EUROFUSION CP(15)06/17

J.-C. Jaboulay et al.

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12th International Symposium on Fusion Nuclear Technology (ISFNT)
Jeju Island, Korea
(14th September 2015 – 18th September 2015)

Nuclear Analysis of the HCLL blanket concept for the European DEMO using the TRIPOLI-4® Monte Carlo code

Jean-Charles Jaboulay[a], Giacomo Aiello[a], Julien Aubert[a], Rosaria Villari[b], Ulrich Fischer[c]

[a]*CEA-Saclay, DEN, DM2S, F-91191 Gif-sur-Yvette, France*
[b]*ENEA, UTFUS-TECN, Via E. Fermi 4, 00044 Frascati (Rome), Italy*
[c]*Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Karlsruhe, Germany*

This paper presents the nuclear analysis of the European DEMO with HCLL blanket carried out in 2014 at CEA with the TRIPOLI-4® Monte Carlo code. A previous analysis was conducted by ENEA, in 2013, using the MCNP code with a detailed 3D Monte Carlo model describing the HCLL blanket modules. This MCNP model was converted into TRIPOLI-4® representation for performing the nuclear analysis at CEA with the objective to demonstrate consistency between the MCNP and TRIPOLI results. A very good agreement was obtained for all of the relevant nuclear responses (neutron wall loading, tritium breeding ratio, nuclear heating, neutron flux distribution, etc.), validating CEA's nuclear analysis approach, based on TRIPOLI-4® Monte Carlo code and JEFF-3.1.1 nuclear data library, for the European DEMO.

Keywords: DEMO, neutronics, blanket, HCLL, tritium breeding, nuclear heating, TRIPOLI-4®

1. Introduction

The EUROfusion Consortium [1] develops a conceptual design of a fusion power demonstrator (DEMO) in the framework of the European "Horizon 2020" innovation and research program [2]. Key issues for DEMO are tritium self-sufficiency and heat removal for conversion into electricity. These functions are fulfilled by the breeding blankets surrounding the plasma chamber. The Helium Cooled Lithium Lead (HCLL) blanket is one of the concepts which are investigated for DEMO [3]. It uses the liquid lithium lead eutectic as tritium breeder and neutron multiplier and helium gas as coolant for both the Eurofer **Error! Reference source not found.** structure and the breeder.

Within the Breeder Blanket project (WPBB) of EUROfusion's Power Plant Physics and Technology (PPPT) programme [5], CEA is in charge for the design of the HCLL blanket for DEMO including the nuclear analyses. In WPBB's framework three other blanket concepts are respectively studied by KIT, ENEA and CIEMAT: a solid breeder blanket (lithium ceramic as breeder, beryllium as neutron multiplier) cooled by helium named HCPB: helium cooled pebble bed, a liquid breeder blanket (lithium lead eutectic acting both as breeder and neutron multiplier) cooled by water named WCLL water cooled lithium lead and a liquid breeder blanket (Li-Pb eutectic) cooled by helium and the Li-Pb itself named dual coolant lithium lead DCLL.

CEA's nuclear analysis approach is based on the TRIPOLI-4® Monte Carlo code [6] and the JEFF-3.1.1 [7] nuclear data library when the other associations mainly use the MCNP Monte Carlo code [8] and the JEFF (3.2 or 3.1.1) or the FENDL (3 or 2.1) [9] libraries. To ensure consistency, these different approaches are compared. The nuclear analysis of DEMO HCLL carried out at ENEA in 2013 within the EFDA work programme [10] is compared to the CEA one.

This paper presents the comparison between TRIPOLI-4 + JEFF-3.1.1 and MCNP5 + FENDL-2.1 of relevant nuclear responses: neutron wall loading, tritium breeding ratio, nuclear heating, neutron flux distribution, etc. in DEMO HCLL configuration. Section 2 briefly describes the HCLL blanket design and section 3 the Monte Carlo models. The Part 4 is devoted to results.

