium Lead ("WCLL") Blanket

- **WCLL MMS blanket design:**
  7 blanket modules inboard, 8 outboard
- **Blanket module:** Eurofer steel box with first wall, caps, back wall, stiffening grid and space for LiPb ("pool"), coolant tubes, back supporting structure with inlet/outlet pipes for water and PbLi.
- **Pb-15.8Li** eutectic alloy acting as breeder (90 at% ^{6}Li enrichment), neutron multiplier and Tritium carrier.
- **Coolant:** Pressured water (15.5 MPa) flowing in small double-walled cooling pipes.
- *Original WCLL breeder blanket design by CEA (J. Aubert et al.), now continued under responsibility of ENEA (A. Del Nevo et al.)*

WCLL breeder blanket module

2015 design



P. A. Di Maio et al, P1.038, *Optimization of the Breeder Zone Cooling Tubes of the DEMO Water-Cooled Lithium Lead Breeding Blanket*

Neutronic Characteristics of Blanket Designs

	HCPB	HCLL	DCLL	WCLL
Breeder material	Li_4SiO_4	Pb-15.8Li	Pb-15.8Li	Pb-15.8Li
^{6}Li enrichment	30- 60 at%	90 at%	90 at%	90 at%
Neutron multiplier	Be	Pb (in PbLi)	Pb (in PbLi)	Pb (in PbLi)
Effect on neutronics	***moderating***	*non moderating*	*non moderating*	*non moderating*
Coolant	He	He	He, PbLi	H_2O, PbLi
Effect on neutronics	*none*	*none*	*non moderating*	*(a bit) moderating*
Structural material	Eurofer	Eurofer	Eurofer	Eurofer
Effect on neutronics	***absorbing***	*absorbing*	*absorbing*	*absorbing*
Dominating material and reactions	Be, elastic scattering, (n,2n)	Pb, elastic sacttering, (n,2n)	Pb, elastic sacttering, (n,2n)	Pb, elastic sacttering, (n,2n)
Effect on spectrum, flux and absorptions	*soft, enhanced parasitic and useful absorptions, low flux*	*fast, high neutron flux*	*fast, high neutron flux*	*partially moderated, lower flux*
Required breeder zone thickness	*30 -50 cm*	*50 – 80 cm*	*50 -80 cm*	*50 - 80 cm*

DEMO Radial Build

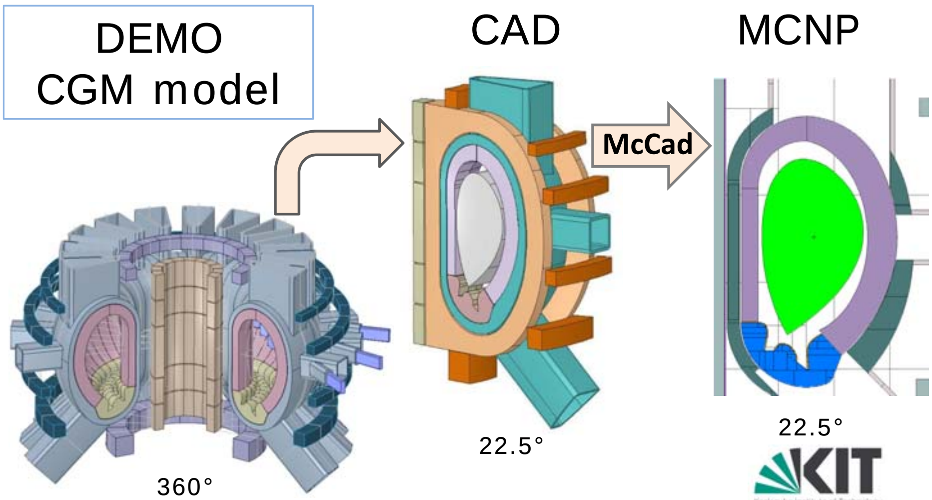
- Available space must be sufficient to accommodate breeding blankets of any considered type and provide sufficient Tritium breeding.
  ⇒ *Crucial for inboard side of DEMO where minimum space is available for the combined breeder/shield system.*
- Shielding of superconducting TFC (mainly) provided by VV with integrated shielding function:
  ⇒ *5 cm thick steel plates at front and back, 47 cm space in between optimized for shielding (and providing thermal and structural-mechanical functions).*
- Radial space available to breeder blanket modules in DEMO:
  80 cm inboard, 130 cm outboard.
  ⇒ *HCPB, HCLL, DCLL and WCLL breeder blanket modules including back supporting structure (BSS) and manifolds designed to fit to these dimensions.*
  ⇒ *Includes space for BSS with inlet/outline piping of coolant and Tritium carrier (PbLi or He purge gas) and manifolds inside breeder modules.*
  ⇒ *Pb-Li based blankets: manifolds carrying Pb-Li liquid metal contribute to Tritium breeding*

