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Conceptual design of the EU-DEMO Dual Coolant Lithium Lead equatorial module

D. Rapisarda, I. Fernandez, I. Palermo, M. Gonzalez, C. Moreno, A. Ibarra
CIEMAT, Avda. Complutense 40
Madrid, Spain

E. Mas de les Valls
BarcelonaTECH, Avda. Diagonal 647
Barcelona, Spain

corresponding author email: david.rapisarda@ciemat.es

***Abstract*— within the framework of EUROfusion Program, the Dual Coolant Lithium Lead (DCLL) is one of the four EU breeder blanket concepts that are being investigated as candidate for DEMO. DCLL uses PbLi as main coolant, tritium breeder, tritium carrier and neutron multiplier. The main structures, including the first wall, are cooled with helium. The EU program proposed for the next years will consider a DCLL version limited to 550 ºC in order to allow the use of conventional materials and technologies.**

During the first year of EUROfusion activities a draft design of the DCLL has been proposed. The main blanket performances were adapted to the new specifications and CAD model of DEMO. The breeder zone has been toroidally divided into 4 parallel PbLi circuits, separated through stiffening grid radial walls. The PbLi flow routing has been designed to maximize the amount of thermal power extracted by flowing PbLi and to avoid the occurrence of reverse flows due to volumetric heating. Thermal-hydraulics, MHD and neutronics calculations have been performed for the first draft design. The new DCLL design employs Eurofer-alumina-Eurofer sandwich as flow channel insert (FCI).

Keywords—DCLL; Breeder Blanket; DEMO; Flow Channel Insert

I. INTRODUCTION

The Dual Coolant Lithium Lead, DCLL, is one of the four EU breeder blanket (BB) concepts that are being considered to be used in DEMO. The DCLL is based on eutectic PbLi as primary coolant, tritium breeder, tritium carrier and neutron multiplier. Helium is used for cooling the wall exposed to the plasma or first wall (FW) and the supporting structures. The liquid metal flows at a different velocity compared to other blanket which use PbLi (higher velocity than HCLL or WCLL concepts, lower than SCLL). Thus, in the DCLL the PbLi extracts most of the reactor power, the remaining being extracted through helium cooling. The presence of an intense magnetic field produces important magnetohydrodynamic (MHD) and thermal-hydraulic effects. Mitigation of these effects is achieved by using composites or ceramic structures called flow channel inserts (FCI).

In the last 20 years the dual coolant concept has evolved considering some different approaches [1-3], mainly considering: the liquid metal operational temperature, leading to low (up to 550 ºC) or high (up to 700 ºC) temperature concepts; the reduction of MHD phenomena through different electrical insulation techniques; and the segment box structure, banana segment versus Multi-Module Segment (MMS). The programme proposed in EUROfusion for the period 2014-2018, in its conceptual phase, will consider a version of DCLL operating at the maximum temperature of the structural material, in order to allow the use of conventional materials and technologies. It is important to note that this limit, imposed for the outlet temperature of the PbLi, reduces considerably the potential thermodynamic efficiency, which is one of the main advantages of this blanket technology. This temperature is, however, higher than the conservative limit of 470°C imposed by corrosion considerations for blankets operating with PbLi at high velocities [1]. This will be verified in future analyses and, if necessary, the maximum operation temperature will be further reduced.

CIEMAT is the lead institution for the blanket engineering design, which includes:

- The definition of system specifications: requirements, integration and operational points.
- The CAD design of the individual blankets and segments.
- The engineering design analyses, in collaboration with CVRez: neutronic, thermal-hydraulic, MHD and thermo-mechanical analysis.
- The design and research on the development of FCI, in collaboration with KIT.

During the first year of EUROfusion activities the main objective has been the proposal of a draft design of a DCLL BB. Its main performances have been adapted to the new DEMO specifications and CAD model. In addition, specification and design guidelines for the DCLL Blanket System have been developed, identifying the main requirements needed for the initial design. An extensive revision on FCI technologies has been done, with special emphasis on concepts related to the ‘low temperature’ DCLL. The baseline FCI is a Eurofer-alumina-Eurofer sandwich, as proposed in [1]. However this concept could present corrosion issues, especially at certain zones with high PbLi temperatures. Therefore other concepts (e.g. semi-open FCI designs [4]) are being investigated.

Other activities related to the DCLL are being carried out within EUROfusion, but they are out of the scope of this proceeding. The most relevant at this design stage are: the definition of the PbLi loops (including auxiliaries and component development); experimental activities on MHD; corrosion experiments at high velocity and coatings development; PbLi purification; definition of the Tritium Extraction System and study of different extraction techniques; modeling of tritium transport; development and testing of permeation coatings. Collaborating institutes are KIT, ENEA and CVRez.

This paper is organized as follows: Section II shows the main requirements adopted for the present design. Section III presents the conceptual design of the DCLL, including the equatorial module as well as the whole segment definition. Preliminary analyses supporting this conceptual design are shown in section IV, including neutronics, thermal-hydraulics and MHD. Finally, conclusions are presented in last section V.

II. Design Requirements

A first list of design requirements for the DCLL BB was produced based on available information, and taking into account previous studies [1-3]. These requirements are based on DEMO 2014 specifications.

A. *General Requirements for blanket definition*

The CAD model for DEMO2014 tokamak is shown in Fig. 1 [5]. It is composed by 16 sectors, distributed every 22.5º. Each outboard sector (the farthest from the tokamak center) is subdivided in 3 segments; the inboard sectors (the closest to the tokamak center) are subdivided in 2 segments. Thus, the whole blanket accounts for 48 outboard/32 inboard segments. The basic parameters of the reactor can be found in Table I, determined by the PROCESS system code [6,7].

