ACCEPTED MANUSCRIPT available at http://dx.doi.org/10.1088/1741-4326/ac26a1
DOI 10.1088/1741-4326/ac26a1

THE EUROPEAN DUAL COOLANT LITHIUM LEAD BREEDING BLANKET FOR DEMO: STATUS AND PERSPECTIVES

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Abstract

During the last years CIEMAT has been leading the activities in the European Program to develop an integral breeding blanket with advanced performances to work in a realistic DEMO scenario. This blanket is the Dual Coolant Lithium Lead (DCLL) working at a limited temperature in order to allow the use of conventional materials and technologies. The design of this blanket was finished, including the definition of the tritium extraction system and tritium simulations. Then, determined by the selection of other two concepts as driver blankets for DEMO, the focus was put on developing a novel BB still based on the DCLL concept but working at higher temperatures, thus increasing the plant net efficiency. In this work, a summary of the status of the DCLL is presented, together with some ideas for developing an advanced high temperature DCLL in the near future.

1. INTRODUCTION

The breeding blanket (BB) will be the component in charge of extracting and amplifying most of the neutronic power in future Fusion Power Plants (FPP). Moreover, it has to warrant the reactor tritium self-sufficiency through efficient breeding and recovery. An additional function is the protection of the vacuum vessel (VV) and magnets against radiation [1]. Various blanket concepts have been proposed along the years based on different breeder materials, neutron multipliers and power extraction methods (coolants). Within the EUROfusion Power Plant Physics and Technology (PPPT) Program (2014-2018) four breeding blanket concepts have been investigated [1]. Among them, the Dual Coolant Lithium Lead (DCLL) breeding blanket, whose potential benefits have stirred up interest from different R&D programs worldwide. Indeed, it has been extensively studied in the framework of other Projects and countries, being the primary blanket candidate in the US [2][3], and under consideration in China [4]. This concept uses the eutectic alloy of lead-lithium (PbLi) as tritium breeder, neutron multiplier and tritium carrier. Additionally, the PbLi acts as main coolant while the secondary coolant, mainly used to refrigerate the first wall (FW) and part of the blanket structures, is helium at a pressure of 8 MPa. The DCLL uses EUROFER as structural material and a ceramic component to electrically isolate the blanket conducting steel walls from the liquid metal, the Flow Channel Insert (FCI). The proposed PPPT program considered a “low temperature” version of DCLL (LT-DCLL), with a maximum operational temperature of 550 ºC, in order to allow the use of conventional materials and technologies [5].

Activities on the European DCLL, coordinated by CIEMAT, started with the system specifications definition, including a series of engineering analyses to prove the feasibility of this concept, leading to an overall design of the blanket. Intensive CAD work was focused on the DCLL geometry adaptation to the space assigned for the blanket in the different DEMO reactor models, as well as to the different load specifications. The result was a pre-conceptual design of DCLL based on a multi-module segment (MMS) configuration, consisting on a number of different blanket modules attached to a common Back Supporting Structure (BSS) [5]. The last DCLL design, for a DEMO reactor with 2 GW fusion power, consisted of 16 sectors distributed every 22.5° and including 5 segments each: 3 outboard (OB) and 2 inboard (IB).

After exiting the breeding zone, the PbLi alloy goes to the tritium extraction and removal system, a key system in charge of the tritium recovery [6] and that has been deeply investigated (technologies, materials, transport models). A consolidated design able of extracting tritium with a minimum efficiency of 80% has been produced to fit with the DCLL design specifications [7]. Finally, specific tritium transport models were also developed to investigate tritium migration to the coolants and expected inventories in the blanket [8].

As mentioned, the developed DCLL works at a maximum temperature of 550 ºC, allowing the use of EUROFER as structural material. This limit is an obstacle for the main advantage of the use of a self-cooled liquid breeder: its potential thermodynamic efficiency. Thus, it was decided focusing the engineering activities on the

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development of an advanced blanket concept, working at higher temperatures and providing a greater net efficiency (above the 45% according to [9][10]) that can compete with other energy sources, being more attractive for a future FPP.

