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Neutronic analyses of the preliminary design of a DCLL blanket for the EUROfusion DEMO power plant

Iole Palermo*, Iván Fernández, David Rapisarda, Angel Ibarra

CIEMAT, Fusion Technology Division, Avda. Complutense 40, 28040-Madrid, SPAIN

In the frame of the newly established EUROfusion WPBB Project for the period 2014-2018, four breeding blanket options are being investigated to be used in the fusion power demonstration plant DEMO. CIEMAT is leading the development of the conceptual design of the Dual Coolant Lithium Lead, DCLL, breeding blanket. The primary role of the blanket is of energy extraction, tritium production, and radiation shielding. With this aim the DCLL uses LiPb as primary coolant, tritium breeder and neutron multiplier and Eurofer as structural material. Focusing on the achievement of the fundamental neutronic responses a preliminary blanket model has been designed. Thus detailed 3D neutronic models of the whole blanket modules have been generated, arranged in a specific DCLL segmentation and integrated in the generic DEMO model. The initial design has been studied to demonstrate its viability. Thus, the neutronic behaviour of the blanket and of the shield systems in terms of tritium breeding capabilities, power generation and shielding efficiency has been assessed in this paper.

Keywords: DCLL, Tritium breeding, Shield, MCNP

1. Introduction

Towards the development of a demonstration power plant DEMO during the design step is crucial the simulation of the fundamental function responses that allow to assess the behaviour of the reactor: tritium breeding ratio (TBR) is essential to determine if the reactor achieves the fuel self-sufficiency; power amplification and power distributions are fundamental to determine the reactor power efficiency and how the thermal load is deposited in the structures to give input for thermal-hydraulics and mechanical assessments; damage responses as helium production, dpa, fluences and nuclear heating are very important to determine if the components are keeping their structural integrity or their functionality as for example the case of the Toroidal Field (TF) coil superconductivity. The neutronic requirements a DEMO fusion power plant needs to fulfil for a reliable operation firstly taken into account in this study are described in [1] and summarized in table 1.

Table 1. Primary Neutronic Requirements under assessment

Design requirements for BB	value
Tritium Breeding Ratio	≥ 1.1
Energy Multiplication factor	> 1
Design limits for the TF-coil superconductivity	
Peak nuclear heating in winding pack [W/m^3]	$\leq 0.05\times10^3$

This paper is focused on the neutronic analysis of the Dual-Coolant Lithium Lead (DCLL) Breeding Blanket (BB) System, one of the 4 BB options conceived for the future European Pulsed Power Plant [2], that in order to be easily achievable have seen relaxed specifications in its power (1572 MW) and in the operational scenario (pulsed instead of continuous one) [3].

The DCLL concept is basically characterised by the use of self-cooled breeding zones with the liquid metal LiPb serving as tritium breeder and as coolant for extracting the heat gained from fusion energy. From the first DCLL design [4] others have been conceived among power plant conceptual studies, and the Test Blanket Modules (TBM) ITER Programme. USA have studied and developed many aspects of the DCLL concept especially for ARIES and ITER [5] while Europe, after the EU model C of the Power Plant Conceptual Studies of 2003 [6], has not dedicated more efforts to the improvement of this concept. Since 2009, based on the concepts proposed in such model C of the PPCS, Spain developed a DCLL DEMO design and its Plant auxiliary systems [7]. The main difference respect to the previous DCLL models was the BB segment structure: the Spanish approach consisted in a single continuous BB module instead of a multi-modular segment. Following the experience acquired on DCLL development, CIEMAT is currently leading the development of a DCLL BB among the EUROfusion Programme. The common specification for the 4 different BB systems consists of a Multi-Module-Segment (MMS) structure to speed up the maintenance procedure.

A DCLL novel design has been developed for the new DEMO 2014 generic design (figure 1a) as described in [8]. The Outboard (OB) equatorial module has been firstly developed in detail (figure 1b). Then, all the DCLL modules have been developed and tested into a specific DCLL segmentation (figure 1c) adapted to the new DEMO 2014 specifications. The details of the neutronic

author's email: iole.palermo@ciemat.es

model and the procedure for its development are given in section 2. The results of the neutronic calculations are detailed in section 3.