Methodological approach for nuclear analyses

- Generic CAD neutronics model generated from DEMO Configuration Geometry Management (CGM) Model
  ⇒ *Includes TFC, VV, divertor, blanket segment box, vessel ports, and plasma chamber, represented with "envelopes" without internal structure.*
  ⇒ *Model converted to analysis model for MCNP/TRIPOLI-4 using the McCad conversion software*
- Resulting generic analysis model used for integration of specific HCPB, HCLL, DCLL and WCLL blankets.
  ⇒ *CAD models provided by design teams for single blanket modules are converted and filled into empty blanket envelope of generic DEMO model.*
  ⇒ ***HCPB, HCLL, DCLL and WCLL DEMO** models consistent with generic DEMO and specific blanket designs*
  ⇒ ***HCPB:** KIT (P. Pereslavtsev), **HCLL:** CEA (J-C. Jaboulay), **DCLL:** Ciemat (I. Palermo), **WCLL**: ENEA (F. Moro)*
- Performance/optimisation analyses with MCNP (HCPB, DCLL, WCLL) and TRIPOLI (WCLL) and JEFF-3.1/3.2 nuclear data.

DEMO Model Development

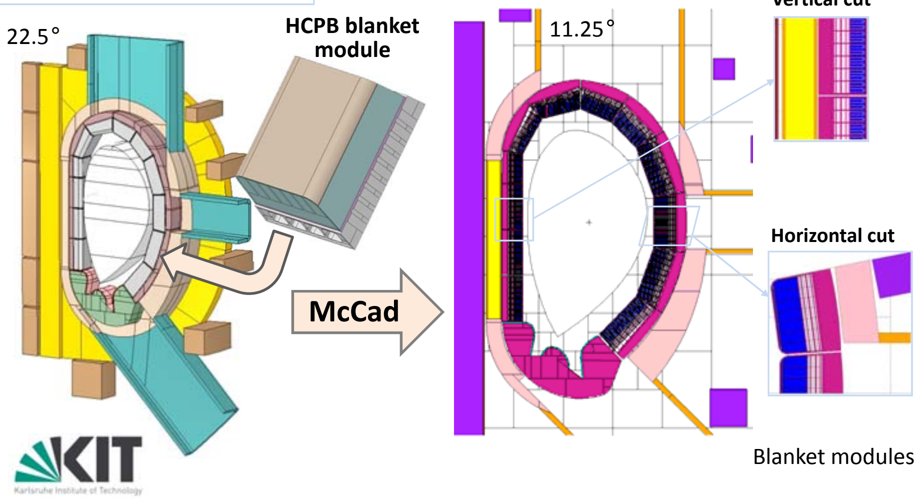
Generic DEMO neutronics model



HCPB DEMO Model Development

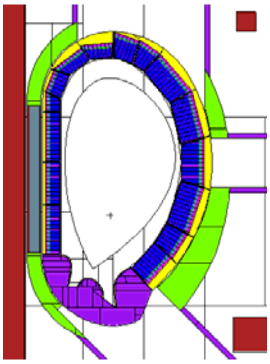
CAD neutronics model
- blanket module segmentation included -