2. HCLL blanket design

The HCLL breeding blanket layout is a multi-module segment design. Modules are welded in a stiff poloidal back plate in order to form a banana-shaped segmentation (Fig. 1) that can be removed from the upper port. The back supporting structure (BSS) also works as a manifold, collecting and distributing lithium-lead and helium in the different blanket modules.

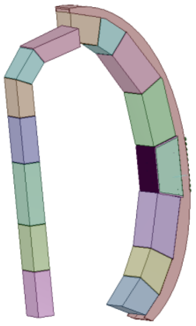

Fig. 1 HCLL DEMO1 segmentation

The design of outboard HCLL module is shown in Fig. 2. Each HCLL blanket module consists of an Eurofer steel box formed by an U-shaped plate composing the First and Side Walls, closed on its sides

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author's email: jean-charles.jaboulay@cea.fr

by Side Cover plates and on the back by a set of Back Plates and tie rods (for BSS attachments).

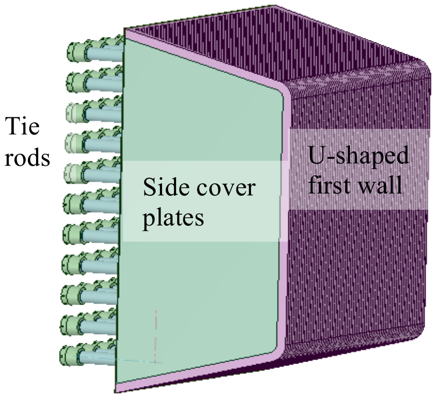


Fig. 2. Isometric view of the equatorial outboard blanket module

The blanket module structure is reinforced by an inner grid of radial-poloidal and radial-toroidal Stiffening Plates (Fig. 3). The Stiffening Plates defines an array of internal cells where the Breeder Units are located. The eutectic Pb-Li (enriched 90% in ^{6}Li) flows around parallel horizontal Cooling Plates. An inlet and an outlet chamber on the Breeder Unit back plate ensure the helium distribution and collection for the Cooling Plates. All the plates, except the back plates constituting the manifolds, have internal cooling channels with a rectangular section.

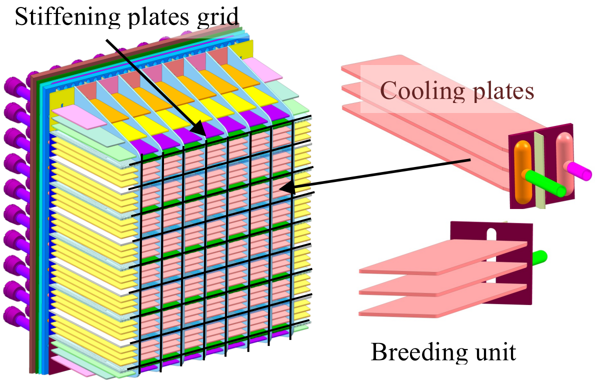


Fig. 3. Isometric view of the inner structure of the equatorial outboard blanket module (left) and detail of a single breeder unit (right)

3. HCLL DEMO model

This part describes the MCNP and TRIPOLI model of HCLL DEMO respectively in sub-section 2.1 and 2.2

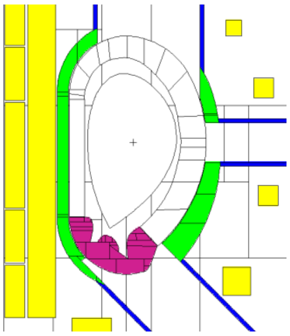
3.1 MCNP model

The MCNP model of DEMO HCLL was built at ENEA; it is mainly based on a generic model generated by KIT [11]. This model serves as a common basis for the integration of the different blankets and eases comparison of nuclear performances of each blanket concepts for the same reactor configuration, presented in Table 1. These parameters correspond to a near-term DEMO, with conservative baseline design as of 2014, called DEMO1 [12].

Table 1. Main parameters of the DEMO reactor (2014 design [12]).