2. THE EU LT-DCLL BREEDING BLANKET

The design of the European LT-DCLL has evolved along the years together with the different DEMO layouts developed by EUROfusion. Thus, during 2014 a conceptual design of a DCLL outboard equatorial module was launched according to the specifications and CAD model of DEMO2014 (16 sectors, 1.5 GW fusion power) [5]. The main objectives of the activities were to prepare specifications and design guidelines for the DCLL Blanket System; to identify the main requirements needed for the initial design; to identify interfaces with transverse EUROfusion packages (Remote Handling, Materials, Balance of Plant…); and to produce a preliminary CAD design. In 2015, specific design elements, such as the breeding zone lay-out or the thermo-hydraulic general scheme for the segments, were consolidated and new operational scenarios were studied, such as in-box Loss of Coolant Accident (LOCA). During 2016 the DCLL design was adapted to the new DEMO2015 layout, with 18 sectors distributed every 20º and with a fusion power of about 2 GW, higher than in DEMO2014. Neutronic calculations included the FCI for the first time in the models, allowing the discrimination of its real effect on the Tritium Breeding Ratio (TBR). Thermal-hydraulics models were developed to characterize global reactor parameters, estimations of the mass flow distribution and the pressure drop, and including an evaluation of the PbLi draining and filling processes in the blanket segments. A preliminary thermomechanical assessment of the BSS was done, showing an important issue related to the thermal gradients present in the BSS and the attachment with the modules. In 2017, one of the most important decisions was the rearrangement of the helium cooling system, which changed the direction from a poloidal to a toroidal cooling of the FW, looking for better thermomechanical behavior. Consequently, the entire route inside the module was modified. Specific magnetohydrodynamic (MHD) calculations were performed to assess heat transfer in PbLi channels electrically insulated by FCI, as well as the effect of the presence of helium cooling channels on the PbLi flow. The response of different FCI configurations against thermal loads was also evaluated. An important activity carried out during the Project was the integration of the Neutral Beam Injector (NBI) system on the DCLL segments, studying the impact both on the TBR and the structural integrity of the blanket segments [11][12]. Later, the influence on the TBR and nuclear heating of a new design of detached FW was also studied [12][13].

The R&D on ceramic FCI technology has been essential, for which two main lines have been followed: the fabrication of the components and their subsequent characterization. At the beginning of the project, some FCI mock-ups were produced based on a sandwich layout (steel-ceramic-steel) [14] but the design was adapted to the needs of the DCLL over the years. In 2016, the work was focused on dense alumina tubes without protective steel jackets (which use introduced new MHD problems), and on looking for relevant channel geometries for the LT-DCLL.

2018 was the final year for the LT-DCLL design activities, where the new DEMO2017 layout [15] was adopted and a detailed description of the blanket was produced, consolidating the design and ideas developed during previous years. The main outcomes are presented in the next subsection 2.1.

2.1. Design rationale and results

The last LT-DCLL blanket consisted of an upgrade to DEMO2017 reactor (16 sectors, 2 GW fusion power) [15], the most recent design produced in the PPPT Program. With this change, the blanket geometry was adapted to the space designated in the new reactor model, which suffered from a critical reduction (30 cm) in the radial thickness of the outboard segments. Thus, the features of the blanket had to counteract the strong impact on the TBR. In addition, the new DEMO layout implied a substantial change in the position and overall shape of the FW, leading to a new specification of heat fluxes, with an important impact on the blanket segmentation and FW cooling. Furthermore, the He circuit was strengthened to achieve a higher safety factor regarding He working pressure. The distribution of the components in the equatorial module of the outboard segment is presented in FIG. 1.