2. Development and features of the neutronic design

Taking advantage of past experience concerning DEMO developments, a similar procedure has been adopted to obtain a detailed neutronic DEMO DCLL design. For the neutronic purposes, an 11.25º sector has been studied exploiting the toroidal symmetry of the tokamaks. Each 11.25º sector is composed by 1 inboard (IB) blanket segment and 1 and half outboard (OB) segments. The CAD model of the OB equatorial module (figure 1b) has been simplified to create a detailed 3D neutronic design using MCAM software tools [9], which allows to reduce the complexity of the CAD models to a level compatible with the geometrical capabilities of the Monte Carlo transport code (simplification of sp-lines, elimination of little components and unnecessary details, completion of the model filling the void spaces, among others). The OB equatorial module has been then extrapolated to the rest of modules (figure 1c). Similarly to the work done for the WCLL development [10], a BB segmentation made by 7 IB entire modules, 8 OB entire modules (7.5º) and 8 OB half modules (3.75º, to complete the 11.25º sector) has been attempted. The modules, adapted to the specific DCLL segmentation have been then introduced into the generic DEMO 2014 (figure 1a) to create a complete DCLL DEMO neutronic model (figure 1d).

The last step before the conversion to MCNP input has been to assign the materials to the components of the model. The components of the generic DEMO have been filled with the following materials:

- Vacuum Vessel/Shield: 80% austenitic steel SS316LN + 18% H_2O + 2%B
- Ports (UPP, EPP, LPP): austenitic steel SS316LN
- Divertor: 80% austenitic steel + 20% H_2O
- TF coil: Nb_3Sn + cryogenic steel + epoxy + bronze + Cu + He + vacuum
- Central Solenoid, PF coils: cryogenic steel

The materials compositions for the breeding modules structures are taken from the detailed design and summarized in table 2. For the whole segment, both IB and OB sides, the breeder zones are fully-described (the homogenization concerns only the helium collector and the manifold region or Back Supporting Structure, BSS). The composition for the Manifold/BSS zone is very dense, and should be an efficient shielding system. Furthermore, having an high LiPb content, a benefit is expected on the TBR due to the tritium produced also in this region. The thickness of each component of the BB system is also shown in table 2. The breeder zone occupies 64 cm in the OB side and 30 cm in the IB one.

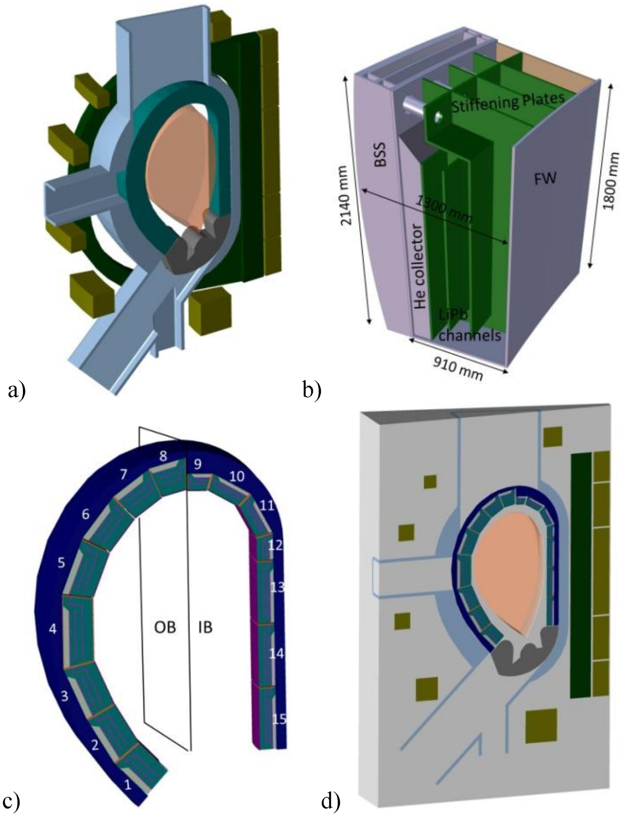


Figure 1: DCLL DEMO model development sequence using MCAM sofware a) generic DEMO model (in dark cyan colour the region available for Blanket and Manifolds); b) detailed OB equatorial module [8]; c) neutronic model of the blankets segment; d) complete DEMO2014 DCLL model

