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Optimization process for the design of the DCLL blanket for the European DEMOnstration fusion reactor according to its nuclear performances

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Abstract. The research study focuses on the neutronic design analysis and optimization of one of the options for a fusion reactor designed as DCLL (Dual Coolant Lithium-Lead). The main objective has been to develop an efficient and technologically viable modular DCLL Breeding Blanket (BB) using the DEMO generic design specifications established within the EUROfusion Programme. The final neutronic design has to satisfy the requirements of: tritium self-sufficiency; BB thermal efficiency; preservation of plasma confinement; temperature limits imposed by materials; and radiation limits to guarantee the largest operational life for all the components. Therefore, a 3D fully heterogeneous DCLL neutronic model has been developed for the DEMO baseline 2014 determining its behaviour under the real operational conditions of the DEMO reactor. Consequent actions have been adopted to improve its performances. Neutronic assessments have specially addressed Tritium Breeding Ratio, Multiplication Energy Factor, power density distributions, damage and shielding responses. The model has been then adapted to the subsequent DEMO baseline 2015 (with a more powerful and bigger plasma, smaller divertor and bigger blanket segments), implying new design choices to improve the reactor nuclear performances.

1. Introduction

The neutronic radiation, coming from the fusion plasma of large machines as the foreseen DEMO, could severely affect the stability and the lifetime of the components which constitute the reactor. Nevertheless neutrons are fundamental to allow the reactor to reach the tritium self-sufficiency and to generate and extract enough nuclear power. This means that, in the nuclear design of a kind of facilities, it is essential to achieve and keep the delicate balance among fuel sustainability and power efficiency vs. radiation shielding.

This paper deals with the neutronic design analysis and optimization of one of the Breeding Blanket (BB) options of fusion reactor designated as DCLL (Dual Coolant Lithium-Lead) among the EUROfusion WPBB (Work Package Breeding Blanket) Project. The main objective has been to develop for the period 2014-2018, a new, reliable, efficient and technologically viable modular DCLL blanket using the DEMO generic design specifications and operational (pulsed) conditions [1] established in the frame of the EUROfusion PPPT (Power Plant Physics and Technology) Programme. Answering the required duties of a BB - tritium breeding, heat recovery and shielding - the DCLL uses PbLi as tritium breeder, neutron multiplier and primary coolant, Eurofer as structural material and Helium at high pressure (8MPa) to cool some parts of the BB structure.

The DCLL is probably one of the BB concepts with highest long term potential of improvement. It provides many advantages with respect to: wider design margins due to the double cooling system intrinsic to the concept (Helium for the FW and the BB structures and PbLi as self-cooler); lower tritium inventory [2] because of the really low partial pressure of tritium in the whole mass flow rate (about 110 mPa [3]); no safety issue related to water cooling (because water is not the cooling option of this concept); good adaptation to the presently available nuclear materials as Eurofer (being the upper temperature limited to 550º) and potential for high-temperature (and thus higher plant efficiency).

In order to demonstrate that the DCLL design is a mature option for a possible future DEMO reactor different nuclear responses have been analysed as they are a measure for the viability of the design.

The priority condition of fuel self-sufficiency for the viability of a fusion reactor is measured through the Tritium Breeding Ratio (TBR). The TBR is defined as the ratio between the number of tritons produced per second in blanket and the fusion neutrons produced per second in plasma. A TBR > 1 is needed for a self-sustained fusion economy, although it is required to obtain a TBR ≥ 1.1 to have a 10% of margin accounting for possible losses and uncertainties [4].

A second blanket function is to transform the kinetic energy of the neutrons, which represents 80% of the energy produced by the D-T reaction, into thermal energy, and then to bring it out. Since the ^{6}Li(n,a)T reaction is an exothermic one, when using Li enriched 90% in Li-6 to improve TBR, there is a good possibility of increasing the energy multiplication M_E, defined as the ratio of total nuclear power generated in reactor to fusion neutron power. Increased energy multiplication improves the power balance of plant. This is important from the viewpoint of lowering electric power costs. M_E values are typically between 0.9 and 1.35 [5].

On the other hand, the plasma confinement can be kept only without overpassing the quench limits posed on the Superconducting Toroidal Field Coils (TFC). Furthermore, structural limits are imposed to the First Wall (FW) and Vacuum Vessel (VV), to maintain their integrity. The requirements, recommendations and limits taken into account and assessed here are summarized in Table 1 [1][4][5]. Nuclear heating deposited in the different components of the reactor has been also calculated to provide inputs for the subsequent thermo-mechanical analysis for determining possible deformations due to thermal stress.

Starting from the plasma specifications [6] and the generic DEMO1 design [7] established in 2014 among the EUROfusion Programme, a conceptual DCLL design was developed and studied [8] and preliminary neutronic assessments were performed [9][10]. In this paper the previous mentioned nuclear responses are deeper analysed. The paper also describes the progress [11][12] in the DCLL neutronic design in light of the observations and requirements explained above. Further work has included the adaptation of the optimized design of the DCLL blanket to the plasma parameters [13] and the generic DEMO1 design established in 2015 [14] in which a reduced divertor and a higher fusion power would allow keeping and improving the generic machine behaviour relaxing the design specifications for the BB. In fact as the TBR margins will be higher, the space reserved for the breeding function will be recovered for shielding purposes as well as to increase the PbLi flow channel section inside the BSS to maintain a profitable velocity along their path and reduce the pressure drop and corrosion rate.

The preliminary results and design improvements applied to the new DEMO2015 specifications are presented. Particle transport calculations have been performed with MCNP5v1.6 Monte Carlo code [15] using JEFF 3.1.1 [16] and JEFF 3.2 [17] nuclear data libraries for DEMO 2014 and 2015, respectively.

Table 1. Limits, requirements and recommendations taken under consideration [1][4][5].

for BB	value	for TF-coil	value
Tritium Breeding Ratio	≥ 1.1	Integral neutron fluence for epoxy insulator [cm^{-2}]	$\leq 1\times10^{18}$
*Energy Multiplication Factor	As high as possible in the range 0.9-1.35 [5]	Peak fast neutron fluence (E>0.1 MeV) to the Nb_3Sn superconductor [cm^{-2}]	$\leq 1\times10^{18}$
***Structural limits**	**value**		
Helium production in steel [appm He]	≤1	Peak displacement damage to copper stabiliser [dpa]	$\leq 0.5\sim1 \times10^{-4}$
Displacement damage in the FW [dpa]	≤ 20(1) [1] ≤ 50-70(2)	Peak nuclear heating in winding pack [W/cm^3]	$\leq 5\times10^{-3}$
Displacement damage in the VV [dpa]	≤2.75		

* Not design requirements but simply recommendations. (1) Limit concerning the "starter" DEMO BB to withstand 1.57 FPY and (2) the "second" DEMO BB to withstand 4.43 FPY for a total of 6 FPY.

2. DCLL DEMO development

The DEMO design used in the 1st phase of the EUROfusion programme, known as "EU DEMO1 Baseline 2014" [7], has 1572 MW fusion power ($5.581\text{x}10^{20}$ n/s), plasma major radius of 9 m, minor radius of 2.25 m and elongation of 1.56 [6]. The torus is divided into 16 sectors of 22.5º (given by the number of TFC), each having 3 outboard (OB) and 2 inboard (IB) BB segments. For the neutronic purposes, an 11.25º half-sector has been studied (Fig.1a).

In the 2nd phase a new generic design called "EU DEMO1 Baseline 2015" has been developed having 2037 MW fusion power ($7.323\text{x}10^{20}$ n/s), plasma major radius of 9.07 m, minor radius of 2.93 m and elongation of 1.59 [13]. The torus is divided into 18 sectors of 20º being the MCNP neutronic model a half-sector of 10º (Fig.2a).

The main change in this design from the BB point of view is that the vertical length of the BB segments has been increased at the expense of the divertor size. In fact in the first year of the project, an ITER-like divertor configuration was considered (Fig.1a). In the second project year (2015) a revised model of cassette was created (Fig.2a) cutting off the outboard and inboard baffles while the breeding blanket segments were extended. The motivation was to increase the TBR by exploiting those areas highly exposed to the plasma [18]. For DEMO2014 austenitic steel (SS316LN) was considered for the divertor composition being the divertor neutronic model a homogenized massive block of 80% steel and 20% water [9]. In DEMO2015 the reduced activation 9Cr steel Eurofer97 has been considered being the neutronic divertor model a solid steel body excepting two thin layers (of tungsten and W/CuCrZr/Cu/water) facing the plasma. Besides these 2 compositions another one has been tested for both DEMO2014 and 2015 substituting the former by a cassette of 54% Eurofer and 46% water with reduced density [20].

For DEMO2014 the DCLL neutronic model is fully heterogenized meaning that the internal components of all the BB modules are represented as shown in Fig. 1b (showing the entire segment) and 1c-d (showing OB equatorial modules). Its description and analyses are explained in section 3 and its sub-sections. For DEMO2015 the conceptual DCLL model adapted to the specific feature of the new baseline has been prepared. The model version 3.0 is a 3D *quasi*-heterogenized segment with the equatorial OB module fully heterogenized (Fig. 2b-c). Its details and preliminary results are given in section 4 and its sub-sections. A first improvement of this, called v3.1, is also shown and examined in section 4.3.

All the analysed neutronic models have been developed though the MCAM (Monte Carlo Modeling Interface Program) tool SuperMC_MCAM 5.2 Professional Version [19], an integrated interface program between commercial CAD softwares (here CATIAv5) and Monte Carlo radiation transport simulation codes (MCNP5v1.6, in this case).