Major radius, (m)	9.0
Minor radius, (m)	2.25
Plasma elongation	1.66
Plasma triangularity	0.33
Plasma peaking factor	1.7
Fusion power, (MW)	1572.
Net electric power, (MW)	500.0

The generic MCNP model was generated from the CAD generic model using the McCad automated conversion tool [13]. The model, shown in Fig. 4, includes the plasma chamber, a banana-shaped space for the insertion of the breeder blankets, the divertor, the vacuum vessel with ports and the toroidal, poloidal and central solenoid magnetic field coils.



Color legend
- plasma chamber (white)
- banana-shaped space for the breeder blankets (white),
- divertor (purple),
- vacuum vessel (green),
- port structures (blue)
- coils (yellow).

For interpretation of the references to color, the reader is referred to the web version of this article

Fig. 4. MCNP plot of the DEMO generic model

The segmentation has been implemented in the MCNP generic model using the MCAM CAD converter [14]. To ease CAD import only empty modules are considered. A single Outboard BU has been converted by means of MCAM. Thus the obtained model has been replicated inside each blanket box to obtain a complete HCLL DEMO MCNP model of the outboard segment using the repeated structure and rotation matrix feature of MCNP (FILL and LAT cards). The model of the inboard BU has been manually implemented and replicated in the inboard modules with the same technique used at the outboard. All the sub-components (including BP, pipes and stiffening rods) up to the rear back-plate of the module (BP-5) are described in detail, while the back-supporting zone is represented as a homogeneous mixture of Eurofer, He and LiPb. Fig. 5 presents a poloidal-radial cut of the whole DEMO HCLL model. Fig. 6 shows the internal structure: stiffening grids, cooling plates, back plates and manifolds of the equatorial module.

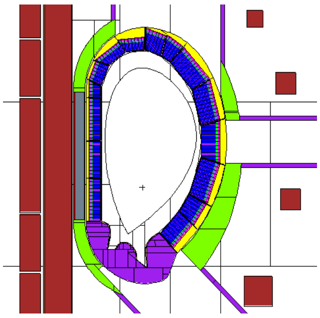


Fig. 5. MCNP plot of the DEMO HCLL model

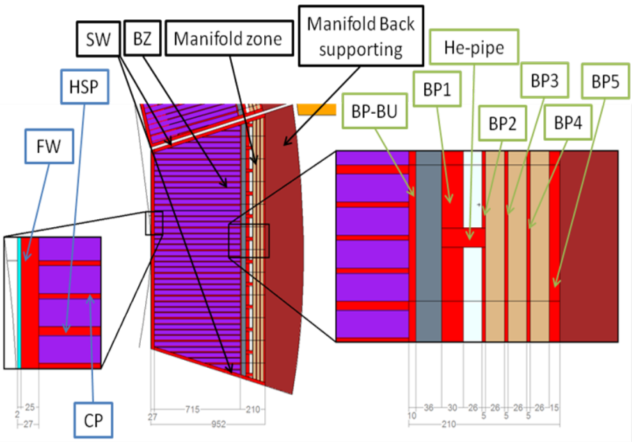


Fig. 6 MCNP model of HCLL Outboard module vertical section (dimensions are in mm)

3.2 TRIPOLI-4® model

In the framework of a previous EFDA task on Monte Carlo codes evaluation and benchmarking, the generic model of DEMO has been built for TRIPOLI-4® [15]. This generic model for TRIPOLI was generated by McCad as the MCNP DEMO generic model. The breeding blanket modules (BBM) segmentation, Breeder Unit geometry and compositions were defined using the MCNP model of the DEMO HCLL, kindly provided by ENEA.

Firstly the BBM were converted from MCNP input deck to TRIPOLI-4 input file, using a python program that automates MCNP to TRIPOLI syntax conversion. Then BBM were implemented in the generic model. Inboard and Outboard BU were converted also and were duplicated in each BBM with an appropriate rotation transformation (rotation transformation of BU in TRIPOLI-4 are not exactly the same than the MCNP model, because we choose to assume parallel conditions of BU's back plate and BBM's first wall surfaces. Nevertheless usually there are slight differences between both rotation transformations.). Currently, there is no suitable rotation feature in TRIPOLI-4 so a major part of the HCLL model building was devoted to the development of a python program that defines the rotation transformation as function of the BBM orientation and create the necessary surface and volume of the rotated BU. Discussions with the TRIPOLI-4 Team are underway to define the proper development to be implemented to this end.