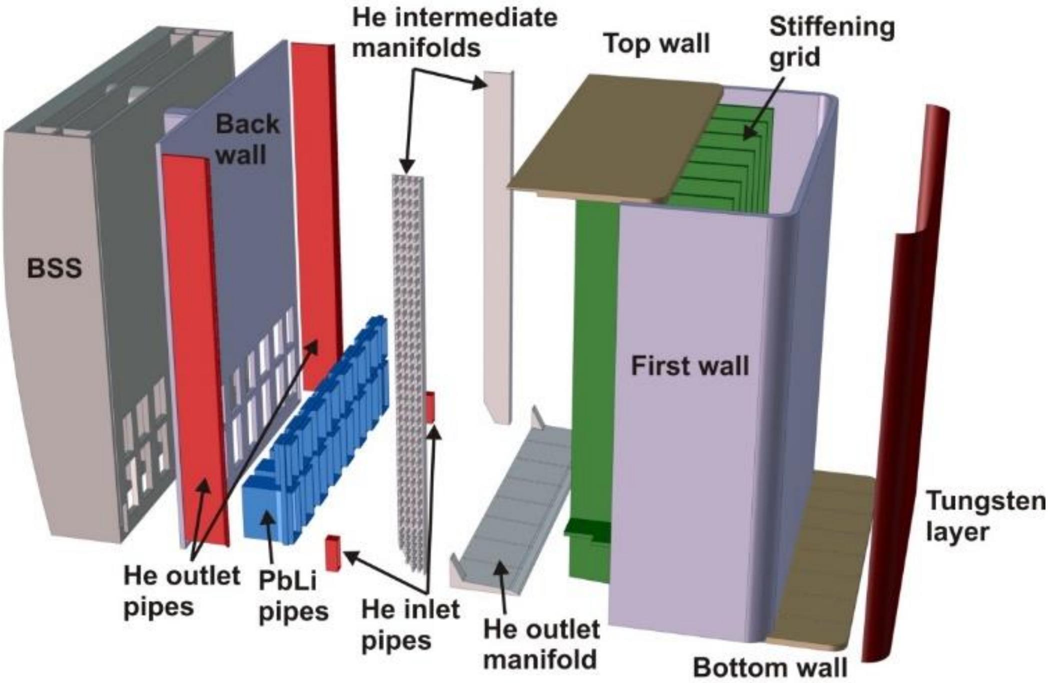

FIG. 1. Distribution of the components in one module of the DCLL breeding blanket.

Calculations in different engineering fields were needed to prove the good performances of the blanket. Firstly, neutronics computations were required to calculate responses such as the tritium breeding and the nuclear heating (NH) distributions (FIG. 2), and the Energy Multiplication Factor (M_E). As mentioned, this version of DEMO included a critical radial reduction in the radial length of the OB segments (~-23%), with a negative effect on the TBR. Nevertheless, the resultant TBR, 1.173, lower than the obtained for previous DCLL versions (1.196 [13]) is still significantly higher than the target of 1.1 [16]. This means that, if needed, there is margin for further design improvements and other systems integration that potentially diminish this critical number [17]. Concerning the assessments on the nuclear heating, assuming a fusion power of 1998 MW and having obtained a total power of 1933.5 MW, the achieved M_E is 1.21. Furthermore, nuclear heating and neutron fluence limits in the Toroidal Field Coil (TFC) remain fulfilled, implying adequate shielding [15].

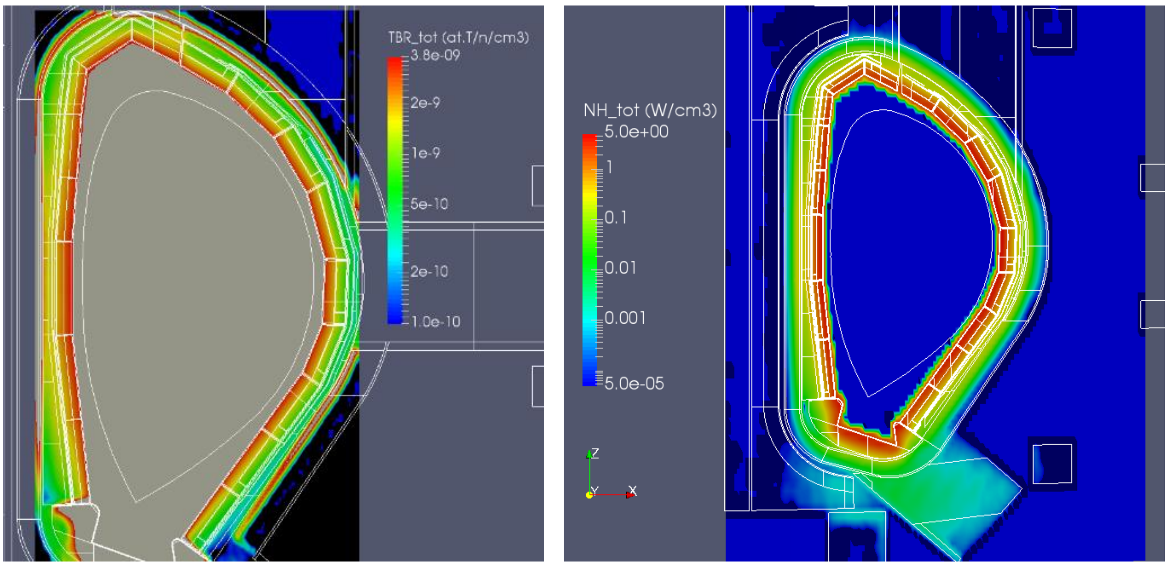

FIG. 2. (left) Radial-poloidal distribution of the tritium generated (at. T/n/cm3); (right) radial-poloidal distribution of the nuclear heating (W/cm3) in the whole DCLL DEMO.