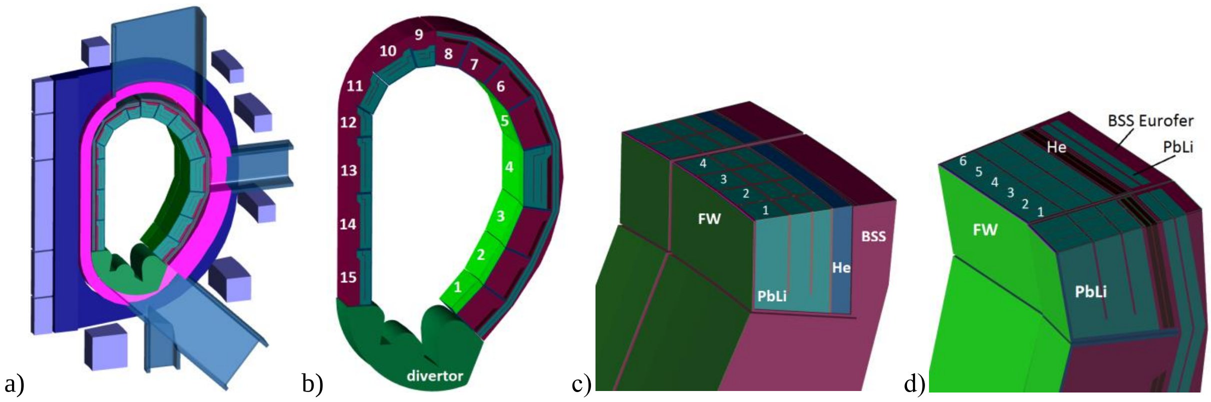


Fig. 1. DCLL DEMO2014: a) whole reactor; b) BB segment, BSS and divertor; c) detail of OB BB equatorial module and the homogenized BSS, version 1; d) OB equatorial module and its heterogenized BSS, version 2.

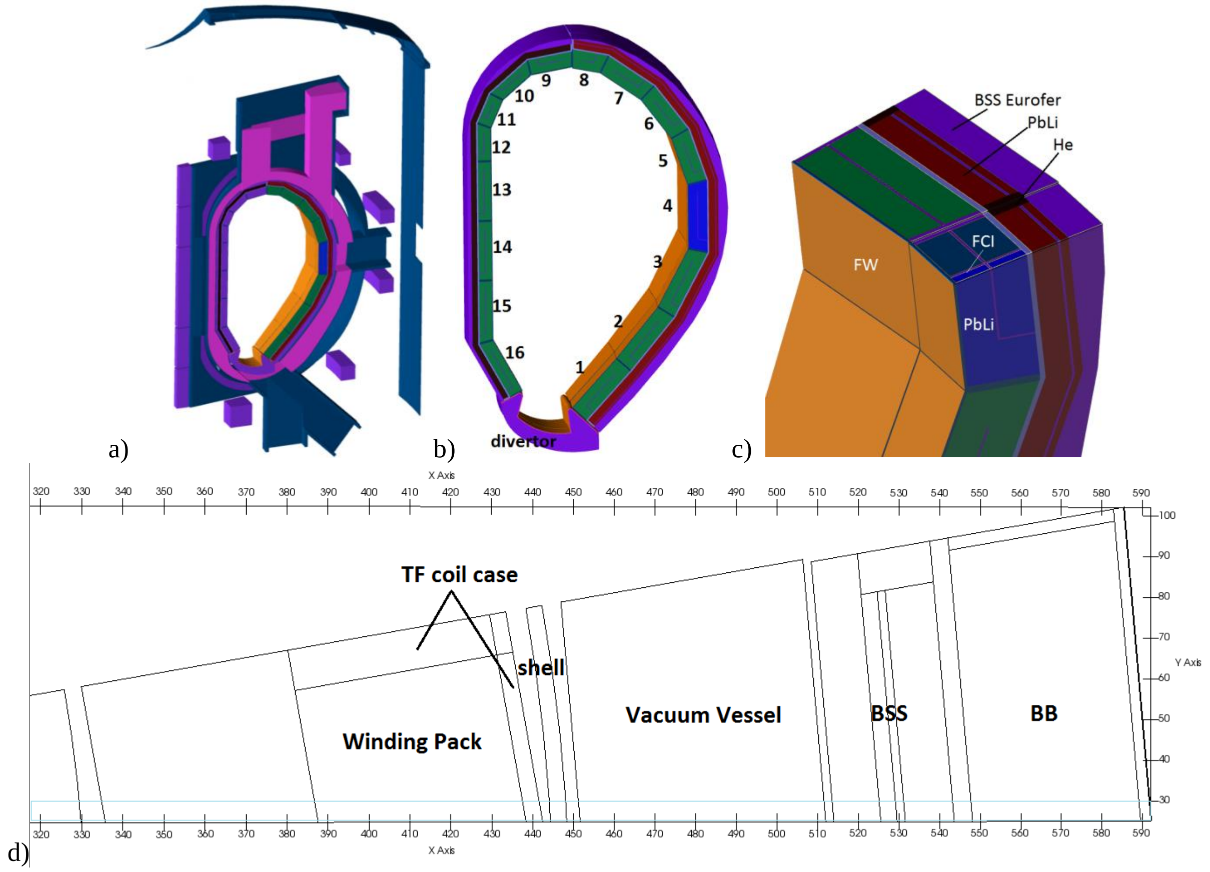


Fig. 2. DCLL DEMO2015: a) whole reactor; b) BB segment, BSS and divertor; c) detail of OB BB module (partially heterogenized) and its fully-heterogenized BSS, version 3.0; d) layout sketch of the IB side with XY coordinates (in cyan the Y=25:30cm region in which radial profiles of neutronic responses have been assessed).

3. First phase: DEMO2014 DCLL improvement and primary neutronic responses

Along the 1st phase of the project different versions of the DCLL model, based on DEMO2014, have been developed in order to achieve the best behaviour in terms of nuclear responses but also taking into account mechanical, manufacturing and chemical aspects.

Of these, two were more deeply analysed. Starting from a version – reported in [8][9] - in which 64 cm of breeder thickness was used in the OB region, the next step was increasing it to 69 cm – as described and analysed in [11][12]. Other changes (Fig. 3) were also implemented in order to improve mainly the structural and safety aspects of the design (with special attention to possible in-box LOCA).

Some of them, relevant for the reactor neutronic behaviour, are described in [12] and summarized as follows: increasing of 1) FW thickness (from 20 to 25 mm) and 2) its He fraction (from 14 to 30%), 3) number of toroidal breeding channels (from 4 to 6), 4) radial thickness of the 3 radial OB breeding channels (from 30+18.5+15.5=64 cm to 30+22.2+17=69.2 cm), 5) radial thickness of the IB upper modules #11/10/9 (from 50 cm to 65/70/70 cm); 6) reduction of Helium manifolds (from 4 to 2); and 7) suppression of 1 stiffening toroidal plate from IB #12-15. Furthermore, from the initial [8] to this 2nd version [11], the use of a detailed Back Supporting Structure (BSS) and helium internal manifold (Fig. 1c-d) was implemented although the Flow Channel Inserts (FCI) foreseen to mitigate the magnetohydrodynamic (MHD) effects were not still included.

With the exception of the points 1 and 3 that would have a strong negative impact on the TBR, the other modifications could balance and have positive influence on it. The influence of those changes on the T breeding performance is more widely described in [12]. Summarizing, a reduction in the TBR from 1.13 to 1.104 is produced, although remaining higher than the target. In the 2nd model, the number of stiffening plates was increased to improve the structural stability and the FW thickness was incremented being crucial to avoid the consequences of an in-box LOCA but with strong implications on the tritium production. Hence, it has been required to take some strategical solutions to balance the negative effects of these two modifications, as enlarging the radial thickness of the upper IB modules (Fig. 3a). This allowed keeping the global TBR higher than 1.1.

The effect of the divertor composition is highlighted in Table 2 showing that the use of a higher amount of water cooling inside the steel cassette implies a deterioration of the breeder structures performances in ~3% meaning that the choice of this component is non-detachable from the breeding performances.

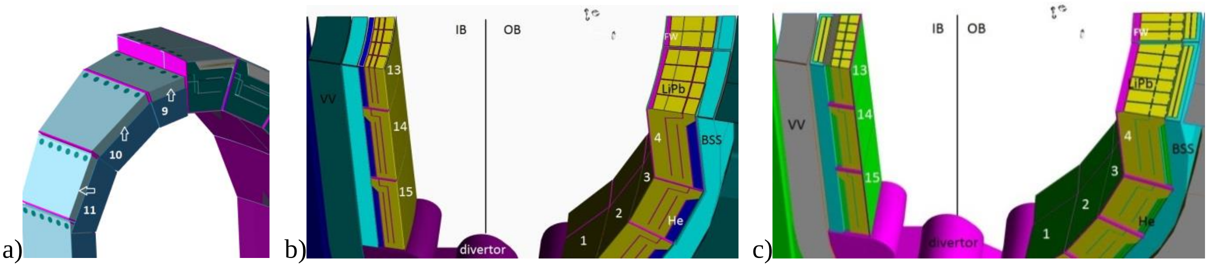


Fig. 3. DCLL evolution: a) increase of IB upper modules' thickness; b) horizontal cut of the 1st DEMO2014 DCLL with 4 toroidal PbLi channels per module and an homogenized BSS; c) 2nd DEMO2014 DCLL with 6 toroidal PbLi channels per module, a more heterogenized BSS, and number of the IB toroidal stiffening plates reduced from 2 to 1.

DEMO2014 Version 2		nº	T/n in 360º prev. div.	new div.	Δ%
BB	OB	1	7.32E-02	7.05E-02	
		2	9.62E-02	9.32E-02	
		3	1.14E-01	1.11E-01	
		4	1.52E-01	1.48E-01	
		5	1.11E-01	1.07E-01	
		6	8.66E-02	8.41E-02	
		7	6.39E-02	6.15E-02	
		8	4.39E-02	4.24E-02	
		tot	0.7408	0.7179	
	IB	9	3.06E-02	2.95E-02	
		10	4.66E-02	4.51E-02	
		11	3.80E-02	3.69E-02	
		12	2.28E-02	2.22E-02	
		13	5.94E-02	5.77E-02	
		14	5.78E-02	5.60E-02	
		15	4.58E-02	4.35E-02	
		tot	0.3009	0.2909	
		Total BB	1.0418	1.0088	-3.26%
BSS		OB	2.50E-02	2.46E-02	
		IB	3.76E-02	3.68E-02	
		total	6.26E-02	6.13E-02	-2.04%
		TBR	**1.104**	**1.070**	-3.19%

Table 2. TBR as local values inside the BB modules and BSS PbLi channels for the 2nd version of DEMO2014 DCLL with a standard divertor composition and with a new highly cooled one.

Table 3. Power breakdown along the main components of the DCLL DEMO2014 reactor.