Finally, using the lattice functionality of TRIPOLI-4 a complete DEMO HCLL TRIPOLI-4 model was obtained. BU is repeated in toroidal and poloidal direction in each BBM. Fig. 7 shows the TRIPOLI-4 model of DEMO HCLL; details of outboard BBM and BU are also given.

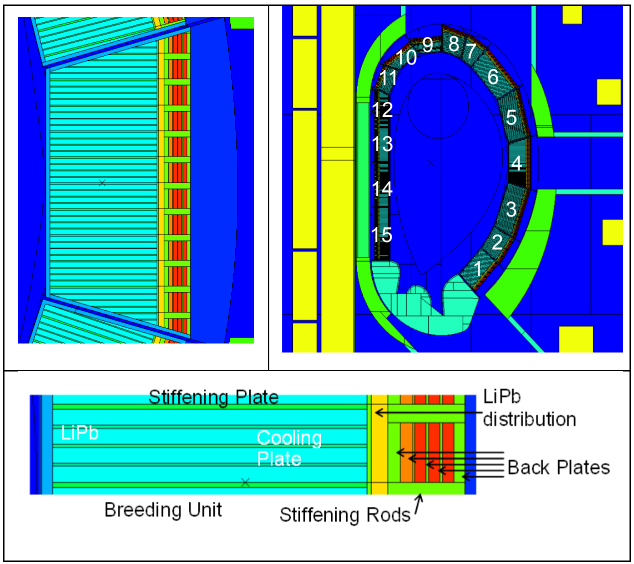


Fig. 7. TRIPOLI-4® plots (poloidal-radial) of the DEMO HCLL: equatorial module (top left), DEMO and BBM (top right), breeding unit (bottom)

4. Results

In this section neutron wall loading, tritium breeding ratio, nuclear heating and neutron flux distribution obtained at ENEA (MCNP5+FENDL-2.1) and CEA (TRIPOLI-4®+JEFF-3.1.1) are compared.

4.1 Neutron Wall loading

First of all, the NWL calculated by TRIPOLI-4® was compared to the ENEA one. This comparison enables neutron sources verification; both models use the KIT FORTRAN subroutine describing the plasma neutron emission. This exercise permits also a quick check of the geometry without errors in compositions issues since the NWL is calculated with an empty geometry. NWL is defined by the neutron current (normalised to the fusion power) crossing the first wall surface divided by the first wall area; NWL is expressed in MW/m². To avoid the back scattering of neutrons in the current tallying (due to reflective surface) the neutrons must be killed after passing of the first wall. In MCNP the importance is set to 0 in all cells except the plasma chamber. In TRIPOLI-4 the importance cannot be defined volume by volume. The TRIPOLI-4 variance reduction technic is based on a mesh given by the user and the code automatically sets the importance in this mesh using various methods described in [6]. Another way was used to kill the neutrons crossing the first wall surface: setting the neutron lower energy cut-off to 20 MeV in every volume except the plasma chamber.

Fig. 8 shows the obtained poloidal NWL. It was estimated on each BBM first wall surfaces numbered 1 to 15 (see Fig. 7). There is a good agreement on the NWL calculated by ENEA and CEA. Discrepancies range from -1.6% to 2.8% with an averaged statistical error of 1% (1σ).