The thermal-hydraulics (TH) performances of the DCLL have to assure a proper power extraction looking for the highest reactor efficiency. In this sense, different activities related to the coolants (PbLi and He) were also conducted to maximize their outlet temperature and, at the same time, maintaining a low value for the pressure drop. The PLATOON 1D code, developed at CIEMAT [11], was employed to characterize key parameters which affect the performance of the primary heat transfer system and the power conversion system. CFD calculations (Ansys FLUENT) were also used to study specific issues in the He cooling system, e.g. the mass flow distribution. A parametric study between several dimensions of the FW channels (pitch, width, length…) was carried out to select the most suitable to work under different operational conditions, considering parameters like the He mass flow rate, the outlet temperature and the pressure drop. Regarding the module structure, the dual cooling system allows keeping the EUROFER components under 550 °C. In general, temperatures at the interface between the tungsten layer and the EUROFER FW are in the range 465-545°C (*FIG. 3*). Temperatures resulting from the TH analyses were used as input for a thermomechanical analysis which also included internal pressure loads.

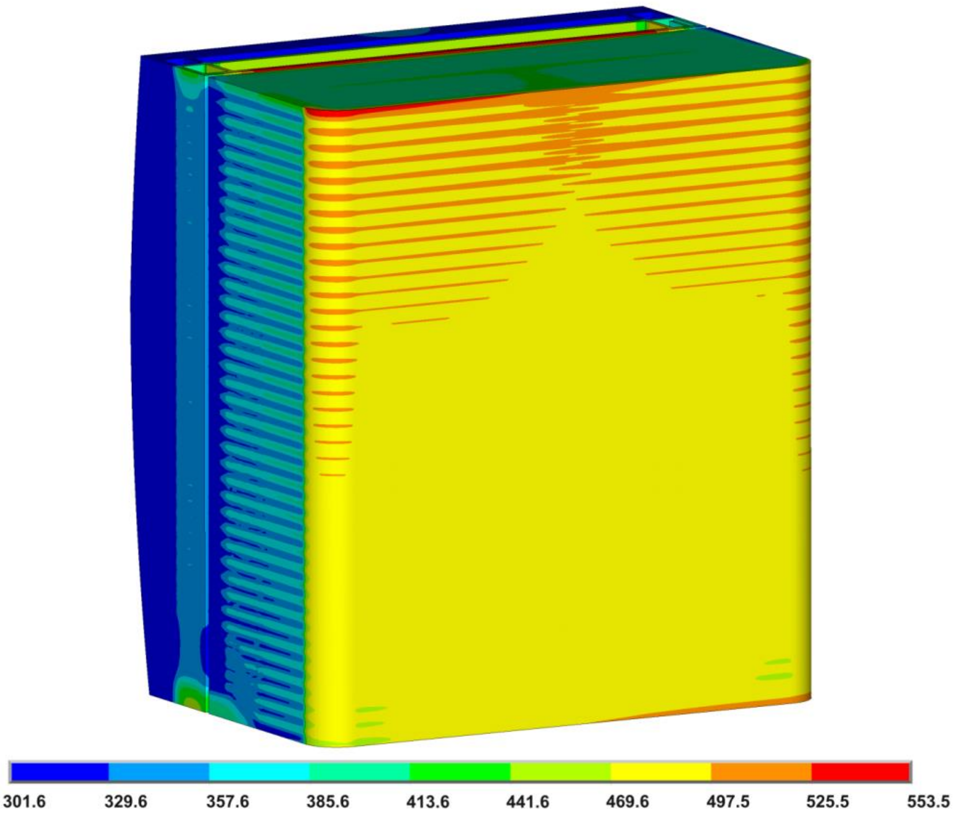

FIG. 3. Temperature map (ºC) in the outboard equatorial module (tungsten layer removed).