DEMO2014 Components	Power generated (MW) Version 1	Version 2
BB + BSS	1229.32	1225.97
Divertor	262.49	265.08
VV + Ports + Coils	11.98	16.17
Total	1503.79	1507.22
$\mathbf{M_E}$	1.195	1.198

The other neutronic responses are also examined with reference to the design improvements. The power breakdown for the major reactor structures is shown in Table 3. Assuming a fusion power of 1572 MW and considering the total generated nuclear power of 1504 MW and 1507 MW for the two DCLL versions of DEMO2014, the obtained Energy Multiplication Factors M_E are 1.195 and 1.198 respectively (higher than the lower limit of the recommended range of Table 1), being M_E the ratio of the total nuclear power over the fusion neutron power (80% of 1572 MW).

For a preliminary evaluation of the shielding efficiency of the design, the nuclear heating (NH) in the reactor components needs to be assessed, paying attention to the TFC at IB equatorial level. It has been calculated as an average over poloidal regions of 50 cm. The results (Table 4) for the two DCLL DEMO2014 versions show that the IB equatorial values satisfy the recommendation for the NH in the winding pack, currently established in 50 W/m^3 (20 times lower than the ITER requirement). The limit is not satisfied in the IB upper zone and in the OB side. The problem is visualized in Fig. 4a and b, in which high streaming from the ports is observed affecting these TFC areas. The lack of shield in these zones is not of concern because the plugs were not developed for the generic DEMO2014.

Nonetheless the high relative uncertainties observed for the IB values of Table 4, the results indicate a certain depletion in the shielding function for the 2nd version of the DCLL, as the same behaviour is also observed for the OB side which values have very low statistic error (4%). The table also highlight the limits of analyses performed averaging over ranges of 50 cm as they are not able to capture small hotspots as evidenced when high resolutions results (Table 5) are provided.

In fact, the NH has been also calculated as radial profile (Fig. 4c) from the FW to the TFC in voxels of 5x5x5 cm^3 for the 2nd version of DCLL2014. The values are given for Eurofer (from FW to BSS) and for 2 compositions of VV steel with and without 2% of boron. While in Table 4 the values in vertical segments of 50 cm (and in the overall TFC thickness) were between 1-3 W/m^3, now the local values (Table 5) highlight peaks of 31-17 W/m^3 although being under the 50 W/m^3 limit. Thus, the use of a well suited spatial resolution to give results is of special importance when the recommendations for the design are based on peak values and not on integral values, as are the established for the TFC quench. It is worth mentioning that in this

DEMO model the TFC is a thick massive block of homogenized material, including steel casing, epoxy insulator, superconductor and winding pack [9]. Therefore fluctuation observed in the tables is only due to the statistics of the calculation.

Table 4. Nuclear Heating on the TF coil for the 2 DEMO2014 DCLL versions.

Distance from plane Z=0 (cm)	Version1 DCLL DEMO2014						Version2 DCLL DEMO2014					
	IB			OB			IB			OB		
	MeV/gr	relative uncert.	W/m^3	MeV/gr	relative uncert.	W/m^3	MeV/gr	relative uncert.	W/m^3	MeV/gr	relative uncert.	W/m^3
>160	1.80E-13	0.010	88.57	5.88E-13	0.007	288.83	2.97E-13	0.0082	145.75	7.74E-13	0.0068	380.25
160:110	9.08E-16	0.200	0.45	1.51E-13	0.053	74.32	2.06E-15	0.2172	1.01	1.89E-13	0.0491	93.00
110:60	1.42E-15	0.323	0.70	1.99E-13	0.045	97.70	3.90E-15	0.2378	1.91	2.63E-13	0.0421	129.12
60:10	2.39E-15	0.350	1.17	2.32E-13	0.040	113.73	2.44E-15	0.2374	1.20	3.01E-13	0.0371	147.67
10:-40	3.32E-15	0.280	1.63	2.51E-13	0.041	123.45	6.08E-15	0.2368	2.99	3.34E-13	0.0385	164.10
-40:-90	3.15E-15	0.383	1.55	2.27E-13	0.043	111.66	6.68E-15	0.2681	3.28	2.89E-13	0.0389	142.14
< -90	9.60E-16	0.113	0.47	4.80E-14	0.022	23.57	1.56E-15	0.0967	0.77	6.37E-14	0.0201	31.26

Table 5. Nuclear Heating (W/cm^3) and integral neutron Fluence (n/cm^2) radial values in the IB TFC mid-plane.

Component	distance from x=0 (cm)	SS316LN Austenitic Steel VV			Borated SS316LN Austenitic Steel (at 2% B) VV		
		Nuclear Heating (W/cm^3)	Total fluence (n/cm^2 x FPY)	at 6 FPY	Nuclear Heating (W/cm^3)	Total fluence (n/cm^2 x FPY)	at 6 FPY
TF coil	502.5	3.14E-05	3.25E+16	1.95E+17	1.70E-05	4.59E+16	2.75E+17
	497.5	1.14E-05	2.04E+16	1.22E+17	3.07E-06	2.80E+16	1.68E+17
	492.5	7.00E-06	1.22E+16	7.33E+16	1.33E-05	1.73E+16	1.04E+17
	487.5	1.50E-05	1.20E+16	7.18E+16	1.10E-05	2.48E+16	1.49E+17
	482.5	1.06E-06	9.44E+15	5.66E+16	1.57E-06	3.03E+15	1.82E+16
LIMITS		**<5e-5 W/cm^3**		**<1e18 cm^{-2}**	**<5e-5 W/cm^3**		**<1e18 cm^{-2}**

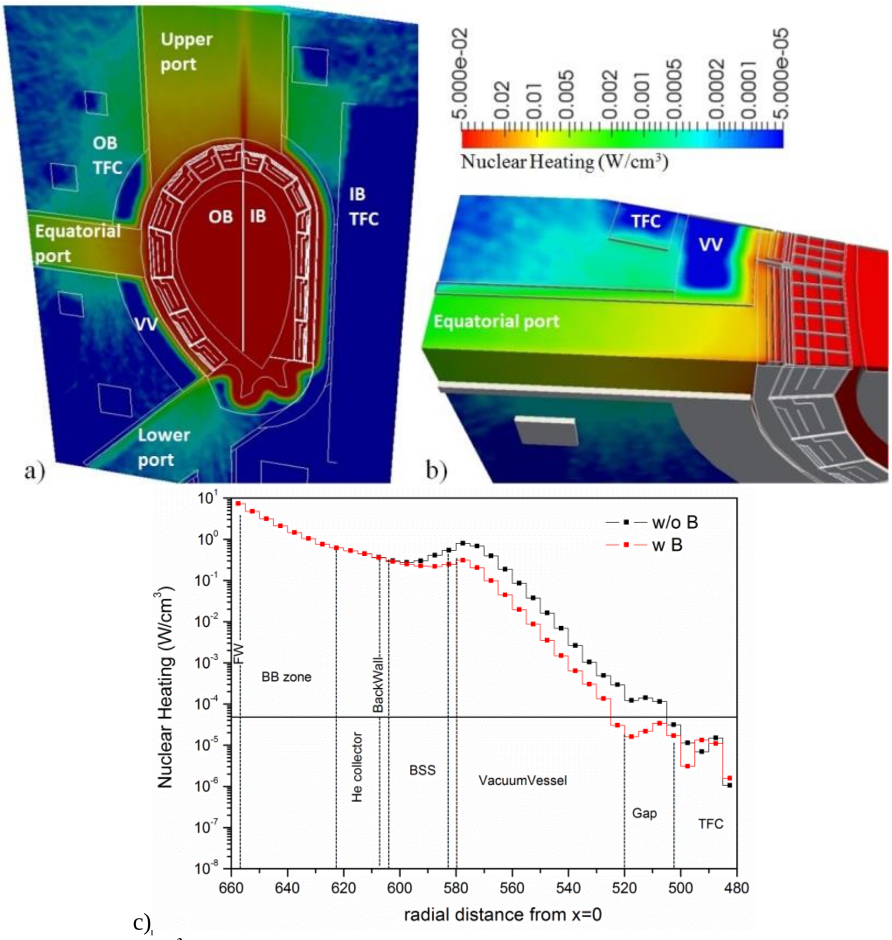


Fig. 4. Nuclear Heating (W/cm^3): a) 3D map "mesh tallies" in the whole DCLL DEMO; b) horizontal cut in the OB side. Due to the unplugged ports the limit ($5 \cdot 10^{-5}$ W/cm^3) is not fulfilled where the colour is warmer than blue (values over the scale are all in red and under the scale are all in blue); c) radial profiles in the IB mid-plane from the FW to the TF coil.

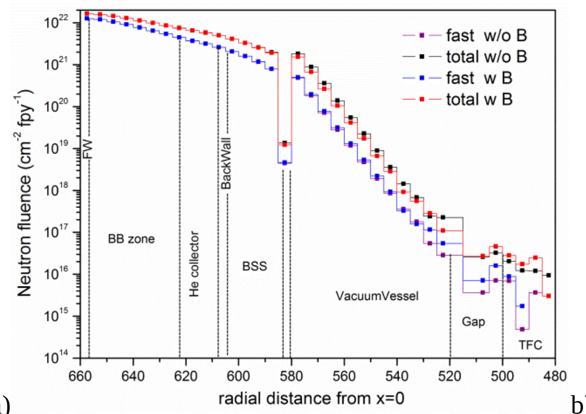
Once the requirements of TBR, M_E and NH have been demonstrated to be fulfilled, the other shielding responses have been examined, although, being very similar in both the two versions of the DCLL DEMO2014, they are shown only for the 2nd version.

3.1 Neutron Fluence

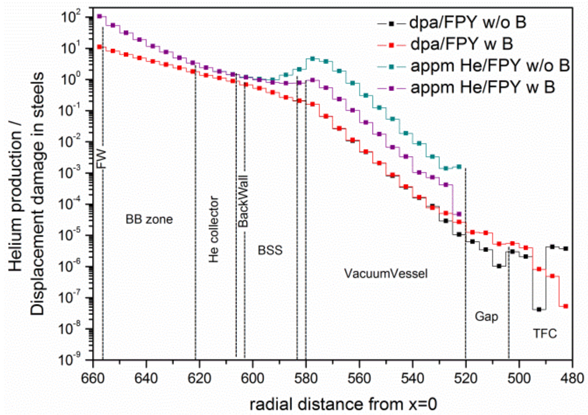
Fundamental requirements regard the total and fast (E> 0.1 MeV) fluence in different parts of the TFC (Table 1). The results, calculated using the same procedure than before, are given in Fig.5a and Table 5. Values multiplied for the TFC lifetime (6 full power years, FPY [1]) indicate that the limit of 10^{18} n/cm^2 is fulfilled for both compositions of VV steel (with and without boron).