Once filled with material the model is ready to be converted *via* MCAM into the MCNP input. The minor conversions errors are then fixed up to reduce the number of lost particles during the transport (finally ~0.00018% of lost particles has been achieved). Particle transport calculation has been then performed with MCNP5 Monte Carlo code [10] using ENDF/B-VII nuclear data library [12] and JEFF 3.1.1 nuclear data library [13]. Parallel computations have been carried-out in CIEMAT EULER cluster. The plasma neutron source was provided by KIT as a FORTRAN90 subroutine [14], sampling the neutron emission for the DEMO1 plasma according to the new plasma parameters [15]. Direct simulation results have been normalized to 5.581×10^{20} neutrons per seconds [n/s] source, corresponding to the 1572 MW fusion power.

3. Results

3.1 Tritium production

The tritium production has been primarily evaluated because it represents the essential condition for the reactor viability.

author's email: iole.palermo@ciemat.es

Table 2. Thickness and composition of the components of the BB modules and of the Manifold/BSS

Components		Thickness (cm)	Radial Thickness OB (cm)	Radial Thickness IB (cm)	Composition (% vol)			
					Eurofer	He	LiPb	W
FW	FW coating	0.2	0.2	0.2				100
	FW	1.98	1.98	1.98	85.54	14.46		
Breeder zone + Helium collector	1st, 2nd and 3rd radial stiffening plates	(each one) 2	6	6	91.33	8.67		
	LiPb channels		64	30			100	
	He plena Eurofer walls		17	10	53	47		
Walls	Side walls	2	-		85.54	14.46		
	Top wall	4	-		85.54	14.46		
	Bottom wall	4	-		85.54	14.46		
	Back wall	2	2	2	85.54	14.46		
Total BB Thickness			91	50				
Manifold/BSS			variable thickness		51.29	4.35	44.36	

The results, calculated with the ENDF/B-VII library, are presented in table 3, in which the tritium production rate (TPR) density, the local TBR per 11.25º modules, and the total per 360º modules and in manifold are shown. The total TBR in the breeder modules is 1.041. The TBR has been also calculated with the JEFF 3.1.1 cross section data, showing an increment of 0.095% (TBR=1.04165).

Nevertheless, the most important aspect to stand out is that the Manifold which contains 44.36% of LiPb contributes considerably to the TBR of the system. Such contribution amounts to 0.089 T/n in the whole reactor [0.0903 T/n (+1%) using JEFF] which implies an increase of the total TBR to 1.13 [1.13199 (+0.172%) with JEFF] fulfilling the auto-sufficiency criterion (TBR ≥ 1.1) described in table 1. The specific contribution of the IB and OB sides of the Manifold is 1.79e-3 and 1.03e-3 T/n, respectively (considering an 11.25º sector). It means that the IB represents a 63.45% and the OB a 36.54% of the total tritium in the Manifold zone.

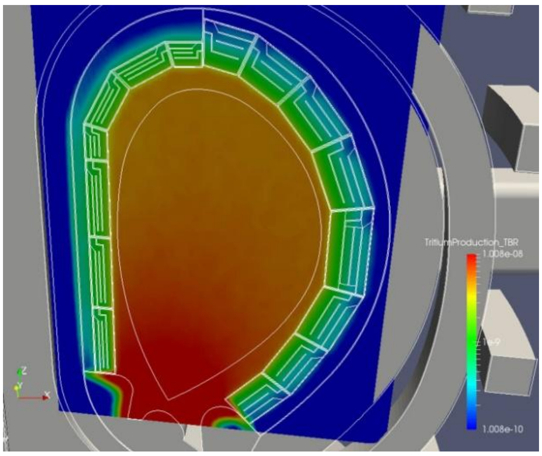


Figure 2. Tritium production as “mesh tally” (in T/n per voxel)

This makes evident the relevance of the IB side of the Manifold because the less space occupied by the breeder allows high tritium breeding potential in the zone behind the modules, as shown in figure 2.