The first wall is cooled by rectangular cross-section helium channels which follow the toroidal direction. These channels are fed from two manifolds located in the back supporting structure which cover the whole length of the blanket segment. The use of both manifolds, symmetrical with respect to the middle poloidal-radial of the blanket segment, allows establishing counterflow circulation in the first wall, which is beneficial to reduce thermal stresses. Afterwards, He flows through the top wall, the radial stiffening plates and the bottom wall. The different streams are finally collected into a common manifold prior to leaving the module and discharging into other two other manifolds analogue to the feeders. The inlet and outlet temperatures for the He in the blanket are 300 and 408 ºC, respectively, mainly due to the temperature gain in the FW. A scheme of this circulation is presented in *FIG. 4*.

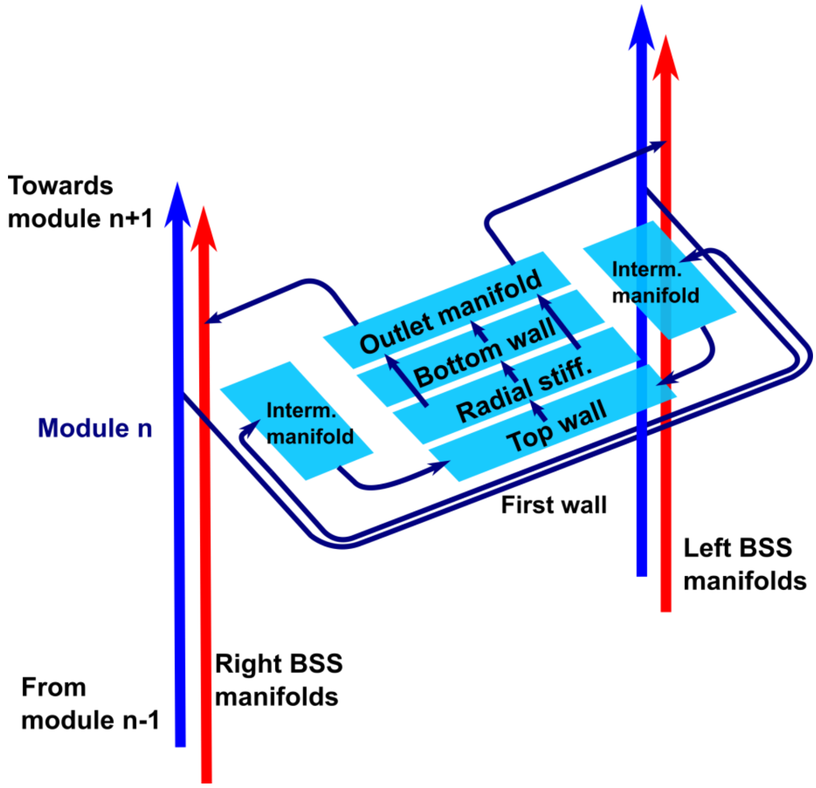

FIG. 4. Scheme of the helium route inside the DCLL module

Due to the interaction between the intense magnetic field of the reactor and the liquid metal (an excellent electrical conductor), MHD effects will appear. MHD forces are expected to be dominant on the PbLi dynamics, producing important pressure drops in the PbLi flows that impact the blanket functionality; thus, MHD analyses are of primary interest [18]. Apart from pressure drop, MHD effects will affect heat and mass transfer from the PbLi to the secondary coolant, for which specific calculations were conducted to estimate the heat transfer between the He and PbLi circuits. In addition, the effect of the FCI on the PbLi velocity profile has been also investigated. The FCI are embedded in the PbLi channels and divide the flow into two main regions: the core flow and gap flow. The former absorbs the majority of the channel flow. The latter is an annular flow in which the two regions perpendicular to the B field (Hartmann gaps) remain practically stagnant. In the other two (side gaps) high velocity jets are developed. This implies that warmer regions arise displaced to the Hartmann walls, while the side walls are well cooled by the PbLi flow. This can be observed in the cross-sectional (radial-toroidal) temperature distribution exposed in FIG. 5. The conditions of the analyses corresponds to those of the central frontal channel of the equatorial outboard module (B_0 = 4.147 T, U_{avg} = 1.74 cm/s). The quasi-stagnant PbLi gaps can have important consequences on tritium transfer as well (section 2.4).