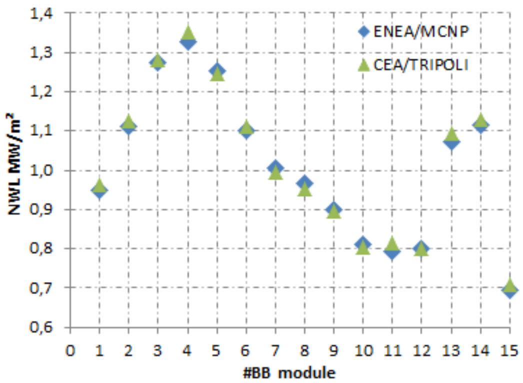


Fig. 8. NWL poloidal distribution

4.2 Tritium breeding ratio

There is no difference in TBR calculation methodology between the two codes; 6Li(n,t)4He and 7Li(n,n')T,4He reaction rates are estimated and divided by the neutron source intensity. The overall TBR is estimated to 1.07, it includes tritium production in the breeding zone, manifolds and BSS. This TBR is close to the ENEA one (1.06). There is also a good agreement in TBR poloidal distribution (TBR breakdown in each BBM) between both simulation; discrepancies ranges from -3.6% to 2.1%. Statistical errors (1σ) are around 0.1% for the overall TBR and 0.2% for the TBR BBM distribution.

4.3 Nuclear Heating

Such as MCNP's tally F6, TRIPOLI-4 has specific estimators for the Nuclear Heating (NH) scoring based on the collision estimator and the energy balance. This estimator called DEPOSITED_ENERGY was completely rewritten in version 8 of the code released in 2013 [6]. A huge effort of code and nuclear data verification was carried out to ensure energy balance coherence (comparison with NJOY HEATR module). An estimator called KINEMATIC_LIMITS enables nuclear data consistencies verification. This estimator gives upper and lower boundaries where NH is possible. If the obtained NH is outside these boundaries it indicates nuclear data inconsistencies. In recent benchmark comparisons, between MCNP & TRIPOLI, a good agreement is noticed for NH calculation: DEMO generic model [15] and ITER A-lite [16].

The obtained energy multiplication (M_E) factor is 1.19, not far from the 1.21 of ENEA (-1.6%). M_E is the ratio of the total nuclear power over the fusion neutron power (80% of FP). NH in DEMO01 HCLL components are reported in Table 2 for both MC code simulations. A good agreement between both codes is observed, discrepancies range from -4% to 3% with a statistical error (1σ) of maximum 1% in VV.

The poloidal NH distribution within each BBM of both simulations (ENEA & CEA) presents a good agreement discrepancies range from -3% to 1%. A statistical error (1σ) of 0.5% is achieved in each BBM. Fig. 9 shows the radial NH profile across inboard mid-plane. Differences in NH (indicated hereafter in parenthesis) are: ±4% in: first wall (20 W/cm^3), breeding zone (6.3 W/cm^3 in the first 5 cm), manifold (around 0.3 W/cm^3) and vacuum vessel (maximum 0.9 W/cm^3), less than 20% in coils (around 90 W/m^3) but statistical error in this region is 20% (1σ).

Table 2. Nuclear heating breakdown

Components	ENEA (MW)	CEA (MW)	Discr.
BBMs	1216	1200	-1%
BSS	24	25	3%
VV	67	64	-4%
Divertor	218	214	-2%
Total	1527	1503	-2%

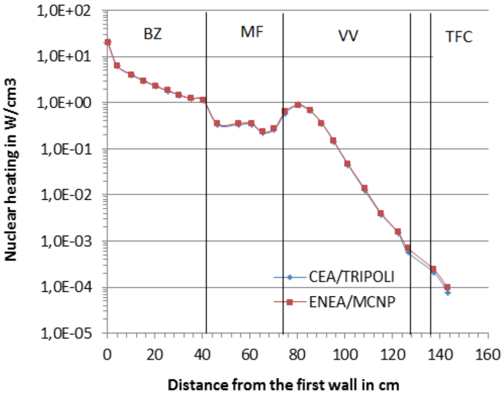


Fig. 9. Nuclear power density radial profile across inboard mid-plane

4.4 Inboard radial profile of neutron flux, displacement damage and helium production

The neutron flux, displacement damage rate and helium production have been calculated along the inboard mid-plane. The nuclear quantity is averaged on a poloidal height of 50 cm (from z=10 to z=60 mm). Variance reduction techniques have been used in both codes to obtain results with reasonably low statistical errors up to the TF coil region. The mesh tallies feature of both codes has been applied to evaluate the neutron flux. Fig. 10, 11, 12 show respectively neutron flux, displacement damage and He production for both simulation. The results are consistent, discrepancies are: ±5% in breeding zone and manifold, up to 10% in vacuum vessel and 16% in toroidal field coils but statistical error (1σ) in this region is around 15%.