MCNP model



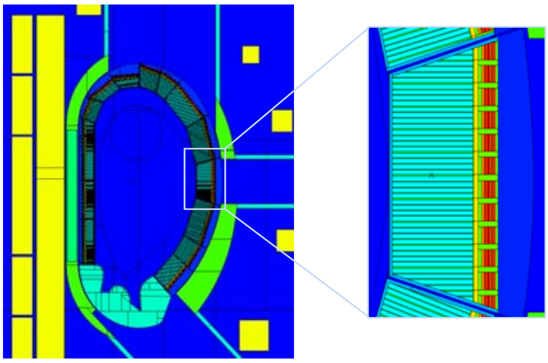
HCLL DEMO Model

MCNP model



TRIPOLI model

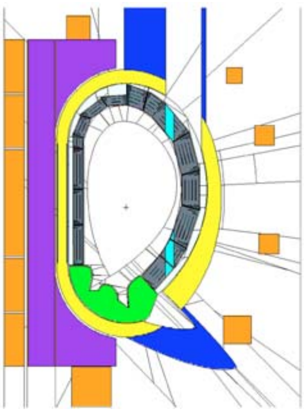
HCLL blanket module
- vertical cut -



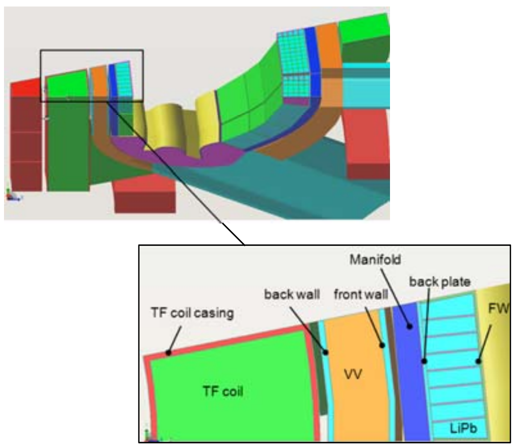
J.-C. Jaboulay et al., P1.042, *Nuclear Analysis of the HCLL Blanket Concept for the European DEMO using the TRIPOLI-4® Monte Carlo Code*

WCLL DEMO Model

MCNP model



Cut-away view at torus mid-plane



Horizontal cut at inboard mid-plane

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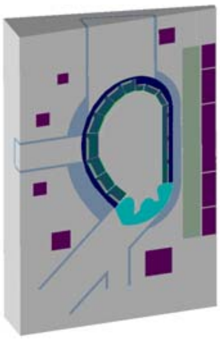
DCLL DEMO Model

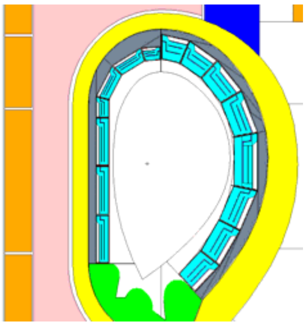
MCNP model

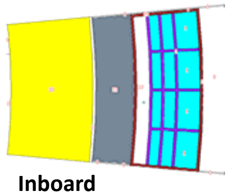
Horizontal cuts at torus mid-plane

MCAM model

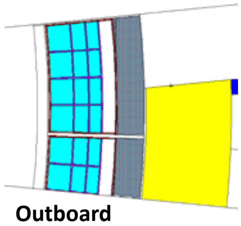


Vertical cut





Inboard



Outboard

I. Palermo et al, ***P3.051***, *Neutronic Analyses of the Preliminary Design of a DCLL Blanket for the EUROfusion DEMO Power Plant*

Tritium breeding potential

- DEMO requires **Tritium self-sufficiency:**

  ⇒*Net Tritium Breeding Ratio (TBR) > 1.0*

- **DEMO design target:** TBR ≥ 1.10

  (To be proven by 3D Monte Carlo calculation without blanket ports).
- All blanket concepts show sufficient Tritium breeding capability as shown in previous studies/analyses.
- Design limitations adopted for the DEMO 2014 affect the TBR performance.
- Design improvements underway to achieve TBR design target for DEMO.

TBR performance for DEMO

	HCPB	HCLL	DCLL	WCLL
DEMO 2014 initial design	1.04	1.07	1.04	1.13
DEMO 2015 current design	1.12 – 1.15	1.09 – 1.11	1.13	1.13

Shielding performance issues

- Blanket/shield system must ensure sufficient protection of the super-conducting magnets

  ⇒ *Limits for the radiation loads on the Toroidal Field Coils (TFC)*

Total neutron fluence to epoxy insulator	$1 \cdot 10^{22}$ m^{-2} ≅ 10^7Gray
Peak fast neutron fluence to the Nb_3Sn super-conductor (*)	$1 \cdot 10^{22}$ m^{-2}
Peak displacement damage to Cu stabilizer between TFC warm-ups	$1 \cdot 10^{21}$ m^{-2} ≅ $0.5 \cdot 10^{-4}$ dpa
Peak nuclear heating in winding pack	**<$0.05 \cdot 10^3$ W/m^3**