3.2 Helium production and radiation damage

The requirements referred as structural ones (Table 1), and also one of the TFC requirements, are relative to helium production (appm He) and radiation damage (dpa). Both have been assessed as radial profiles in the IB mid-plane from FW to TFC (Fig.5b). Tabulated values are given in Table 6. Here the annual values of FW have been multiplied by 1.57 and 4.43 FPY to cover the 2 irradiation scenarios foreseen for blankets [1], while 6 FPY values are extrapolated for VV and TFC. All the limits are satisfied with the exception of the He production in the first 15-25 radial cm of VV (with-w/o B), implying it could be not re-welded. The helium due to the extra boron in VV has been not taken into account since only the produced inside steel has been considered for comparison. Those values which not fulfil the limits are highlighted in bold and red.



a)



b)

Fig. 5. a) Neutron fluence (total and fast as n/cm^2 per FPY); (b) Helium production (appm He/ FPY) and damage (dpa/FPY) radial profiles in the IB mid-plane from the FW to the TF coil.

General 3D maps as annual values have been represented in Fig. 6 a) for helium production in Eurofer and austenitic steel components; and in Fig. 6 b) for dpa with a reduced scale to show deeply the results in the TFC. Multiplying the annual values by 6 FPY, we can see that there are not hotspots overpassing the 10^{-4} dpa TFC quench limit.

Table 6. Helium production (appm He) and damage (dpa) radial profiles in the IB mid-plane for the VV, TFC and FW using two steel VV compositions with and without boron.

		SS316LN Austenitic Steel VV				Borated SS316LN Austenitic Steel (at 2% B) VV			
Component	distance (cm) from x=0	appm He/ FPY	at 6 FPY	dpa/FPY	at 6 FPY	appm He/ FPY	at 6 FPY	dpa/FPY	at 6 FPY
Vacuum Vessel	577.5	4.60	**27.62**	0.159	0.953	0.944	**5.66**	0.161	0.967
	572.5	3.75	**22.49**	6.49E-02	0.390	0.535	**3.21**	0.066	0.396
	567.5	1.85	**11.12**	2.62E-02	0.157	0.232	**1.39**	0.027	0.162
	562.5	0.757	**4.54**	1.08E-02	6.50E-02	0.102	0.609	0.011	0.068
	557.5	0.303	**1.82**	4.69E-03	2.81E-02	4.15E-02	0.249	4.84E-03	2.90E-02
	552.5	0.124	0.743	2.06E-03	1.24E-02	1.75E-02	0.105	2.08E-03	1.25E-02
	547.5	5.37E-02	0.322	8.09E-04	4.86E-03	6.68E-03	0.040	8.62E-04	5.17E-03
	542.5	1.86E-02	0.112	3.46E-04	2.08E-03	3.34E-03	2.00E-02	3.64E-04	2.18E-03
	537.5	8.86E-03	5.32E-02	1.59E-04	9.54E-04	1.03E-03	6.18E-03	1.66E-04	9.97E-04
	532.5	3.32E-03	1.99E-02	8.53E-05	5.12E-04	7.20E-04	4.32E-03	7.58E-05	4.55E-04
	527.5	1.39E-03	8.35E-03	2.89E-05	1.73E-04	4.18E-04	2.51E-03	5.11E-05	3.07E-04
	522.5	1.57E-03	9.44E-03	1.06E-05	6.36E-05	4.75E-05	2.85E-04	2.65E-05	1.59E-04
LIMIT			**> 1 appm He**		**< 2.75 dpa**		**> 1 appm He**		**< 2.75 dpa**
TF coil	502.5			2.99E-06	1.79E-05			5.47E-06	3.28E-05
	497.5			2.06E-06	1.23E-05			3.97E-06	2.38E-05
	492.5			4.17E-08	2.50E-07			8.16E-07	4.90E-06
	487.5			4.25E-06	2.55E-05			4.88E-07	2.93E-06
	482.5			3.73E-06	2.24E-05			5.28E-08	3.17E-07
LIMIT					**<10^{-4}dpa**				**<10^{-4}dpa**
FW Eurofer	657.5	dpa/FPY	10.94	at 1.57 FPY	17.18	**<20 dpa**	at 4.43 FPY	48.47	**<50 dpa**

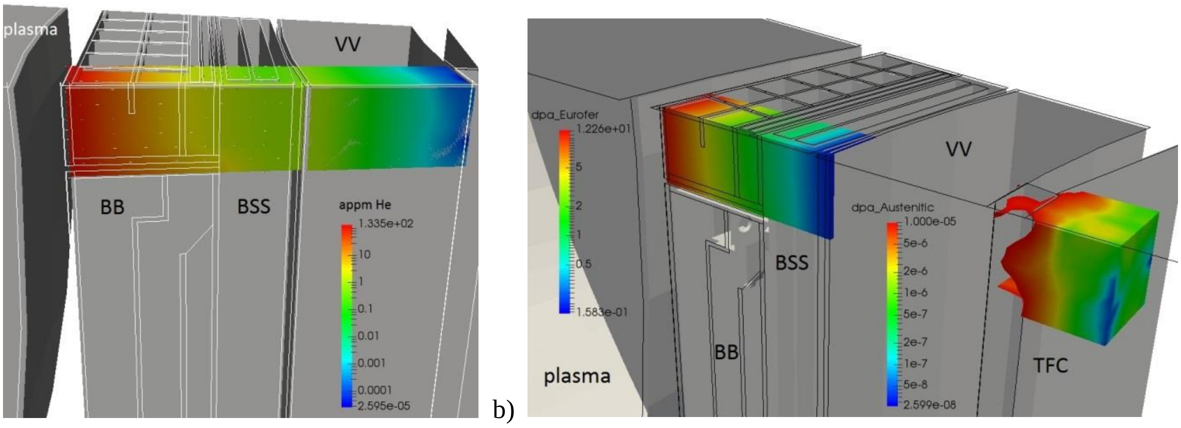
a)  b)

Fig. 6. Helium production (appm He/ FPY) and damage (dpa/FPY) 3D maps ('mesh tallies') around the IB mid-plane for Eurofer and austenitic steel from the FW to the TF coil.

4. Second phase: from optimized DCLL DEMO2014 to DCLL DEMO2015

In 2015 an important change was produced among the EUROfusion Programme resulting in the implementation of a strongly different DEMO design. The aspect ratio was identified as one of the most important parameters still relatively unconstrained. For a given major radius, a lower aspect ratio implies a larger plasma volume and lower toroidal field, resulting in a higher TBR, better vertical stability, and lower disruption forces, amongst other benefits [21]. The relation with the TBR is implicit in the fact that with these conditions a smaller divertor and thus a major space for the breeding structure is possible. The DEMO aspect ratio was consequently changed from 4 to 3.1. Thus, the baseline for DEMO determined by the PROCESS system code also changed [13] resulting in a larger and more powerful plasma (from 1400 to 2500 m^3 of volume and from 1572 to 2037 MW of fusion power). The divertor was reduced [18] and the higher breeding blanket vertical size (Fig. 2a) allowed reducing its radial dimension maintaining a high TBR potential.

The previously described DCLL model has been adapted to the specific features of DEMO2015 and has been studied from the nuclear perspective. Some of the preliminary design features of the 1st DCLL DEMO2015 version (named version 3.0) which have been investigated from the neutronic point of view (and improved where needed) are summarized as follows: 1) Toroidal breeding channels increased from 6 to 7; 2) Helium internal manifold reduced and inserted horizontally in the bottom of the module instead of vertically in the back; 3) Reduction from 3 to 2 radial OB BB channels (1 stiffening toroidal plate suppressed); 4) Thickness of the 2 breeding channels is 29+29.65=58.65 cm /19.65+20=39.65 cm OB/IB; 5) The BB radial size is 65/46 cm OB/IB while the BSS occupies 66/32 cm in the equatorial plane for a total of 130/78 cm (to be compared with the previous 91/50 BB, 39/24.5 BSS, 130/74.4 cm total); 6) number of IB modules in one segment passed from 7 to 8 (as the vertical dimensions increased).

The model is a 3D *quasi*-heterogenized model with the equatorial OB module fully heterogenized (stiffening plates, FCI, breeder channels and walls are all separately described). The main nuclear responses have been studied as described in the following.

4.1 Primary neutronic responses: Neutron Wall Loading, TBR and Nuclear Heating.

The Neutron Wall Loading (NWL) and TBR have been firstly examined for the newly established DCLL DEMO2015 version. The NWL poloidal distribution allows seeing the regions in which a special care for shielding could be considered. Such poloidal distribution in comparison with the previous DCLL DEMO2014 is presented in Fig. 7, where the same mean value (1.03 MW/m^2) is shown. A similar strong poloidal variation is observed with two peaks at the equatorial level (now shifted to modules OB#3 and IB#14).

The tritium production has been also evaluated as essential condition for the reactor viability. The results are presented in Table 7 in which local values are shown. The total TBR in the BB modules is 1.158. Adding up the contribution of the BSS PbLi channels the final value reach 1.266. Due to the previously shown relevance of the divertor composition on the breeding performances of the reactor the new highly cooled divertor (at 46% of water) has been also tested. In such case the TBR would drop to 1.203 (-5.24%) being now the difference even stronger than before due to the extreme difference in the divertor composition of the new generic DEMO2015 (Eurofer cassette without water).

The power breakdown for the major reactor structures and the sharing-out among BB modules are shown respectively in Table 8 and 9. Assuming now a fusion power of 2037 MW and considering the total generated nuclear power of 1932 MW for the preliminary DCLL versions of DEMO2015, the obtained Energy Multiplication Factor M_E is 1.185 (within the recommended values and higher than the lower limit of the range of Table 1), being M_E the ratio of the total nuclear power over the fusion neutron power (80% of 2037 MW).