Two operational concepts for the DEMO Power Plant are currently being studied: (i) pulsed operation (DEMO1 reactor) and (ii) steady-state operation (DEMO2 reactor). Within EUROfusion period only pulsed operation will be considered for components (blanket) development, therefore from now on DEMO will refer to DEMO1. The assumed operational sequence is based on nine pulses per day each with a burn time of 2 hours. In this scheme it is assumed that the DEMO Power Plant will be either operated or maintained continuously, i.e. 24 hours per day, 365 days per year. This scheme affects the blanket segments in such a way that maintenance operations can only be performed during the stop of the whole machine. A "starter" blanket receiving around 20 dpa in steel is considered, with a lifetime of 6.6 calendar years. In addition, the blanket has to provide minimum aging of components related to erosion, corrosion, cyclic loads and neutrons embrittlement.

TABLE I. Basic DEMO-2014 tokamak parameters

Parameter	Unit	Quantity
Plasma power	MW	1572
Thermal power including n-multiplication in blanket	MW	1972
Plant electricity output capability	MW	500
Lifetime neutron damage in steel in the FW	dpa	20+50
Major radius, R_0	m	9.0
Minor radius, a	m	2.25
Plasma current	MA	14
Toroidal field, B_0 at R_0	T	6.8
Elongation, κ_{95}		1.56
Triangularity, δ_{95}		0.33
Plasma volume	m^3	1453
Plasma surface area	m^2	1084
Auxiliary heating power, P_{inj}	MW	50
Auxiliary ramp-up power, $P_{ramp\text{-}up}$	MW	>60
Average neutron wall load	MW/m^2	1.067
Nuclear heating in blanket	MW	1380
Power to divertor	MW	180

B. *Functional Requirements for DCLL*

Main requirements for the DCLL are shared with other blanket concepts: tritium self-sufficiency, power extraction and amplification and shielding performance.

1) *Tritium self-sufficiency*

Reactor tritium self-sufficiency must be warranted through efficient breeding and recovery, allowing ongoing plasma operations without the need to produce tritium in external sources. To guarantee tritium self-sufficiency the global

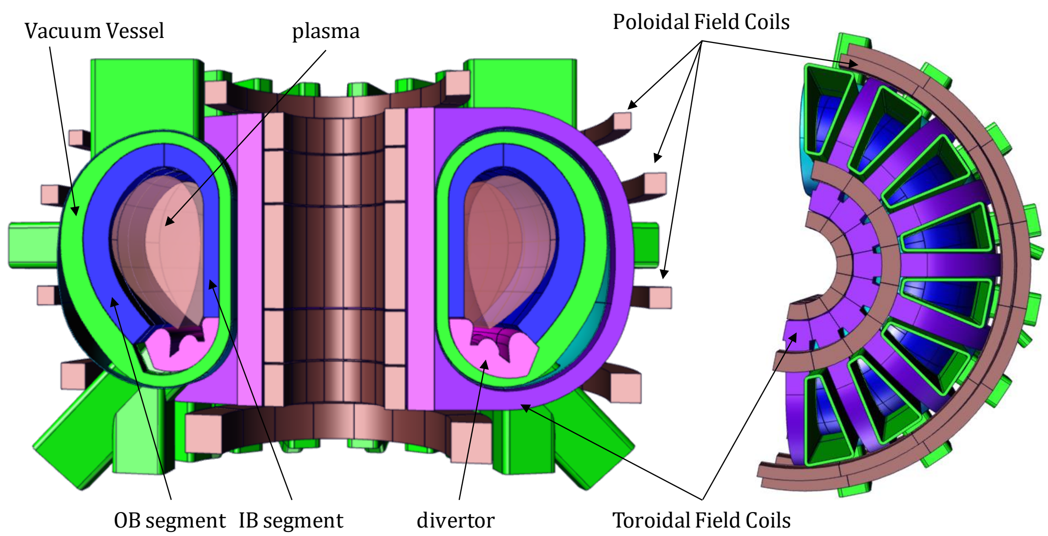

Fig. 1. 2014 DEMO CAD model provided by EUROfusion.

Tritium Breeding Ratio, TBR, must exceed unity by a safety margin that accounts for the following uncertainties and effects: nuclear cross-section data uncertainties, statistical uncertainties, uncertainties due to modeling assumptions, uncertainties due to specific engineering design assumptions, the effect of the ^{6}Li burn-up, the effect of blanket ports without breeder material and the tritium losses in the fuel cycle. Thus, a target value of TBR = 1.10 has been set [8].

2) *Power extraction and amplification*

The blanket must guarantee the extraction and amplification of the neutronic power, assuring the extraction of thermal power allowing for efficient electricity production. This implies the following requirements for the coolant:

- High operating temperature (typically higher than 300°C).
- Minimized outlet temperature variation during flat top.
- Minimized flow variation.
- Minimized pressure drop to ensure an adequate overall energy balance.

The energy multiplication factor, M_E, must be higher than 1 (typically $1.1 \leq M_E \leq 1.3$). It is defined as the ratio between the nuclear power generated in reactor to the fusion neutron power (80% of 1572 MW). Only a part of the deposited energy is recovered by the power conversion system and then useful in terms of electricity production.

3) *Nuclear Shielding*

In DEMO each component is a "shield" for the structures behind itself. The blanket has also a shielding function of the vacuum vessel and the superconducting magnets from plasma radiation. There are two essential shielding requirements that must be fulfilled for a fusion power reactor: firstly, the re-weldability of components and connections/pipes made of steel such as the vacuum vessel; secondly, the sufficient protection of the superconducting toroidal field coils (TFC). Table II shows the DEMO quantitative criteria concerning the radiation loads to the superconducting magnet coil [8].