(*) Results for DEMO conditions in a fast neutron flux limit of ≅ 10^9 cm^{-2}s^{-1}

- Displacement damage accumulation of the vessel to be limited to prevent degradation of the stainless steel properties

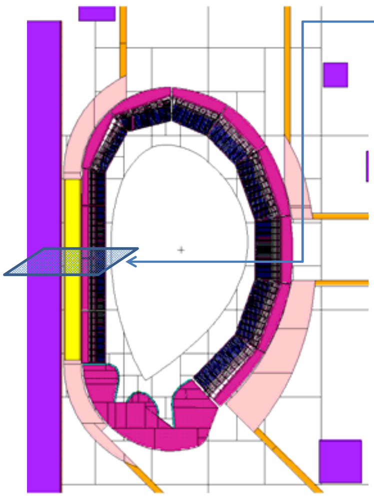
  ⇒ *2.75 dpa limit for vacuum vessel made of austenitic steel*

- Irradiation induced gas production accumulation to be limited to enable re-welding of components and connections/pipes made of steel (1appm)

  ⇒ *DEMO design goal: Re-welding only in areas where sufficient shielding can be provided*

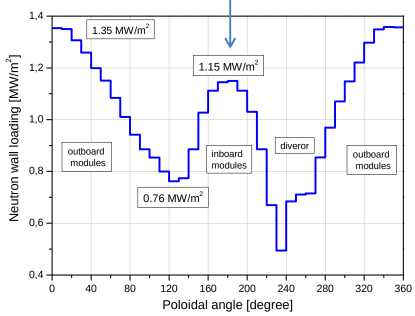
⇒ ***To be proven for DEMO inboard mid-plane where minimum space is available for shielding !***

Shielding calculations



Shielding calculations in torus mid-plane (inboard)

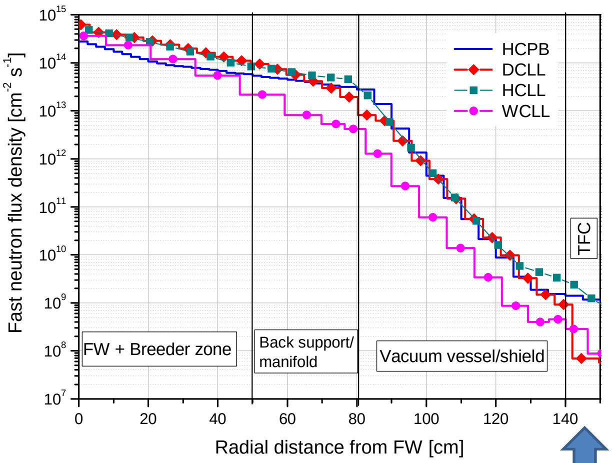
Inboard mid-plane



Poloidal distribution of Neutron Wall Loading (NWL) in DEMO

Radial profile of fast neutron flux density

DEMO inboard torus mid-plane



TFC

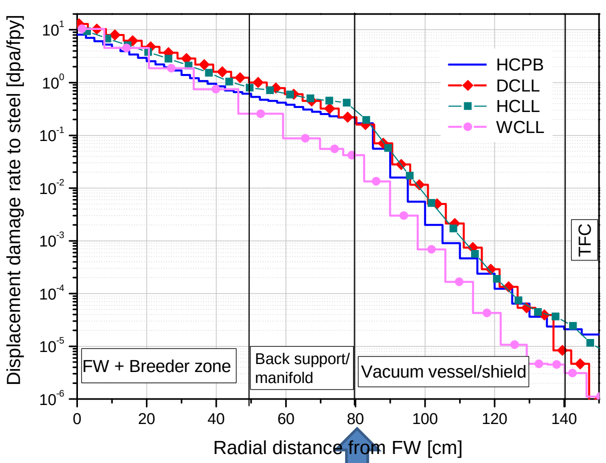
Fast (>0.1 MeV) neutron flux densities [$cm^{-2}\ s^{-1}$]

	FW	TFC front
HCPB	$2.8\ 10^{14}$	$\approx 1.7\ 10^{9}$
HCLL	$6.8\ 10^{14}$	$\approx 2.4\ 10^{9}$
DCLL	$6.2\ 10^{14}$	$\approx 1.0\ 10^{8}$
WCLL	$3.6\ 10^{14}$	$\approx 5.3\ 10^{8}$