The nuclear heating has been also calculated as radial profile (Fig. 8a) from the FW to the TFC in voxels of 1x5x5 cm^3 (xyz). The values are given for Eurofer (from FW to BSS) and for Austenitic steel 316LN (from the VV to the TFC). The NH “mesh tally” map in the IB equatorial region is also provided from the FW to the TFC in steels materials (Fig. 8b). In both pictures it is possible to observe some small hotspot in the front position of the TFC steel case that seems able to protect the inner part (winding pack) of the coil and in the boundary gap between sectors. Tabulated values for the TFC Case and Winding Pack are also given in Table 10.

Once the requirements of TBR, M_E and NH are fulfilled, the other shielding and damage response have been assessed to answer the other fundamental requirements for the reactor viability.

Table 7. TBR as local values inside the BB modules and BSS PbLi channels for the DEMO2015 DCLL with a standard divertor composition and with a new highly cooled one.

DEMO2015		nº	T/n in 360º prev. div.	new div.	Δ%
BB	OB	1	8.81E-02	7.92E-02	
		2	1.19E-01	1.14E-01	
		3	1.42E-01	1.37E-01	
		4	1.49E-01	1.43E-01	
		5	1.08E-01	1.03E-01	
		6	9.80E-02	9.32E-02	
		7	8.25E-02	7.83E-02	
		8	4.28E-02	4.06E-02	
		tot	8.29E-01	7.87E-01	
	IB	9	4.81E-02	4.55E-02	
		10	3.65E-02	3.46E-02	
		11	2.44E-02	2.33E-02	
		12	2.63E-02	2.51E-02	
		13	4.98E-02	4.79E-02	
		14	5.03E-02	4.83E-02	
		15	4.52E-02	4.27E-02	
		16	4.78E-02	4.35E-02	
		tot	3.28E-01	3.11E-01	
		total BB	1.158	1.098	-5.4%
BSS		OB	6.93E-02	6.72E-02	
		IB	3.92E-02	3.77E-02	
		total	1.09E-01	1.05E-01	-3.49%
		TBR	**1.266**	**1.203**	-5.24%

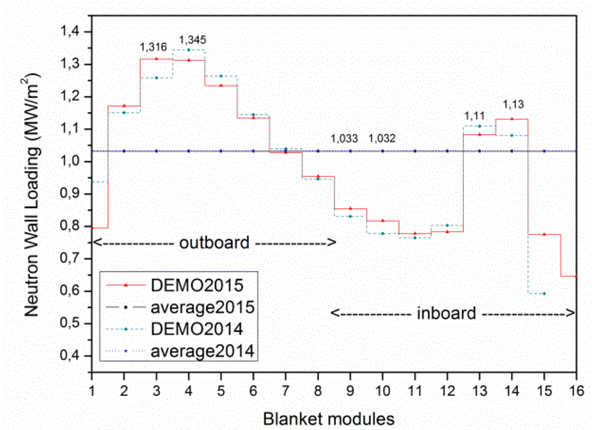


Fig.7. NWL poloidal distributions and averages for DCLL DEMO2014 and 2015.

Table 8. Power breakdown between the main components of the DCLL DEMO baseline 2015.

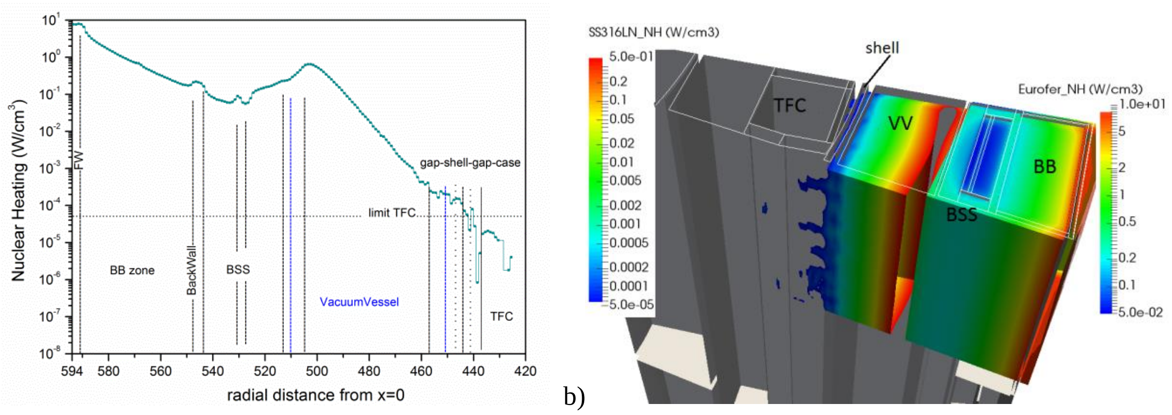
DCLL2015 Components	Power generated (MW)
BB	1678
BSS	81.94
Divertor	118.14
VV + Ports + Shell+ Coils	54.58
Total	1932.67
M_E	1.185

Table 9. Power distribution among BB modules for DCLL DEMO baseline 2015

MW		OBL	OBC
OB	1	1.956	1.335
	2	3.119	1.699
	3	3.999	1.869
	4	4.258	1.876
	5	3.028	1.377
	6	2.628	1.310
	7	2.054	1.204
	8	0.966	0.694
	total	**22.01**	**11.37**
IB	9	1.884	
	10	1.414	
	11	0.962	
	12	1.034	
	13	2.152	
	14	2.208	
	15	1.789	
	16	1.795	
	total	**13.24**	
Total half-sector	**46.61**	**Total 360º**	**1678**

Table 10. Nuclear Heating (W/cm^3) and radiation damage (dpa/fpy) radial values in the IB TFC mid-plane (in voxels of x=1cm, y=5cm, z=5cm).

TFC components	distance (cm) from x=0	dpa/fpy	at 6fpy	Nuclear Heating (W/cm^3)
LIMITS			**<10^{-4}dpa**	**<5e-5 W/cm^3**
Case	441.5	5.66E-07	3.40E-06	2.20E-05
	440.5	1.56E-08	9.38E-08	**7.97E-05**
	439.5	1.96E-08	1.17E-07	2.77E-05
	438.5	2.25E-08	1.35E-07	8.39E-07
	437.5	1.51E-08	9.05E-08	5.20E-06
Winding Pack	436.5	0.00E+00	-	1.73E-05
	435.5	2.18E-08	1.31E-07	1.93E-05
	434.5	2.79E-08	1.68E-07	2.07E-05
	433.5	4.99E-09	2.99E-08	1.90E-05
	432.5	1.99E-08	1.19E-07	1.80E-05
	431.5	3.16E-07	1.90E-06	1.39E-05
	430.5	1.54E-06	9.27E-06	1.16E-05



a) b)

Fig. 8. Nuclear heating a) radial profiles in the IB mid-plane from the FW to the TFC; b) 3D maps: in the IB side of the DCLL DEMO2015; the limit ($5{\cdot}10^{-5}$ W/cm^3) for the TFC is not fulfilled if the colour is warmer than blue. Values under and over the scale are hidden.

4.2 Neutron Fluence, helium production and radiation damage

Nuclear fluences, helium production and dpa have been calculated as radial profiles giving values in radial ranges of 1cm per vertical and toroidal ranges of 5 x 5 cm (1 x 5 x 5 cm^3 voxels). The same discretization has been adopted for the “mesh tallies” results to obtain very precise 3D maps. Results of total and fast fluences from the FW to the TFC are shown in Figure 9 where it is possible to observe that the limit of 10^{18} n/cm^2 is fulfilled also when multiplying for the 6FPY foreseen for the tokamak operation.

The radial profiles and the mapped results of dpa/fpy and appmHe/fpy are all shown in Figure 10. Tabulated values are also given in Table 11 for the FW and in Table 12 for the VV. In the maps it is to notice that, as for the fluence, the dpa limit in the TFC is not overpassed even for a period of 6 FPY. The re-welding of the VV remains as unaccomplished criterion (as for DCLL 2014 versions) since the helium production (Table 12) in the first centimetres of the VV is over the limit of 1 appm already after 1 year of operation. There is still not too much concern about this, since the re-welding of the VV is an issue still under study.

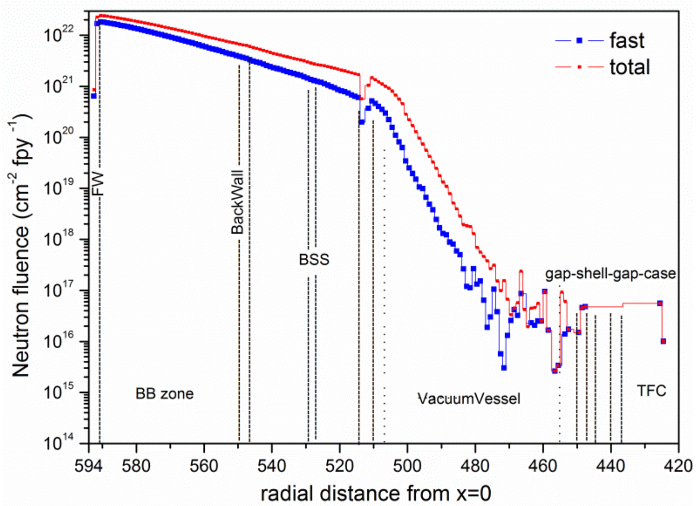


Fig. 9. Neutron fluence (total and fast as n/cm² per FPY).

