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

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HIGHLIGHTS

- We perform neutronic calculations for the preliminary DCLL Blanket design.
- We study the tritium breeding capability of the reactor.
- We determine the nuclear heating in the main components.
- We verify if the shielding of the TF coil is maintained.

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ABSTRACT

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. The results demonstrate that the primary nuclear performances are already satisfactory at this preliminary stage of the design, having obtained the tritium self-sufficiency and an adequate shielding.

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, displacement per atom (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 primary nuclear requirements and performances studied in this paper to demonstrate a reliable operation of the DEMO fusion power plant are summarized in Table 1.

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 Power Plant based on the DEMO 2014 design assumptions [3,4] (i.e. 1572 MW and pulsed scenario).

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 [5] others have been conceived among power plant conceptual studies, and the Test Blanket Modules (TBM) ITER Programme. In USA many aspects of the DCLL concept have been studied and developed especially for ARIES and

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Table 1
Primary nuclear responses under assessment.

BB parameters	value
Tritium Breeding Ratio	≥1.1 [1]
Energy Multiplication factor	As high as possible in the range 0.9–1.35 [2]
Design limit for TF-coil superconductivity	
Peak nuclear heating in winding pack	≤50 W/m^3 [1]

ITER [6] while in Europe, after the EU model C of the Power Plant Conceptual Studies (PPCS) of 2003 [7], it has been not dedicated more efforts to the improvement of this concept. Since 2009, based on the concepts proposed in such model C of the PPCS, a DCLL DEMO design and its Plant auxiliary systems [8] have been developed in Spain by CIEMAT. 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 facilitate the maintenance procedure.

A DCLL novel design has been developed for the new DEMO 2014 generic design (Fig. 1a) [3] as described in Ref. [9]. The Outboard (OB) equatorial module has been firstly developed in detail (Fig. 1b). Then, all the DCLL modules have been developed and tested into a specific DCLL segmentation (Fig. 1c) adapted to the new DEMO 2014 specifications. The details of the neutronic 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 11.25° sector has been studied (Fig. 1a) exploiting the toroidal symmetry of the tokamaks. Each 11.25° sector is composed by 1 inboard (IB) blanket segment and 1 and half outboard (OB) segments. The CAD model of the OB equatorial module (Fig. 1b) has been simplified to create a detailed 3D neutronic design using MCAM software tools [10], 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 repeated to the rest of modules (Fig. 1c) adapting it to the specific features (i.e. dimensions, available space, shape, etc.) of each one. Similarly to the work done for the WCLL development [11], a BB segmentation made by 7 IB entire modules, 8 OB entire modules (7.5°) and 8 OB half modules (3.75°, to complete the 11.25° sector) has been chosen. The modules, adapted to the specific DCLL segmentation have been then introduced into the generic DEMO 2014 (Fig. 1a) to create a complete DCLL DEMO neutronic model (Fig. 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
- Upper, Equatorial and Lower Ports: austenitic steel
- 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.

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 [12] and JEFF 3.1.1 nuclear data library [13]. For tritium production assessment ENDF/B-VII nuclear data library [14] has been also used having the comparison between libraries special relevance in the TBR prediction which usually has to account for different sources of uncertainties, as the case of the nuclear cross-section data uncertainties. Parallel computations have been carried-out in CIEMAT EULER cluster. The plasma neutron source was provided by KIT as a FORTRAN90 subroutine [15], sampling the neutron emission for the DEMO1 plasma according to the new plasma parameters [16]. Direct simulation results have been normalized to 5.581 × 1020 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.

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 11.25° modules, and the total per 360° modules and in manifold are shown.

The total TBR in the breeder modules is 1.041. Due to the relevance of the cross-section data uncertainties in the TBR prediction (among other factors) [1], the total value 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 highlight 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 self-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 11.25° sector). It means that the IB represents a 63.45% and the OB a 36.54% of the total tritium in the Manifold zone. 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 Fig. 2.

In this figure the values of Tritium production outside the breeder regions have not to be taken in consideration. In fact, the "mesh tally" tool of MCNP is able to calculate the nuclear responses only for one material each time. Thus, in this case, the values outside the LiPb breeder zone (i.e. inside the helium collector, the stiffening plates, the walls, etc.) are fictitious values as the components were

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