Table 3. Tritium production in the BB modules (nº position in figure 1c) and in Manifold cells in terms of local TBR, total TBR and TPR density

Component	nº	T/n in 11.25º	Total in 360º	T/cm^{3}s
OB modules	1	2.34E-03		8.81E+11
	2	3.04E-03		9.53E+11
	3	3.56E-03		9.94E+11
	4	4.82E-03		9.92E+11
	5	3.48E-03		9.59E+11
	6	2.73E-03		9.37E+11
	7	2.03E-03		8.95E+11
	8	1.39E-03	0.749	8.37E+11
IB modules	9	7.99E-04		1.46E+12
	10	1.25E-03		1.44E+12
	11	1.13E-03		1.43E+12
	12	6.66E-04		1.45E+12
	13	1.93E-03		1.62E+12
	14	1.88E-03		1.58E+12
	15	1.48E-03	0.292	1.24E+12
Total BB		1.041/1.042 (ENDF/JEFF)		
Total Manifold (43 Cells)		0.089/0.09 (ENDF/JEFF)		
Total TBR (BB + Manifold)		1.13/1.132 (ENDF/JEFF)		

3.2 Neutron wall loading

Once assured the first neutronic fundamental requirement on the TBR, additional calculations have been performed. Figure 3 shows the poloidal variation of the Neutron Wall Loading (NWL) along the first wall, where a mean value of 1.002 MW/m^2 is also shown.

author's email: iole.palermo@ciemat.es

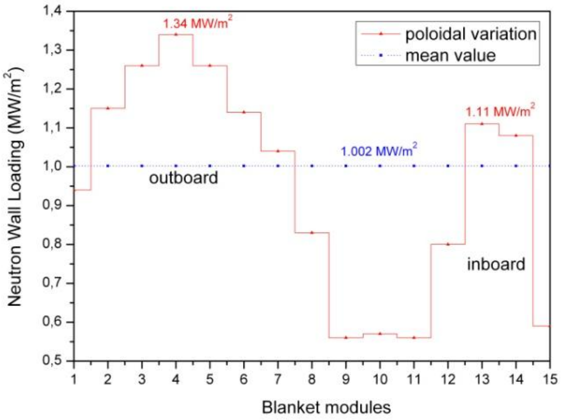


Figure 3. Neutron wall loading poloidal distribution on the FW

3.3 Power generation and Energy multiplication

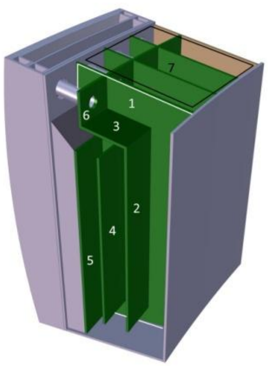
The power breakdown for the major reactor structures is shown in table 4. Considering the total generated nuclear power of 1503 MW, the obtained energy multiplication factor M_E is 1.195, being M_E the ratio of the total nuclear power over the fusion neutron power (80% of the 1572 MW of fusion power). The target value of 1 for the multiplication factor (table 1) is then overpassed.

Table 4. Power breakdown along the components of the reactor

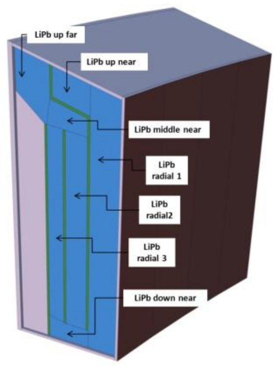
Component	Power generated (MW)
BB + Manifold	1229.32
Divertor	262.49
VV + Ports + Coils	11.98
Total	1503.79

3.4 Radial distribution of the Power deposition

The power density has been assessed as radial distribution from the FW to the Manifold, for the OB equatorial module, as shown in table 5. The JEFF 3.1.1 library has been used with this aim and a greater refinement in the specification of the results has been pursued.



a)

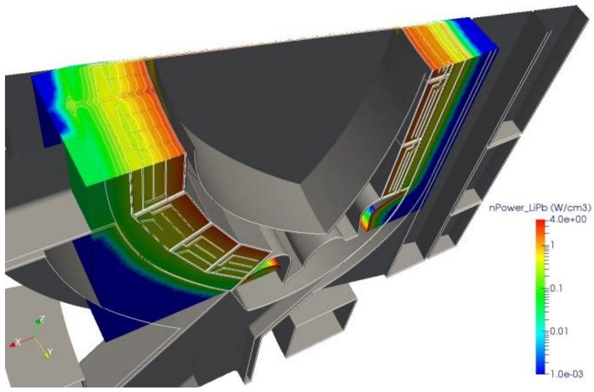


b)