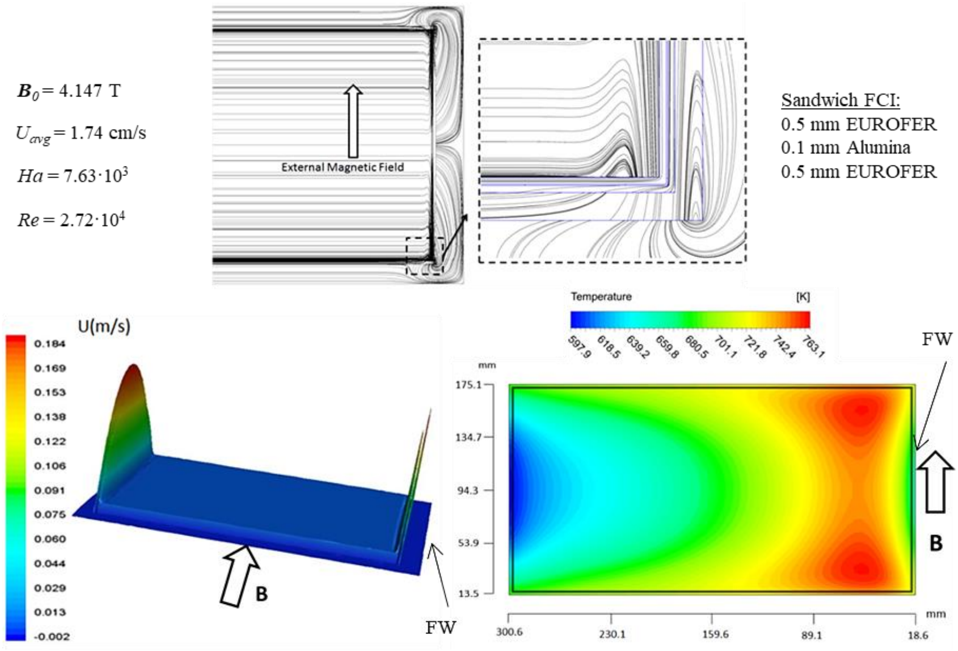

FIG. 5. Main results of the MHD-thermal computations for a channel with a thin sandwich FCI. (top) Electric currents induced in the PbLi channels. (bottom-left) MHD fully developed velocity profile in a frontal PbLi channel. (bottom-right) Temperature distribution in the same channel considering the neutronic volumetric heating.

2.2. R&D on flow channel inserts

The associated R&D for the DCLL concept includes the development and characterization of ceramic components, the so-called Flow Channel Inserts, to mitigate the MHD effects. CIEMAT has developed an ambitious work-program to fabricate ceramic components made of alumina and SiC, with different arrangements and geometries (FIG. 6) [19]. Once longitudinal square-sectioned tubes, elbow-shaped and elbow-shaped with surface texture tubes were finished, the manufacturing process was consolidated by the production of an 800 mm high prototype of a complete BB segment. The functionality of the produced components has been tested in terms of electrical resistivity, thermal conductivity and thermomechanical properties, and the achieved conclusions are supported by the microstructural inspection [20].

A good dispersion on flexural and compressive strength data is obtained when the alumina ceramic is mechanically tested after submitted to different thermal and radiation treatments. Helped by the digital analysis of SEM images, a correlation of the grain size with the flexural and compression properties of the studied ceramics is followed to conclude on the partial degradation of the mechanical behavior with treatments. The high strength values obtained are satisfactorily explained by the small average grain size (0.85 ± 0.15 µm calculated mean grain size at the 50% of cumulative population) and the high grain boundary density calculated for the initial ceramic, together with the absence of grain growth after the thermal cycling or the ionizing irradiation. Furthermore, neither the presence of internal fractures or grain detachment may explain the marked decrease of compression strength in the gamma-irradiated batches, which is still under study.

A first approach to the accumulation of hydrogen in ceramic insulators for FCI applications has been addressed. Proton implantation by means of accelerated ion beams was performed at the CMAM facility (Cantoblanco, Spain), and the damaged ceramic has been characterized afterwards by transmission electron microscopy. A high density of nano-cavities, because of hydrogen aggregation and accumulation, were observed inside alumina grains, pointing out the slow diffusion process that takes place in the ceramic body with possible swelling consequences. Swelling in solids is an effect that is tolerated to a certain degree in future reactors and therefore should be minimized through the introduction of design or microstructural strategies. At least, at the total proton dose delivered, cavities seem to accommodate in the crystalline structure, because no local strain effect was revealed. The absence of gas accumulation and the lack of the typical depletion zone showed that the grain boundaries are not acting as gas sinks.