TABLE II. REQUIREMENTS ON RADIATION LIMITS FOR THE TFC MAGNETS AND THE STRUCTURAL MATERIALS [8]

Radiation design limits for the superconducting TF-COILS		
Integral neutron fluence for epoxy insulator	m^{-2}	$\leq 1\times10^{22}$
Peak fast neutron fluence (E>0.1 MeV) to the Nb_3Sn superconductor	m^{-2}	$\leq 1\times10^{22}$
Peak displacement damage to copper stabilizer, or maximum neutron fluence, between TFC warm-ups	m^{-2}	$\leq 1\text{~}2\times10^{21}$ Equivalent to $0.5\text{~}1\times10^{-4}$ dpa
Peak nuclear heating in winding pack	W/m^3	$\leq 0.05\times10^{3}$
Structural limits		
Helium production - reweldability limit – for steel		≤1 appm He
Displacement damage in the austenitic stainless steel Vacuum Vessel		2.75 dpa
Displacement damage in the FW		50 dpa

C. *Remote Maintenance*

One of the most important requirements that have been considered for this first DCLL concept is related the remote handling operation. In the new DEMO scheme segments must be extracted from the vacuum vessel through the upper port by remote handling equipment [9]. All connection pipes are also routed through this upper port. This requirement imposes a severe constrain in terms of segment definition, since the central one in each sector must have parallel radial walls. Previous DEMO designs have considered outboard part of one sector subdivided in 3 identical segments distributed every 7.5º. The present version with parallel walls implies the existence of three kinds of segments: one IB and two OB. The last is composed by one central segment, from now on OBC, and two laterals, from now on OBL, see Fig. 2. Thus, the whole blanket is formed by 16 OBC, 32 OBL and 32 IB segments.

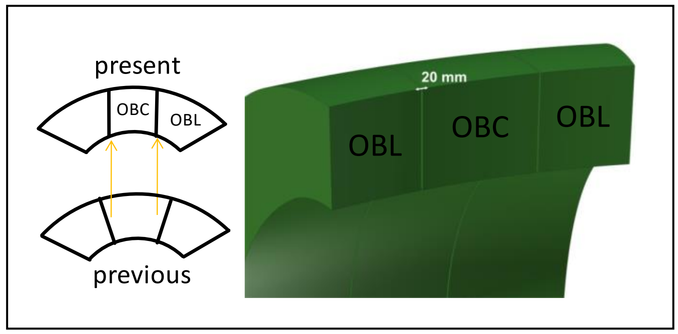

Fig. 2. Change in the definition of the sector segments. Parallel-walls are preferred in order to extract the segments through the VV upper port.

D. *Balance of Plant*

To restrict the transport of tritium and the resulting confinement implications it is assumed that the DEMO balance of plant will be an indirect cycle. Neither the primary or secondary coolant media for the DEMO reactor has been selected as yet. In the case of the DCLL, the primary coolant is the PbLi. For secondary coolant the options are water/steam, supercritical CO_2, molten salts, etc.

The most strong point of DCLL balance of plant is that most of the blanket heat is removed by the liquid metal. As the mass flow of helium involved in the DCLL is less than other helium concepts some benefit is expected in the total pumping power. However it presents some disadvantages due to the low He inlet/outlet temperature to the blanket. Different thermal sources (divertor, PbLi, He) with different temperatures and power ranges difficult the matching, being necessary to test different layouts. Therefore, apart from conventional Rankine cycles, supercritical CO_2 (S-CO_2) Brayton power cycles have been proposed due to their good adaptation to medium/high temperature sources and because it presents some strong points such us low volume of turbomachinery, low thermal inertia or easy detritiation of CO_2 [10].

III. THE EUROFUSION DCLL

The conceptual design of the DCLL has been made according to currently available technologies and materials.

A. *Blanket materials*

Good compatibility between the different blanket materials is necessary to prevent their interaction and, hence, changes in their properties, which can lead to the malfunctioning and shortening of the life of the blanket components. As stated, DCLL concept foresees helium as coolant for the FW and main structures, and PbLi with the dual function of coolant and tritium breeder and neutron multiplier. The structural material is Reduced Activation Ferritic/Martensitic (RAFM) steel, Eurofer. The plasma facing wall of the FW is protected with a tungsten cover in order to avoid pollution of plasma by heavy ions as the result of sputtering between the particles escaping the plasma and the blanket structural material. 2 mm thickness has been considered for preliminary studies.

In addition other functional materials, in particular ceramic components (alumina) to be used as thermal and electrical insulators inside the PbLi channels, see section III.C, are considered. This component is called Flow Channel Insert, FCI. Depending on its final design, corrosion barriers could be also envisaged. Due to the high velocity of the PbLi in the DCLL and therefore the low concentration of tritium, tritium permeation to the secondary coolant (He) is not foreseen; therefore permeation barriers could not be necessary.

TABLE III. LIST OF MATERIALS USED IN THE PRESENT DCLL DESIGN

Armor	Tungsten
FW channels	Eurofer
Breeding module box and stiffening grid	Eurofer
Manifold/backplate	Eurofer
Breeder/multiplier	PbLi
Flow channel insert	Eurofer–alumina–Eurofer

B. *Segment definition*

As explained in section II.C the OBC segment toroidal built is conditioned by requirements coming from the remote maintenance group, thus having parallel side walls. The distance between the segment side walls is 1300 mm. In addition, a linear gap of 20 mm between the central and the lateral segments has been assumed.

Following the philosophy of the rest of blanket concepts considered in EUROfusion a modular blanket configuration assembly has been adopted (Multi-Module Segment, MMS). Thus, a number of breeding modules are attached to a common Back Supporting Structure (BSS) with the aim of minimizing thermal stresses. Each of the modules is protected from the plasma by a FW, accommodates a breeding zone (BZ) and a helium collector. A poloidal distribution of the OB segment modules have been defined taking into account the following criteria:

- The ratio used-volume/available-volume has been maximized.
- The height of the modules is limited to 2 m according to manufacturing constraints, with 20 mm gap between modules.
- Identical radial build for every module. For this preliminary version it has been set in 910 mm.
- Parallelism between the FW and the rear wall, as well as between the upper/lower limits with respect to adjacent modules.

The result is that an OB segment is subdivided in 8 independent modules, whose characteristics lengths are shown in Fig. 3.