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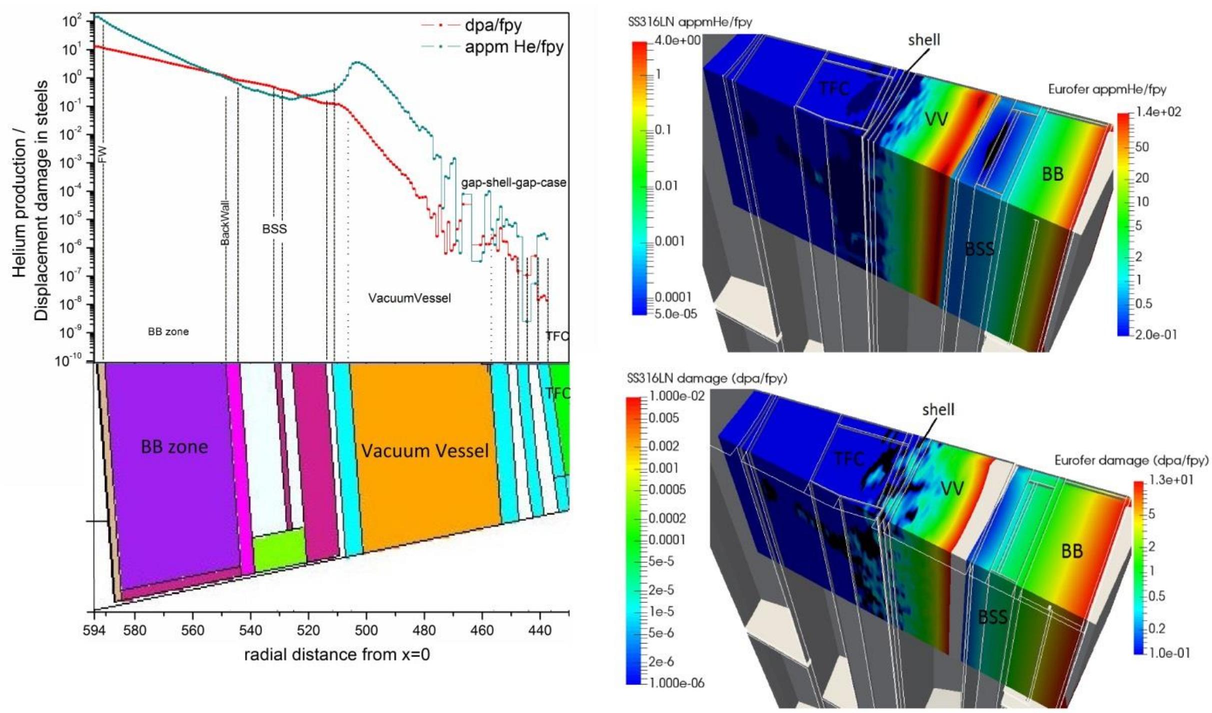

Fig. 10. Helium production (appm He/ FPY) and damage (dpa/FPY) radial profiles and 3D maps ('mesh tallies') around the IB mid-plane for Eurofer and austenitic steel from the FW to the TF coil.

Table 11. Helium production (appm He/fpy) and radiation damage (dpa/fpy) radial values in the IB FW mid-plane (in voxels of x=1cm, y=5cm, z=5cm).

	distance (cm) from x=0	appm He/ FPY	dpa/fpy	at 1.57 FPY	at 4.43FPY
LIMITS				**<20 dpa**	**<50 dpa**
Eurofer FW	591.5	1.24E+02	1.22E+01	19.15	**54.04**
	590.5	1.04E+02	1.13E+01	17.75	50.09
	589.5	8.88E+01	1.07E+01	16.85	47.55

From Table 11 it is outstanding that the first centimetre of the FW would not fulfil the limit of 50 dpa for the second BB phase which should withstand the 4.43 FPY of operation foreseen. This apparent deterioration from DCLL2014 to 2015 could be due both to the different plasma specifications or could be simply the most precise results that make evidence this behaviour (to recall that the results in DCLL2014 were averaged on radial thicknesses of 5 cm, thus for the

2.5cm FW only one value was given). It will be possible to clarify this point when a heterogenized neutronic model of the FW with a complete description of the helium channels will be available.

In Table 12 it is shown that the damage limit of 2.75 dpa for the VV is already observed at the front part of the VV and along all its thickness.

Further improvements are ongoing in order to reduce the radiation impact on the structures since the margin to keep the target TBR is high.

Table 12. Helium production (appm He/fpy) and radiation damage (dpa/fpy) radial values in the IB VV mid-plane (in voxels of x=1cm, y=5cm, z=5cm).

	distance (cm) from x=0	appm He/ FPY	at 6 FPY	dpa/fpy	at 6 FPY
	LIMITS		**<1 appmHe**		**<2.75 dpa**
SS316LN austenitic steel Vacuum Vessel	511.5	3.59E-01	**2.15**	1.28E-01	7.66E-01
	510.5	3.95E-01	**2.37**	1.18E-01	7.06E-01
	509.5	4.88E-01	**2.93**	1.22E-01	7.31E-01
	508.5	6.22E-01	**3.73**	1.07E-01	6.42E-01
	507.5	8.56E-01	**5.14**	9.35E-02	5.61E-01
	506.5	1.24E+00	**7.46**	7.84E-02	4.71E-01
	505.5	2.28E+00	**13.68**	6.22E-02	3.73E-01
	504.5	3.26E+00	**19.56**	4.63E-02	2.78E-01
	503.5	3.61E+00	**21.65**	3.51E-02	2.10E-01
	502.5	3.58E+00	**21.50**	2.68E-02	1.61E-01
	501.5	3.24E+00	**19.41**	2.00E-02	1.20E-01
	500.5	2.85E+00	**17.08**	1.49E-02	8.96E-02
	499.5	2.34E+00	**14.03**	1.14E-02	6.82E-02
	498.5	1.98E+00	**11.87**	8.48E-03	5.09E-02
	497.5	1.66E+00	**9.94**	6.02E-03	3.61E-02
	496.5	1.23E+00	**7.38**	4.65E-03	2.79E-02
	495.5	9.40E-01	**5.64**	3.59E-03	2.15E-02
	494.5	7.62E-01	**4.57**	2.85E-03	1.71E-02
	493.5	5.52E-01	**3.31**	1.96E-03	1.18E-02
	492.5	4.42E-01	**2.65**	1.48E-03	8.87E-03
	491.5	3.34E-01	**2.01**	1.18E-03	7.11E-03
	490.5	2.53E-01	**1.52**	9.22E-04	5.53E-03
	489.5	2.03E-01	**1.22**	7.49E-04	4.49E-03
	488.5	1.33E-01	0.80	6.05E-04	3.63E-03
	487.5	9.54E-02	0.57	4.20E-04	2.52E-03
	…	…	…	…	…
	447.5	2.72E-06	0.41	1.63E-07	2.35E-03

4.3 Accuracy of the results

Regarding the statistic uncertainty of the simulations, the variance reduction technique of importances [15] has been used to improve the accuracy of the responses. As general behaviour, good relative uncertainties are obtained for cell based tallies: from 0.06% to 0.7% (the maximum in the farthest points of the BSS from plasma) for the TBR; from 0.03% to 0.3% (from the FW to the PF coils) for the power deposited in the OB components and from 0.05% to 8% in the IB components (from the FW to the PF coils) calculated as global cell values; for mesh tallies values the error is less than 5% up to the half of the VV thickness although for zones very far from plasma points with more than 10% uncertainty are observed.

In fact, the radial profiles (Figures 8, 9, 10) extracted from the maps obtained at very High

Resolution (HR) ($1x5x5cm^3$) have shown high relative uncertainties from a radial distance of 480 cm (due to the very low absolute values in such shielded regions far from plasma). Hence, the variance reduction technique of importances seems to be not enough in certain zones such as the VV. In fact, the central part of this component, in the common neutronic model provided [14], is made by only one very thick cell of 1m and thus the method fails in attributing it a radial variation of importances. For this reason the previous HR radial profiles have been verified and complemented by profiles obtained in coarse meshes over 5 cm in radial dimensions (X), 50 cm as vertical size (Z) and "Wall-to-Wall" in toroidal direction (from the plane Y=0 to the plane Y=102 cm at the boundaries of the IB segment) in which averages done on bigger volumes allow lower statistic uncertainty.

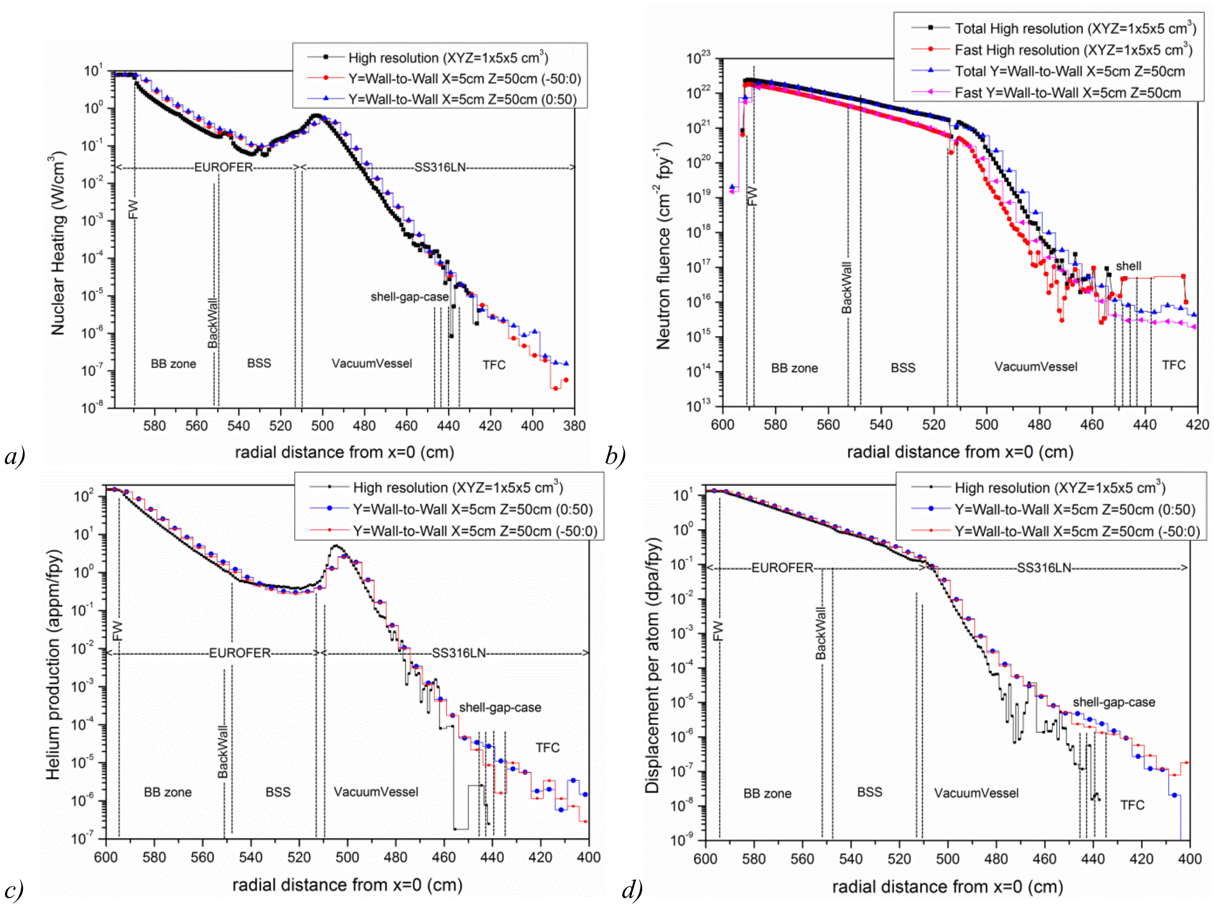

Fig. 11. Comparisons among the results obtained with a low spatial resolution mesh of X=5cm, Y=wall-to-wall, Z=50cm and the previous high spatial resolution mesh of X=1cm, Y=5cm, Z=5cm. a) Nuclear Heating, b) Neutron fluence, c) Helium production and d) Displacement per atom.