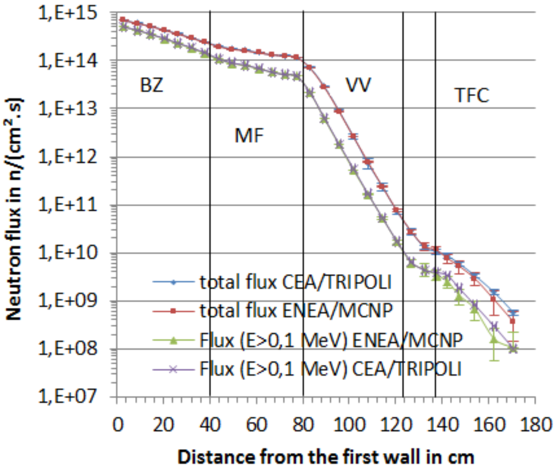


Fig. 10. Inboard radial neutron flux profile

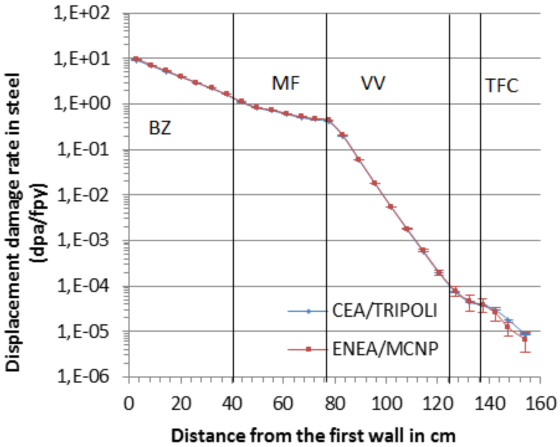


Fig. 11. Inboard radial displacement damage rate profile

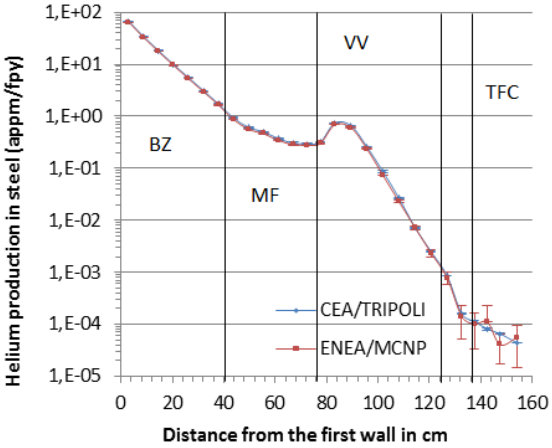


Fig. 12. Inboard radial helium production profile

Maximum values obtain in neutron flux (total and E>0.1 MeV), dpa and helium production are respectively: 6.9 10^{14}, 5.0 10^{14} $n/(cm^2.s)$, 9.5 dpa/fpy, 65 appm/fpy in the first wall; 6.9 10^{13}, 2.2 10^{13} $n/(cm^2.s)$, 0.2 dpa/fpy, 0.7 appm/fpy in the vacuum vessel and 8.0 10^{9}, 3.0 10^{9} $n/(cm^2.s)$, 2.7 10^{-5} dpa/fpy, 9.0 10^{-5} appm/fpy in the toroidal field coil case.

Conclusions

This paper proofs consistency of the nuclear analyses performed by ENEA and CEA on the HCLL DEMO using a different methodology with different calculation tools: MCNP5 MC code and FENDL-2.1 nuclear data library at ENEA and TRIPOLI-4® MC code and JEFF-3.1.1 library at CEA. This consistency is a pre-condition for the application to DEMO nuclear analyses within the PPPT breeder blanket program to ensure that results are comparable. The overall difference between CEA and ENEA nuclear analysis is around ±2% in TBR and M_E, ±5% in neutron flux, nuclear heating, displacement damage and He production radial profile this is mainly due to nuclear data and their treatment by each code.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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