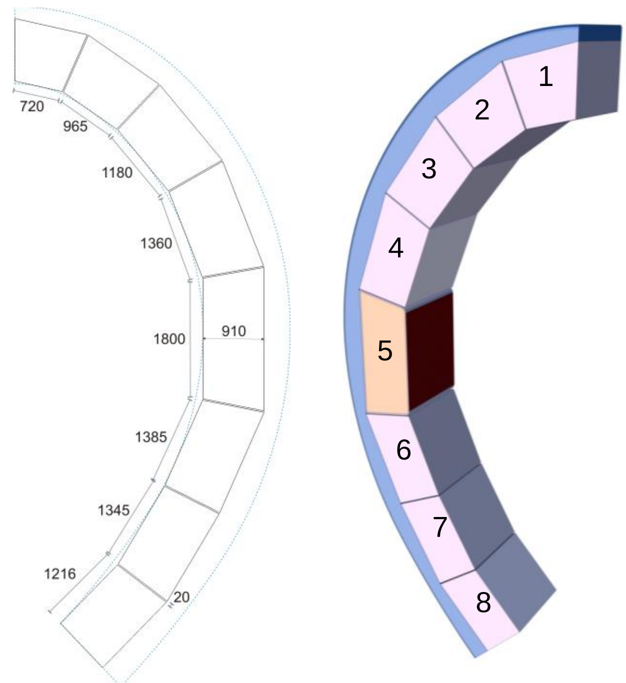

Fig. 3. Left: Definition of the modules distribution and FW lenght. Right: Outboard segment modules numbering, highlighting the equatorial module OB5

C. *Equatorial Module*

A number of models of the DCLL OBC equatorial module have been developed taking into account different widths for the BZ, different PbLi and He circuits, different approaches to define the BSS, distribution of pipes and manifolds, etc. The result can be summarized as:

First Wall: plasma facing structure that interfaces directly the plasma. Its main function is to remove the high surface heat flux from the plasma with an effective coolant system. The preliminary choice in DEMO is to integrate this FW in the breeding module design; therefore it cannot be repaired or exchanged separately. It consists on a 2 mm thickness tungsten cover attached to a Eurofer plate. It is important to notice that the problem of W-EUROFER bonding has not been solved yet. The FW must withstand with high thermal and nuclear loads of the order of 0.5 MW/m^2 (peaks of 1.5 MW/m^2) and for this reason must be appropriately cooled. Therefore, as initial condition it will be part of the power cycle since it will extract an important part of the nuclear heating. It is cooled by means of rectangular helium channels, which have been arranged in counter-flow.

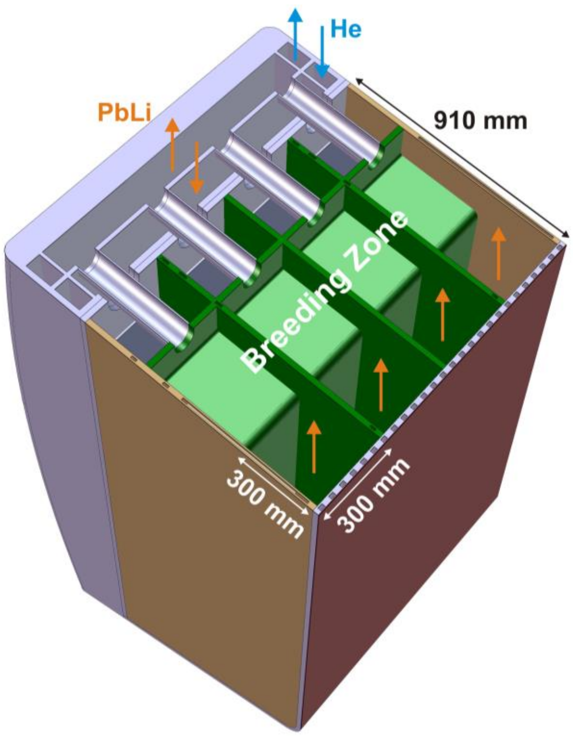

Fig. 4. DCLL OBC equatorial module showing the breeding zone (BZ), the back supporting structure (BSS), the He manifold zone and the first wall (FW).

PbLi circuit: four independent circuits compose the BZ where the PbLi flows in parallel through rectangular channels, Fig. 4. A stiffening grid, composed of vertical and radial plates, separates the different circuits. The walls thicknesses have been assumed to be 20 mm, this value being only preliminary and modifications are expected as a consequence of neutronics, thermal hydraulics and thermomechanical analyses. Main dimensions of the equatorial module are depicted in Fig. 5.

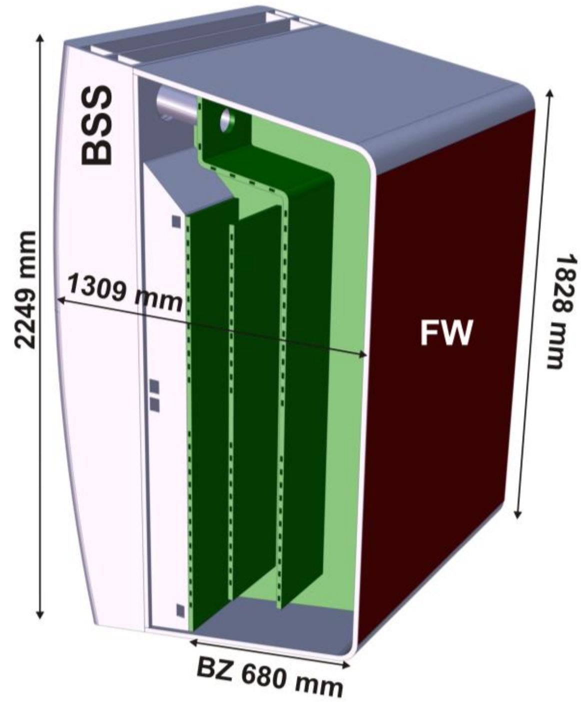

Fig. 5. Main dimensions of the DCLL OBC equatorial module.

The routing has been selected to maximize the power extracted by PbLi and to avoid the occurrence of reverse flows due to volumetric heating [11]. The outlet temperature must be as high as possible in order to maximize the thermal efficiency of the power conversion system. However, in the present DCLL version it is limited to 550°C in order to avoid creep of the structural material (Eurofer) [12] and extreme corrosion rates [13]. Therefore, a very narrow operational window is expected in terms of PbLi temperatures, i.e. 300 - 550 ºC.