For all the responses the general behaviour is similar comparing among the Low Resolution (LR) and the previous HR profiles, as observed in Figures 11a-d, meaning that the qualitative conclusions regarding the viability of the design - based on compliance with the limits - do not change. But, notwithstanding the averages over bigger volumes allow seeing accurate results very far from the plasma and much deeper inside the TFC, their limit is that the peak values shown in the HR profiles are now dumped and the fluctuations observed at the interfaces between materials are now eliminated by the homogenizing effect of the integral over big voxels. As already mentioned, this effect can be of special importance when the recommendations for the design are based on peak values and not on integral values, as those established for the TFC quench.

The differences in the maps' results by using a low spatial resolution vs. a high spatial resolution are also highlighted in figures 12a-b with their relative uncertainties displayed in figures 12c-d. For the HR results and uncertainties (fig. 12b-d) only the equatorial IB zone has been meshed (section 3) while for the LR maps (fig. 12a-c) all the reactor can be easily meshed (although a cut in the Z=0 plane has been done to display the values in such horizontal plane). The HR allows visualizing higher values in the FW zone (dumped down when LR is used) but poorest accuracy is obtained for values from the middle of the VV up to the Central Solenoid. The two sets of results are therefore a useful complement one of the other, to obtain very local results at good accuracy.

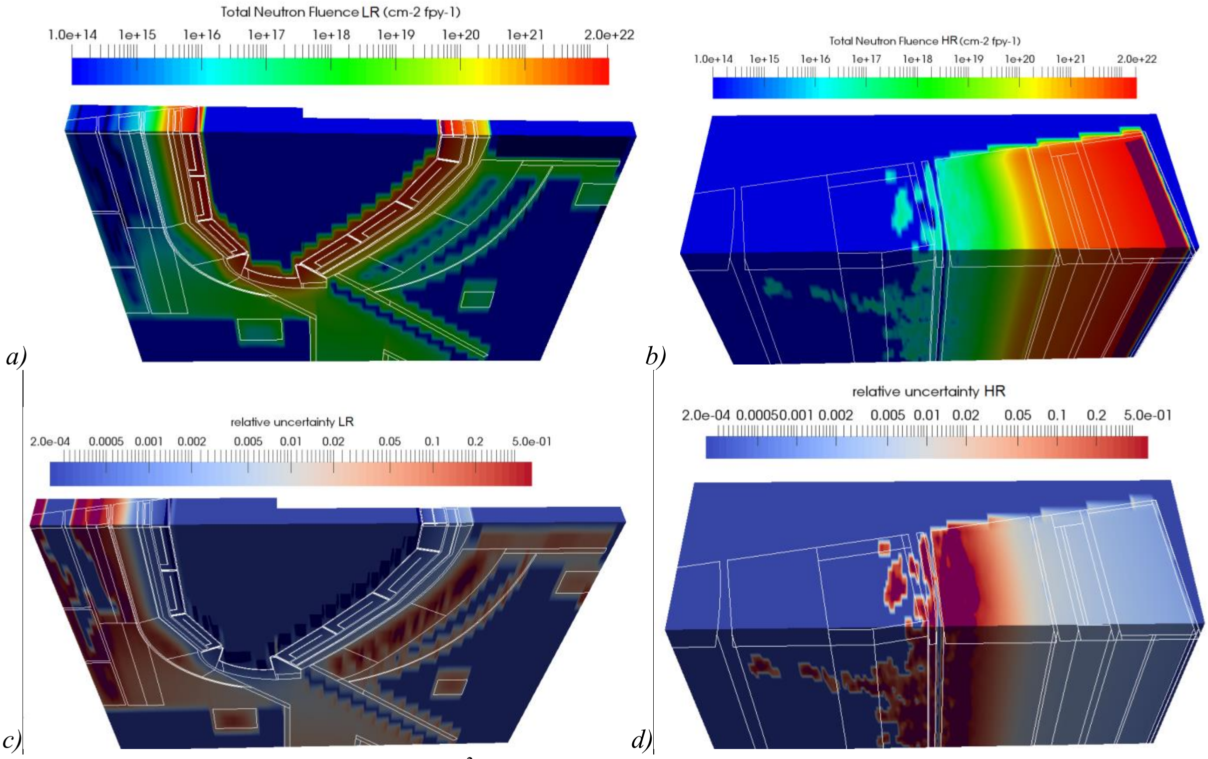

Fig. 12. (Up) Total Neutron fluence (n/cm² per FPY) and (down) statistical error associated. Left: Low spatial resolution meshs of X=5cm, Y=wall-to-wall, and Z=50cm for the entire reactor. Right: High spatial resolution mesh of X=1cm, Y=5cm, Z=5cm only for the IB equatorial region.

4.4 DCLL DEMO2015 improvements

As first improvement of the preliminary DCLL baseline 2015 v3.0 design, the IB side has been more accurately developed since it shows the most critical issues regarding shielding performances and, as known, a more accurate model could evidence a loss of these shielding performances.

At this purpose all the stiffening plates inside the IB modules have been included and their cooled zones have been separated from the plates' areas that are not required to be cooled, using different compositions for them. The same has been done for the Top and Bottom walls (since only the front area requires to be cooled with helium). Furthermore, the attachments between each BB module and the BSS have been introduced (which design has been justified by the structural analyses [22]) producing a more detailed model as depicted in Figures 13 and 14. Namely, the BB modules are attached to the BSS by means of bolts (100 mm width; 200 mm height) which are part of the Back Wall of the modules and pierce the BSS through the PbLi channels. They are separated from the PbLi by a common envelope and bonded to the rear side of the BSS.

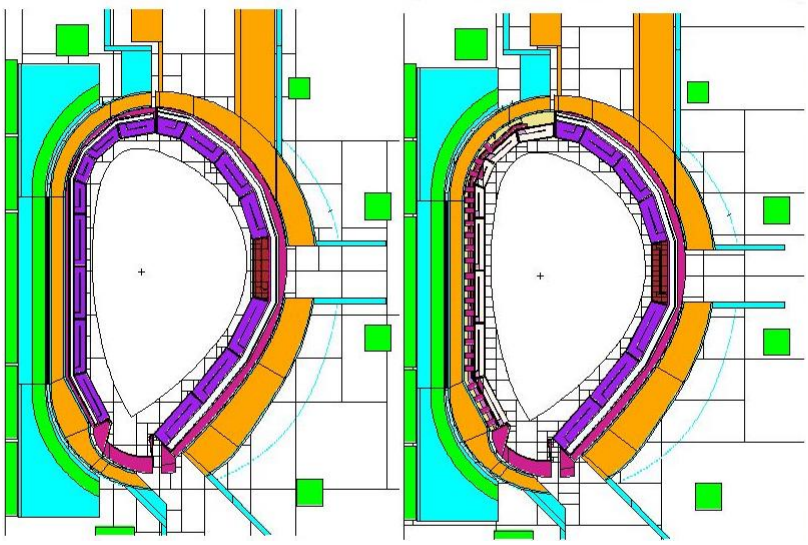

Fig. 13. DCLL DEMO2015 MCNP plot: (left) v3.0 DCLL design; (right) v3.1 with modified IB BB and BSS.

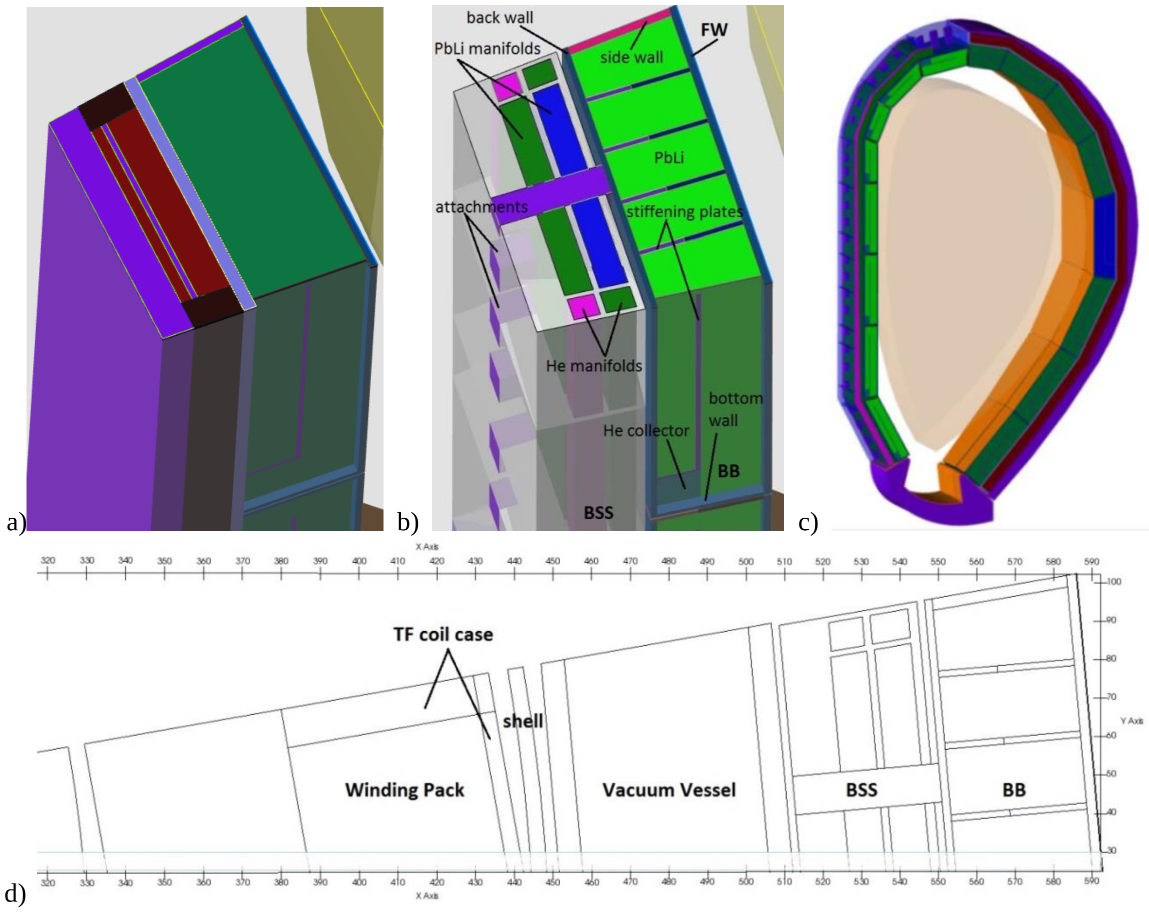

Fig. 14. DCLL DEMO2015 IB equatorial module comparison: a) v3.0 DCLL design; b) v3.1 with modified IB BB and BSS; c) complete segment to compare with fig. 2b; d) layout sketch of the IB side to compare with fig. 2d (in cyan colour the region in which radial profiles of the responses have been assessed).