Assumed DEMO limit at TFC front: $\approx 10^{9}\ cm^{-2}s^{-1}$

Radial profile of displacement damage in steel

DEMO inboard torus mid-plane



VV front

Displacement damage rate in steel [dpa/fpy(*)]

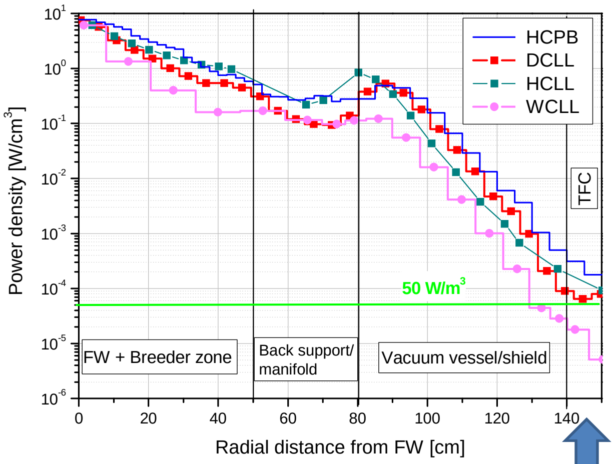
	FW	VV front
HCPB	8.1	0.22
HCLL	9.4	0.20
DCLL	10.4	0.15
WCLL	10.4	0.04

(*)fpy = full power year

DEMO limit for VV : 2.75 dpa

Radial profile of power density in steel

DEMO inboard torus mid-plane



TFC

Nuclear power density [W/cm³]

	FW	TFC front
HCPB	8.4	≈ 3 10^{-4}
HCLL	6.4	≈ 2 10^{-4}
DCLL	5.7	≈ 9 10^{-5}
WCLL	6.1	≈ 2 10^{-5}

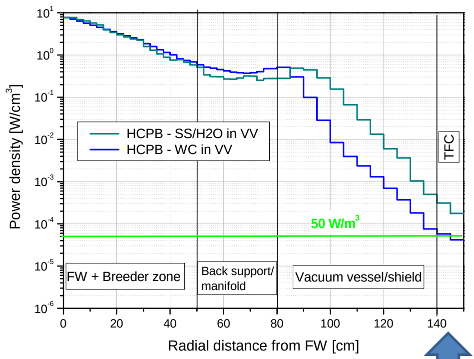
Recommended DEMO limit for TFC : 5 10^{-5} Wcm^{-3}

⇒ ***VV/shield composition: 80 % SS-316/20 %H_2O***

Efficient shielding materials in VV

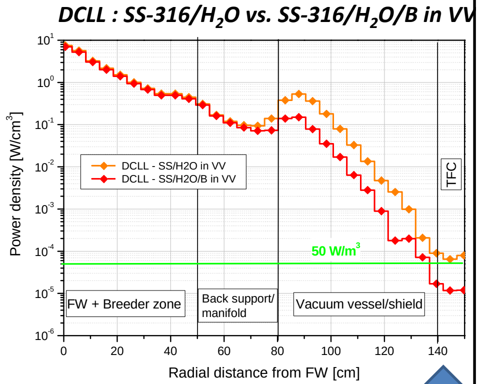
- Effect on nuclear heating profiles (inboard torus mid-plane) -

HCPB : SS-316/H_2O vs. WC in VV



TFC

DCLL : SS-316/H_2O vs. SS-316/H_2O/B in VV



TFC

Conclusions

Nuclear performance of HCPB, HCLL, DCLL and WCLL for DEMO

- Tritium breeding potential
  - ✓ *Considered sufficient although initial 2014 design versions of HCPB, HCLL and DCLL require design improvements .*
  - ⇒ *Suitable measures shown to be sufficient to achieve TBR ≥ 1.10*
- Shielding performance
  - ✓ *Sufficient to protect the TFC from provided that efficient shielding materials including WC or borated water are utilized in the VV (HCPB, HCLL, DCLL).*
  - ✓ *WCLL does not require such materials provided the considered BSS/manifold configuration can be verified.*
  - ✓ *VV can be safely operated over anticipated DEMO lifetime of 6 fpy*