The PbLi enters the equatorial module through the annulus (external duct) of the concentric pipes located at the top of the module. It goes downwards through two rows of parallel poloidal channels located at the rear part of the module. It turns 180º at the bottom through radial channels and then circulates upwards in parallel front poloidal channels. Finally, the PbLi goes outside through the internal duct of the concentric pipes; see Fig. 6, where the complete routing of one of the circuits is displayed.

He circuit: the helium circuit cools down the RAFM steel structure in order to maintain its temperature under 550ºC to avoid the occurrence of creep phenomenon. In addition, it allows preheating the structure prior to the PbLi injection into the segment (PbLi melting temperature ~235 ºC). On the other hand, the helium inlet temperature must not be lower than 300ºC to minimize radiation-induced embrittlement of EUROFER (DBTT increase) [12]. As in the case of the PbLi circuit, these limits restrict the operation temperature range, therefore reducing the achievable cycle efficiency in the power conversion system.

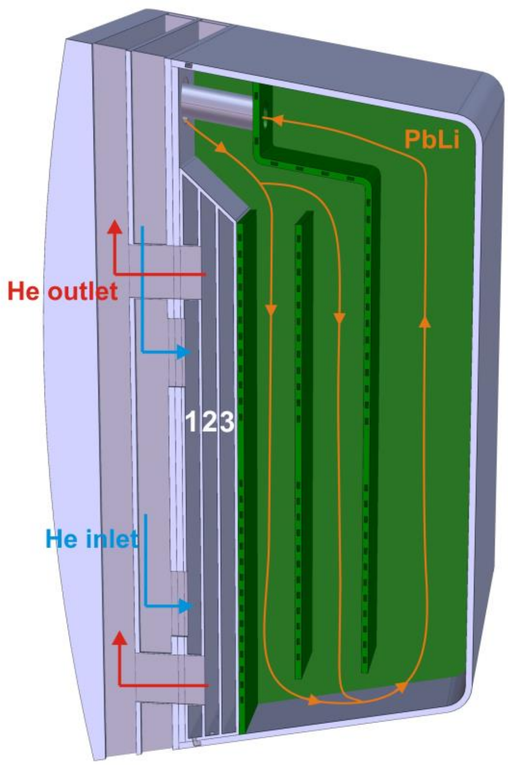

Fig. 6. Detail of the Back Suporting Structure, He internal manifolds and schematic of PbLi circuit layout.

The helium circuit consists of small rectangular cross-section channels and internal manifolds to distribute the flow between the different structural elements. About 90% of the thermal load on the blanket structure (including the FW tungsten layer) must be extracted by the FW helium circuit. This involves the main cooling requirements in terms of coolant channels density and helium mass flow. The FW and the lateral walls channels are fed in parallel from the most external of the helium internal manifolds (manifold 1 in Fig. 6). Besides, the FW circuit is also fed in parallel from the top wall and the bottom wall. Thus, counter-flow causes a more uniform temperature distribution in the FW. A double pass in each FW circuit allows increasing the helium outlet temperature improving the thermodynamic cycle efficiency, since the temperature gain in the rest of the circuit is significantly lower.

Both lateral walls are communicated through the internal toroidal walls channels, so that helium circulates from the left side to the right one and vice versa. Afterwards, it is recovered by the manifold 3 and distributed among the three internal radial walls, where the helium flows to the FW and returns. Later it joins the helium flow coming from the FW circuit at the manifold 2 and is then extracted to the general back manifolds. The complete sequence of He distribution inside the module is illustrated in Fig. 7.

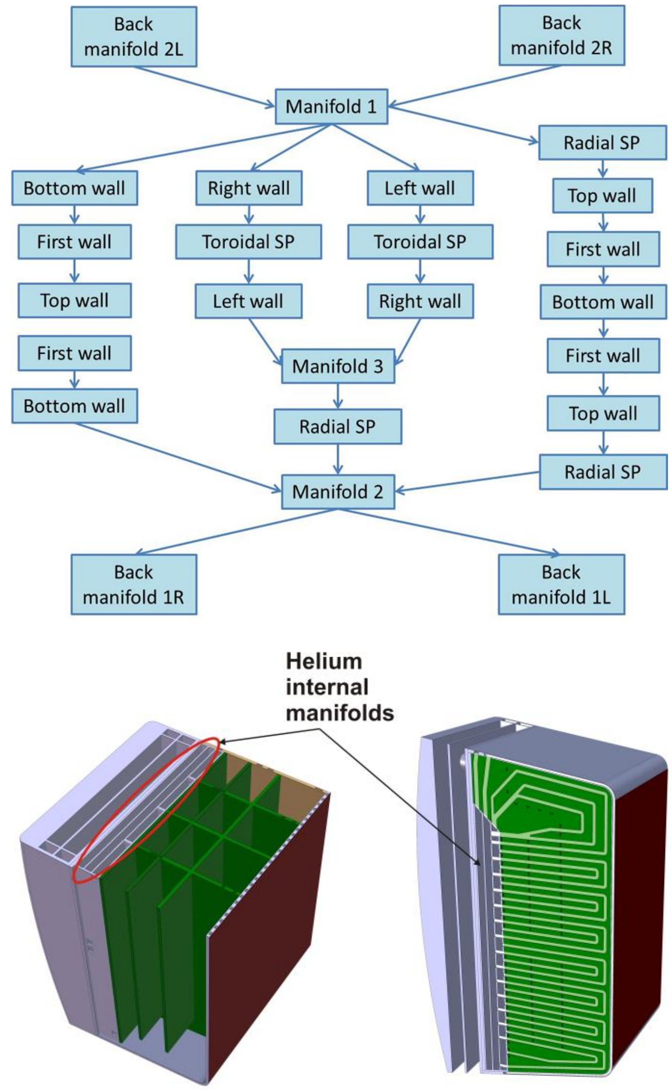

Fig. 7. He flow routing through theDCLL module.