Taking into account the concern about the IB mid-plane shielding performances emerged from the previous analyses a new layout has been planned for the IB side reducing the BB IB thickness in favour of the IB BSS one (also considering the big margins of TBR available). Furthermore it has been re-defined the required mass flow rates distribution for both the PbLi and He, implying that their channels thicknesses inside the BSS has been redesigned in order to maintain a profitable velocity along all their path reducing the pressure drop and corrosion. Such new redistribution has implied a thicker BSS - of 36 cm in the equatorial plane (instead of 32 cm) - and a reduced BB thickness - of 40 cm in the same plane (instead of 46 cm) – introducing a 2 cm gap in the middle (keeping the total size of BB+BSS to 78cm).

This new design version produced is called v3.1.

Thus, notwithstanding the new very detailed IB model, the global shielding performances are almost all maintained as shown in the graphs depicted in Figure 15 for nuclear heating, neutron fluences, helium production and dpa.

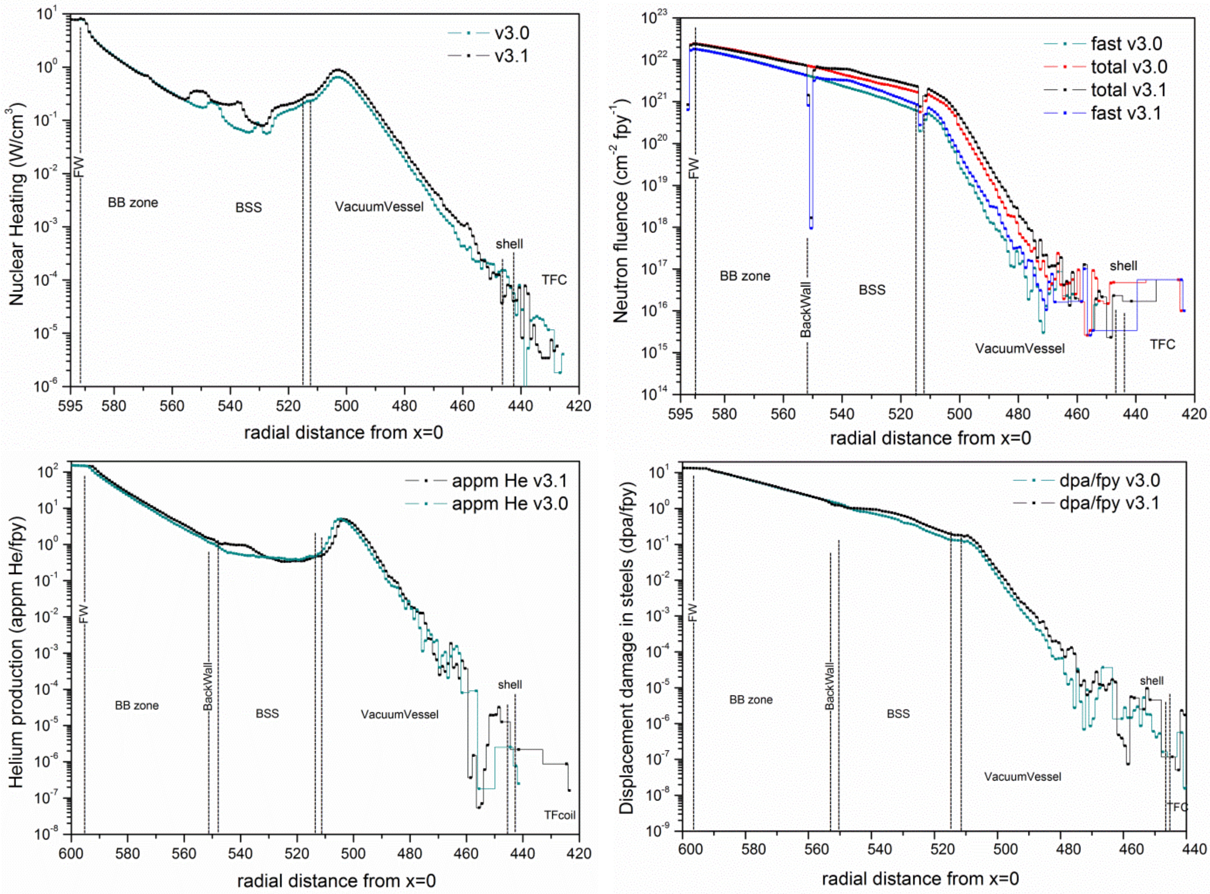

Fig. 15. DCLL DEMO2015 v3.0 and v3.1 shielding responses comparison in the IB mid plane.

The 3D map result of the nuclear heating shown in Figure 16 answers more in detail to the questions about shielding. In there it is depicted the nuclear heating from the FW to the BSS (Eurofer) and from the VV to the TFC (Austenitic steel) in the equatorial region of the IB v3.1. The values under and above the two scales are hidden, black or grey, to easily show where the limits are fulfilled or not. Hence, it is possible to observe that the limit of $5{\cdot}10^{-5}$ W/cm^3 for the TF coil winding pack is respected since the scale cover up to the steel case of the coil. Some higher values can be found in the lateral between segments in correspondence with the helium internal BSS manifolds and also with the gaps between segments.

Further analyses are ongoing to demonstrate it and once the OB side will be also developed in detail the global performances of the model will be exhaustively evaluated like the TBR performances.

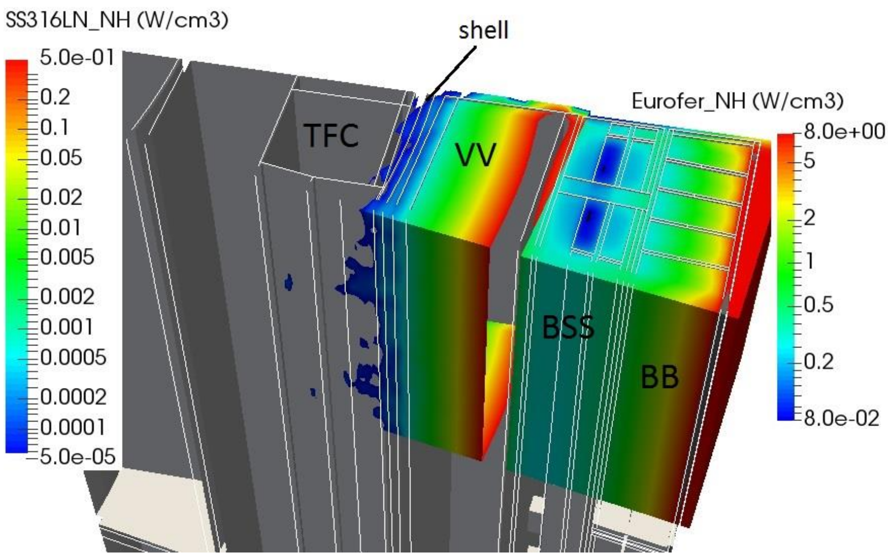

Fig.16. Nuclear heating 3D map in the DCLL DEMO2015 IBv3.1in Eurofer (from the FW to the BSS) and in Austenitic steel SS316LN (from the VV to the TFC): the limit ($5\cdot10^{-5}$ W/cm^3) for the TFC is not fulfilled if the colour is warmer than blue. Values under and over the scale are hidden, black or grey.

5. Discussion and Conclusions

The optimization of the design of a DCLL DEMO reactor developed among the EUROfusion Programme has been pursued based on its nuclear performances: tritium breeding functions, power extraction efficiency, shielding, structural damage protection, plasma confinement integrity, etc.

Starting from the plasma specifications and the generic DEMO design established in 2014, a conceptual DCLL design has been developed and analysed under different field of study being the neutronic results one of the drivers conditioning the evolution of the design. The paper highlights the progress made in the DCLL design in light of the observations and requirements explained. The design has been subsequently adapted to the novel DEMO2015 specifications in which a lower aspect ratio, larger plasma and reduced divertor have allowed improved tritium breeding performances leaving high margins for further evolutions. In fact the DCLL is probably one of the BB concepts with highest long term potential of improvement. The analyses carried out have demonstrated that the DCLL design is a mature option for a possible future DEMO reactor since it complies with highly demanding requirements on BB components and also on Vacuum Vessel and TF coils, such as tritium breeding, heat recovery and shielding, further providing many advantages as: wider design margins due to the double cooling system, lower tritium inventory, no safety issue related to water cooling, good adaptation to the presently available nuclear materials as Eurofer and potential for high-temperature.

Notwithstanding this consideration, other improvements are ongoing in order to evolve in a more complete design touching those missing or sketchy points that continue to be found in a so complex machine in which many interfaces with other fields are present: arrangements of H&CD systems, introduction of the FCI in all the BB modules, best sharing out of the available space among BB and BSS, best definition of the type of the divertor which influence on the T breeding performances has been demonstrated to be not trivial, etc.

Acknowledgements

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