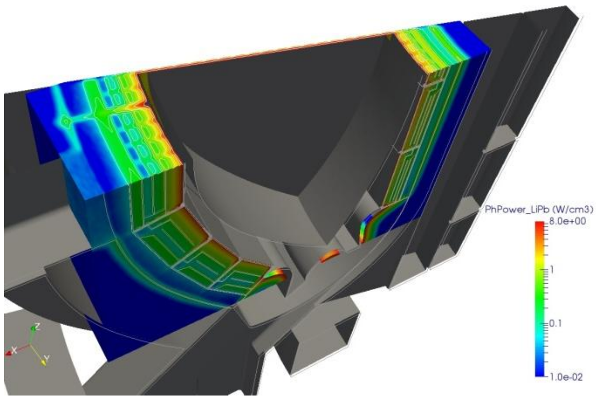
Figure 4. a) Numbers of the stiffening plates and b) names of the LiPb volumes of the OB equatorial module in which the nuclear heating has been calculated, as resumed in table 5

Table 5. Radial distribution of the nuclear heating (W/cm^3) along the components of the DCLL OB equatorial zone

components		JEFF 3.1.1		
OB equatorial module		MeV/gr	uncert.	W/cm3
walls	FW W	1.55E-08	0.0006	26.624
	FW Eurofer	1.17E-08	0.0005	6.964
	top wall	1.46E-09	0.0023	0.873
	bottom wall	1.42E-09	0.0023	0.849
	side wall	1.76E-09	0.0021	1.052
	side wall	1.75E-09	0.0018	1.046
LiPb	LiPb radial1	3.58E-09	0.0007	3.044
	LiPb radial2	9.42E-10	0.0018	0.801
	LiPb radial3	4.76E-10	0.0029	0.405
	LiPb up near	7.56E-10	0.0036	0.643
	LiPb middle near	6.74E-10	0.0041	0.573
	LiPb down	6.80E-10	0.0039	0.578
	LiPb up far	2.63E-10	0.0063	0.224
stiffening grid	plate 1	1.43E-09	0.002	0.911
	plate 2	7.91E-10	0.0038	0.504
	plate 3	2.93E-10	0.013	0.187
	plate 4	2.08E-10	0.0076	0.132
	plate 5	1.17E-10	0.0119	0.075
	plate 6	9.94E-11	0.0267	0.063
	plate 7	7.02E-10	0.0012	0.447
	He collector	1.07E-10	0.0047	0.040
	back wall	7.15E-11	0.0075	0.043
	manifold inner wall	2.14E-10	0.0059	0.161
	manifold block	8.20E-11	0.0025	0.062



a)



b)

Figure 5. Power deposition in LiPb generated by (a) neutrons and (b) photons, as "mesh tally" 3D maps

author's email: iole.palermo@ciemat.es

In fact, all the plates that constitute the stiffening grid have been singly analyzed (figure 4a) and furthermore, the power deposited in all the walls and in a larger numbers of LiPb positions have been determined (figure 4b). In addition, the power deposition maps in LiPb calculated through the "mesh tally" capabilities of MCNP are also given, as shown in figure 5a (neutrons) and 5b (photons).

3.5 Nuclear heating in the TF coil

In order to allow a preliminary evaluation of the shielding efficiency of the DEMO radial build, the nuclear heating in the reactor needs to be assessed, paying special attention to the values on the TF conductor at inboard equatorial level.

Table 6. Nuclear heating in TF coil

Distance from plane Z=0 (cm)	W/m^3	
	IB	OB
>160	79.16	270.22
160:110	0.63	64.44
110:60	1.10	74.93
60:10	1.11	115.93
10:-40	1.52	118.85
-40:-90	0.38	122.74
< -90	0.59	23.71

Specific values of the power density have been calculated over poloidal regions of 50 cm thickness around the mid-plane (table 6). The IB equatorial values satisfy the recommendation for the nuclear heating currently established (table 1) in 50 W/m^3 (20 times lower than the ITER analogue requirement), except for the global zone above the plane at z=160 cm. On the other hand, the limit is not satisfied for the major part of the OB side, due the presence of the equatorial and upper ports. Detailed 3D maps are also given showing the same behaviour (figure 6). The lack of shield in these zones is not of concern because the port plugs have not been already included in the generic DEMO design and it is not a question of the specific blanket design. If the IB side is well protected we can affirm that the OB side also will be.