D. *Back Supporting Structure*

In the MMS concept the modules are connected to a back structure with shielding and supporting functions. A 90 mm steel plate fitted to the vacuum vessel internal shape was designed at an initial stage to accomplish with such functions. The thickness is limited by the need of allocating all the pipes feeding PbLi and He to the lower modules. However, the available space between the modules and the back plate is not enough for the considerable number and diameter of pipes. For this reason, integrating all the service connections for every module in a common back manifold assuming also shielding and supporting functions has been proposed.

The design of the general manifolds includes two long poloidal ducts, where the PbLi flows downwards and upwards, covering the whole segment length (see Figs. 3 and 4). The concentric pipes feeding the PbLi circuits are connected to the general manifolds ducts. Additionally, two poloidal ducts with smaller dimensions are located close to the lateral walls, where helium flows downwards and upwards to feed the different modules. Connection with the cooling system of the module has been explained in section III.C.

E. Flow Channel Inserts

One of the peculiarities of the DCLL concept is that the liquid metal flows at relatively high velocity compared to other BB concepts in order to extract most of the reactor power (in previous works 1 m/s [1]; 0.1 m/s [3]). Since an intense external magnetic field will be present along the entire breeder unit, interacting with the liquid metal, important MHD effects can appear, which has been demonstrated that affect the overall blanket efficiency [11]. To achieve the best performance of the DCLL, the use of inserted ceramic insulators, the FCI, has therefore been considered.

The baseline for the new EU-DCLL is the sandwich-like FCI, initially proposed in [1]. It consists in a thin alumina layer between two Eurofer plates presenting low electrical conductivity, sufficient PbLi compatibility at working temperatures and good behavior under irradiation, as main requirements. The FCI has no structural function but it must present sufficient strength and dimensional stability to maintain its adequate performance, which in this case is given by the outer metallic sheet. In addition, it prevents the liquid metal contact with the ceramic. A scheme of the sandwich FCI is presented in Fig. 8. High ceramic purity is not required in this concept with respect to the liquid metal corrosion, since it has no contact with the liquid metal. Thus, different ceramic filler material would be considered, e.g. powder, foam, spray or glue [4]. Different fabrication methods are being explored, mainly bent-tube and tube-in-tube concepts [4]. Their characterization, in terms of electrical and thermal conductivity, is being carried out at CIEMAT.

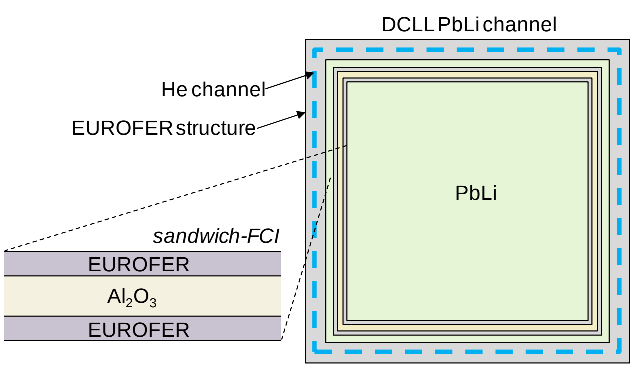

Fig. 8. Schematic of DCLL PbLi channel with sandwich-like FCI.

In the present version of DCLL good thermal insulation against the PbLi is desirable, although not mandatory, since to obtain improved efficiencies the PbLi temperature should be increased. In addition the amount of heat extracted by helium can be kept as low as possible since the structure is thermally isolated from the PbLi. One of the major constraints of the sandwich FCI concept is the possible Eurofer corrosion due to PbLi at 550 °C [4, 13].

IV. Design Analyses

A. Thermal-hydraulics

In this preliminary stage thermal-hydraulics analyses have been focused on determining the key parameters affecting the performance of the primary heat transfer system and the power conversion system (mass flows, inlet and outlet temperatures, PbLi and He circuits pressure drop, etc.). A preliminary 1D thermal-hydraulic model of the outboard equatorial module has been developed. The model integrates the different PbLi and He circuits, as well as the structure walls. The PbLi and He fluid domains are discretized into a number of volume elements. The corresponding solid elements between fluid elements are included, as well as other solid elements which act as boundary condition (e.g. first wall).

It is assumed that heat flux inside solid elements only occurs in direction perpendicular to wall surface, whereas heat transfer between elements occurs by convection. The Dittus-Boelter correlation has been used to calculate the Nusselt number in helium. In the case of PbLi, the Ji and Gardener correlation -assuming absence of high velocity jets near the side walls and in consequence electrically insulated walls- has been used [14].

The mass flow in each fluid element is obtained from applying the Hardy Cross iterative method, whereas the internal heat generation terms have been taken from neutronics calculations. A heat flux of 0.5 MW/m^2 is imposed in the FW, whereas the external sides of the top, bottom, left and right walls are considered adiabatic.

The model has been implemented in MATLAB Simulink by using a set of sub-system blocks which represent the different types of thermal elements (FW steel, internal walls steel, PbLi channel, He channel, He manifold, etc.). Energy balance equations are solved in each fluid block using the boundary conditions coming from the coupled blocks. The outlet temperature and the pressure drop (in the case of He elements) is calculated, as well as the maximum temperature in the solid elements.

The model allows making sensitivity studies by varying parameters like inlet temperatures, mass flows and channels cross section. Furthermore, it can be coupled to a model of the power conversion system to obtain cycle, gross electric or net electric efficiencies and to improve the design characteristics and the operation parameters. The latter will be done in further studies.

A preliminary study has been performed in order to obtain the main thermalhydraulics parameters in the DCLL equatorial module. An inlet temperature of 300 ºC has been selected for both He and PbLi, as explained in section III.C. The prediction of the model for the He heat transfer coefficient in the first wall is 6848 $W/m^2/K$, at 84.5 m/s and 8 MPa, which allows keeping the FW temperature always below 550 ºC. Thus, the maximum temperature achieved in the Eurofer of the FW is 544 ºC, to be confirmed through FEM calculations. The He outlet temperature is 420 ºC, a value that could be optimized in future iterations of DCLL designs. The PbLi outlet temperature is also calculated, being 550 ºC, with a pressure drop of 1.8 bar (its calculation is explained in section IV.C). Other important result is the power extracted by the coolants: a 60% of the total corresponds to the PbLi and the rest, 40%, to the He (which mainly corresponds to the FW cooling). A summary of main results from the model is shown in Table IV. According to these numbers, and based on the dimensions given in Fig. 5, the PbLi velocity in the front poloidal channels is around 1.4 cm/s.

All these results will be used in future as input data for more detailed 3D FEM calculations of the different parts of the equatorial module.

TABLE IV. MAIN THERMALHYDRAULICS PARAMETERS CALCULATED WITH THE 1D MODEL FOR THE DCLL

He parameters	
Mass flow rate	2.5 kg/s
Inlet temperature	300 ºC
Outlet temperature	420 ºC
Pressure drop	3.7 bar
% extracted power	40 %
PbLi parameters	
Mass flow rate	50.04 kg/s
Inlet temperature	300 ºC
Outlet temperature	550 ºC
Pressure drop	1.8 bar
% extracted power	60 %

B. Neutronics

The CAD model of each blanket module has been simplified (Fig. 9a) for the neutronics purposes to a level compatible with the geometrical capabilities of the Monte Carlo transport code (MCNP5). The blanket modules (with specific BZ of 64/30cm OB/IB) are heterogeneously divided in their main components, with the exception of the helium cooling channels that are included into walls/stiffening plates using homogenized mixed compositions. The helium collector and the back supporting structure are also homogenized, being the compositions 53%Eurofer/47%He for the collector and 51.29%Eurofer/4.35%He/44.36%PbLi for the BSS. This very much dense composition for the BSS zone will allow an efficient shielding system, and, furthermore, due to the presence of PbLi, high TBR is expected.

The blanket sector neutronic model has been integrated into the generic DEMO model [5], which main components 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

Hence, the complete DCLL DEMO model has been converted through the interface software MCAM into the geometrical input of the MCNP code (Fig. 9b). The plasma neutron source has been provided by KIT as a FORTRAN90 subroutine, sampling the neutron emission according to the established parameters of Table I.

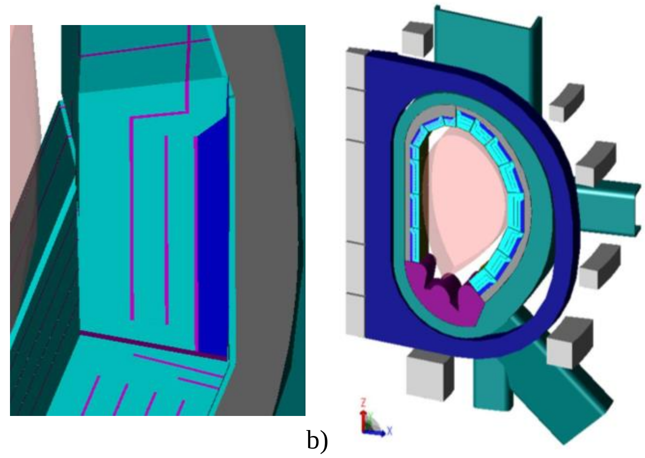
a) b)

Fig. 9. DCLL neutronic model: a) simplified OB ecuatorial blanket module, b) complete DEMO DCLL model with the integrated DCLL blankets modules

Preliminary neutronic analyses have been performed for the DCLL DEMO model. First of all, the poloidal variation of the Neutron Wall Loading (NWL) along the FW has been assessed. A mean value of 1.002 MW/m^2 has been observed (a result to be compared with the value predicted by the PROCESS system code, 1.07 MW/m^2).

The fundamental neutronic function response of tritium production has been also evaluated. The total TBR in the breeder region is 1.041. Furthermore the BSS contribution to the TBR in the whole reactor is 0.089 T/n which implies an increase of the total TBR to 1.13, fulfilling the auto-sufficiency criterion described in section II-B.

The total power generation in all the BB modules and BSS has been found to be 1229 MW. The power breakdown for the major reactor structures is shown in Table V. Considering the total generated nuclear power of 1503 MW, the obtained energy multiplication factor M_E is 1.195, above the target detailed in section II-B.

TABLE V. POWER BREAKDOWN (MW) ALONG THE MAIN COMPONENTS OF THE DCLL DEMO

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

In order to allow a preliminary evaluation of the shielding efficiency of the DEMO DCLL radial build, the nuclear heating in the reactor components needs to be assessed, paying special attention to the Power density on the TF conductor at inboard equatorial level. The nuclear heating in the equatorial region of the TF coil conductor has been examined providing results in 5 regions of 50 cm thickness each, and also the averages above the plane z = 160 cm and below the plane at z = -90 cm, from z = 0. As it can be seen in Fig. 10 the IB equatorial values (except the value calculated above the plane at z = 160 cm) satisfy the recommendation for the nuclear heating in the winding pack, currently established in 50 W/m^3 (20 times less than the ITER analogue requirement) as defined in Table II. On the other side, the limit is not satisfied for the OB side, due the presence of the equatorial and upper ports. 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 furthermore it is not a question of the specific blanket design. If the IB side is well protected it can be stated that the OB side also will be.