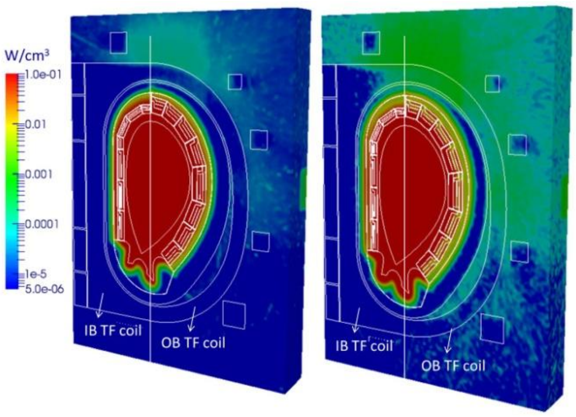


Figure 6. Nuclear heating by neutrons (left) and photons (right) calculated as "mesh tally" in the material of the TF coil.

author's email: iole.palermo@ciemat.es

4. Conclusions

Preliminary neutronic analysis have been performed to support the design of a new DCLL breeding blanket concept, for the development of the newly established pulsed European DEMO reactor. As general results, a TBR of 1.13 has been achieved, thanks to the BSS design, as well as an average NWL of 1.002 MW/m^2, and a M_E of 1.19. Shielding performances have been also assessed, demonstrating that the DCLL fulfils the current limit of nuclear heating in the TF coils established for DEMO (50 W/m^3). Other results have been also obtained as the radial/poloidal profile of the tritium production and different distributions of the nuclear heating in order to give inputs to the mechanical, thermal, safety and tritium modeling activities needed to upgrade the design. Further analyses are also ongoing to establish if other structural and damage criteria are also observed.

Acknowledgments

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References

[1] Fischer U *et al*, Neutronics requirements for a DEMO fusion power plant, http://dx.doi.org/10.1016/j.fusengdes.2015.02.029 (2015)

[2] Meszaros B, DEMO CAD model modifications 2013/2014 EFDA_D _2D4NYN v1.2 April 2014

[3] Harman J, DEMO Fusion Power Plant, Plant Requirements Document (PRD), EFDA_D_2MG7RD_v1.8, 14 March 2014

[4] Malang S *et al*, Dual Coolant Blanket Concept, Kernforschungszentrum Karlsruhe, *KfK 5424*, November 1994.

[5] Malang S *et al*, Development of the Lead Lithium (DCLL) Blanket Concept, Fus. Sci. Tech. Vol. 60 July 2011.

[6] Maisonnier D *et al*, EFDA, A conceptual study of commercial fusion power plants, Final report of the European fusion power plant conceptual study (PPCS), *EFDA-RP-RE-5.0*, (2005).

[7] Palermo I *et al*, Neutronic design of a conceptual DCLL fusion reactor for a DEMO and a Commercial Power Plant, submitted in Nuclear Fusion (2015)

[8] Rapisarda D *et al*, Overview of DCLL research activities in the EU/Spain, Proceeding of 26th IEEE SOFE (2015)

[9] Wu Y, F.D.S. Team, CAD-based interface programs for fusion neutron transport simulation, Fus. Eng. Des. 84 (2009) 1987–1992

[10] Palermo I *et al*, 'Neutron transport analysis of DEMO with WCLL blanket', EFDA_D_2M4FDJ v1.1, (2013)

[11] X-5 Monte Carlo Team, 'MCNP – A general Monte Carlo N-Particle Transport Code, Version 5'

[12] Chadwick M B et al, ENDF/B-VII.0, Nuclear Data Sheets 107 (2006) 2931–3060

[13] The JEFF-3.1.1 Nuclear Data Library, JEFF Report 22, NUCLEAR ENERGY AGENCY, OECD (2009) NEA No. 6807.

[14] EFDA, 'DEMO1 Source subroutine in FORTRAN90', EFDA_D_2MH7CP.B (2013)

[15] Kemp R, DEMO1_July_12, EFDA_D_2LBVXZ v1.0, (2012)