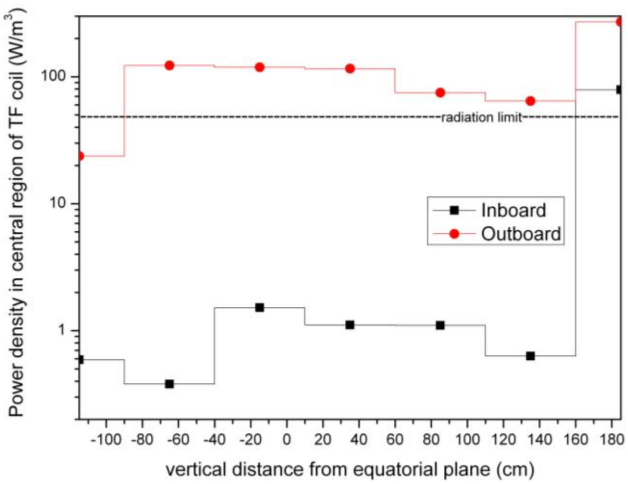

Fig. 10. Nuclear heating in the equatorial IB and OB side of the TF coil. The dashed line represents the current limit established for DEMO (50 W/m^3).

Other preliminary results have been also achieved for the current model as the radial and poloidal profiles of the nuclear heating in all the DEMO components in order to give inputs to the structural, mechanical and thermal activities. Further analyses are also ongoing to establish if the other damage criteria are also observed.

C. *MHD pressure loss*

A preliminary analysis of pressure losses due to MHD phenomena has been performed. The objective is to estimate the total pressure drop by means of simple correlations; therefore identifying critical zones for further studies and optimization. In [15] a numerical approach was made for channels with FCI consisting in sandwich of alumina. It assumes a toroidal uniform magnetic field, fully developed flows and a rectangular shape of the channel. Thus, in order to estimate the pressure drop in poloidal flows with the sandwich FCI, the following formulas were used:

$$\mathrm{k} = \frac{\beta b}{(Ha-\eta)\tanh \beta b + \eta \beta b} \qquad (1)$$

$$\eta = \frac{c+1}{c+Ha^{-1}};\ \beta = \sqrt{\frac{cHa+1}{c\kappa}} \qquad (2)$$

$$\Delta P = \sigma v B^2 k \qquad (3)$$

b is the half-length of the Hartmann wall scaled by the half-length of the Side walls; *c* is the wall conductance parameter; *κ* is the insert conductance parameter; *P* stands for dimensional pressure and k for non-dimensional pressure; *Ha* refers to the Hartmann number. Straight channels in the DCLL, including the BSS, have been analyzed through this approach which considers electrical insulation via FCI, Table VI. A FCI with 0.5 mm metallic and 0.1 mm ceramic thickness has been considered. Electrical resistivity for Eurofer and Al_2O_3 are $0.5x10^{-6}$ and 10^{11} Ωm, respectively [4]. The magnetic field is around 5-5.5 T.

For 3D complex geometries there is a lack of correlations for the same geometries and flow conditions than those of the DCLL. Therefore, a simplified approach has been adopted based on the proportionality between 3D pressure losses and the fluid kinetic energy. The following general correlation, which depends on the ζ parameter, has been used:

$$\Delta p_{3D} = \zeta \frac{1}{2} \rho v^2 \qquad (4)$$

ζ has been roughly extrapolated from [16], and is a general function of the non-dimensional Ha and N numbers. The range of (ζ/N) is relatively small, mostly in the interval 0.1 < ζ/N < 2.0. This argument has been followed in this approach. Last column in Table VI shows the estimated pressure loss in DCLL critical zones using (4).

TABLE VI. PRESSURE DROP IN DCLL CRITICAL ZONES

Straight channel ⊥ B type zones (3)	**Pressure drop**
BSS channels (cold and hot)	0.01 bar
1st cold downward poloidal channel	23 Pa
2nd cold downwards poloidal channel	20 Pa
Hot upwards poloidal channel	30 Pa
Complex 3D geometries (4)	**Pressure drop**
90º turn at module inlet through annular region	0.85 bar
90º turn, approx. constant flow section area	0.03 bar
180º turn at module bottom	0.10 bar
90º turn at module top	0.03 bar
Narrowing at inlet nozzle	0.50 bar
90º turn at nozzle outlet	0.28 bar
Total OBC eq. module	1.79 bar
Total OBC Segment	1.80 bar

This first assessment has identified main critical points on the DCLL design, showing that a pressure loss of about 1.79 bar is expected inside the module. 0.01 bar pressure loss is expected in the BSS long poloidal channels. Since the present DCLL design suggests a parallel cooling of the different blankets a segment will present a 1.8 bar pressure drop. Next step will be a refined 3D MHD estimation based on CFD studies, mainly related to nozzle zones (approximately a 80% of the MHD pressure drop inside the module).

V. CONCLUSIONS

A DCLL breeding blanket, adapted to the actual EU DEMO conditions, has been proposed (based in previous activities). The design is based on poloidal circulation of PbLi in order to extract most of the reactor power (60% in preliminary estimations), the first wall including He channels for cooling purposes. The breeder zone consists of 4 parallel PbLi circuits, separated through stiffening grid radial walls. These channels include FCI consisting on Eurofer-alumina-Eurofer sandwich, in order to prevent large MHD pressure drops. The segment includes a novel Back Supporting Structure consisting in two long poloidal ducts covering the whole length. He channels are also included to feed the DCLL internal manifolds.

Analyses including thermal-hydraulics, neutronics and MHD are ongoing and will serve as support for upgrading the module design. As general preliminary results, a tritium breeding ratio of 1.13 has been achieved, thanks to consider the new Back Supporting Structure definition. The neutron wall loading is 1.002 MW/m^2, and the M_E is 1.195. Shielding performances have been also obtained, demonstrating that the DCLL fulfills the current limit in the TF coils established for DEMO (50 W/m^3). Main cooling parameters have been obtained by means of a 1D numerical model which integrates the different PbLi and He circuits, as well as the structure walls. Results show a PbLi inlet/outlet temperature of 300/550 ºC; a He inlet/outlet temperature of 300/420 ºC; 60% of power extracted by the PbLi and a 40% by the He. Detailed 3D FEM calculations will be performed in future works to support this conceptual design. Thanks to the MMS design, the PbLi velocity has been considerably reduced inside the modules, resulting in lower MHD pressure losses. Preliminary estimations in the OBC segment show a pressure drop of about 1.8 bar, being mostly contributed by 3D effects. Critical points have been identified to be at the rear PbLi manifolds.

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