In addition, the functional behavior of the produced alumina grade in contact with PbLi was also addressed, in collaboration with Centrum výzkumu Řež, Czech Republic. The electrical resistivity of an alumina tube previously gamma-ray irradiated up to 4 MGy was monitored while being cycled between 300 and 450 ºC. Helped by microstructural studies of the ceramic surface, the absence of the ceramic degradation due to chemical reaction with the liquid metal was firstly concluded. The alumina conductivity after a total test duration of 2300 hours is calculated to be far below the requirements for the FCI component under DCLL operational conditions [21]. The ionizing radiation dose, previously applied, is unlikely to have produced an effect on the electrical conductivity. These results are promising, concluding that pure alumina ceramics obtained by slip casting could be implemented in the DCLL as electrical and thermal requirements could be fulfilled. However, some issues are still unsolved and will be addressed in upcoming activities (e.g. swelling under nuclear radiation, difficulty of producing pieces with complex shapes, other compositions…).

Other activities have been developed in support of the DCLL design. A longitudinal prototype including the arrangement of the ceramic tube and steel flange by means of a ceramic cement has been successfully manufactured at CIEMAT for its future testing in a liquid metal circuit (FIG. 7). The mechanical stability of the prototype by subjecting the ceramic-steel assembly to high temperature under high loads was tested. After 100 hours at 550 ºC, results are satisfactory, as concluded from the external and internal inspection with penetrating liquids without the development of cracks. Future gas and hot liquid tightness tests are under preparation.

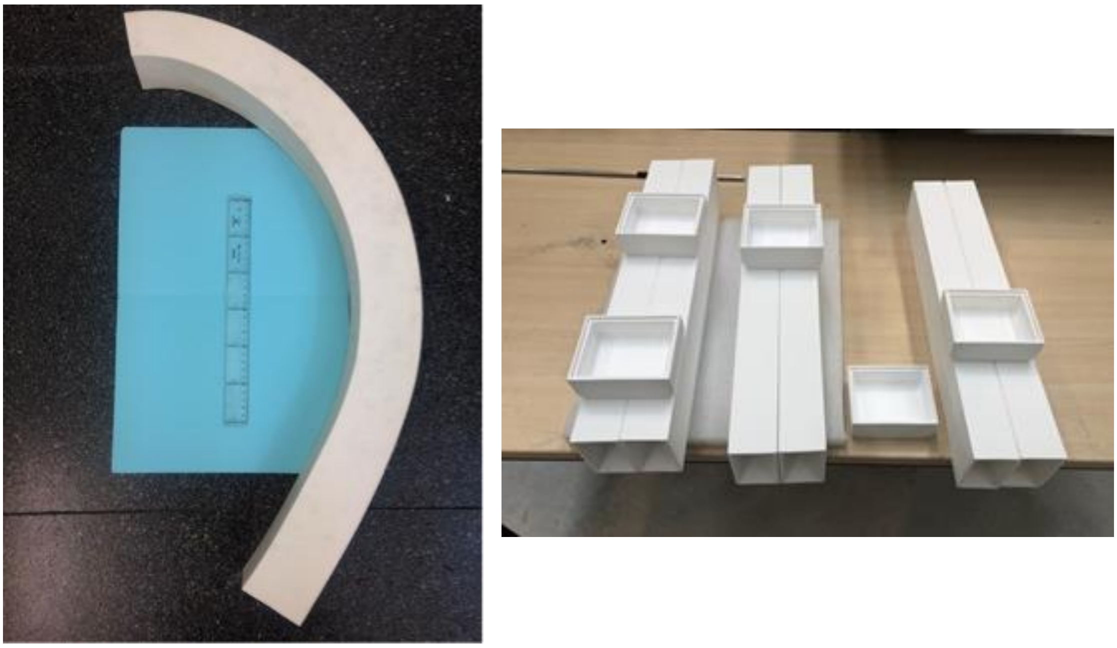

FIG. 6. Left) Final sintered banana-shaped FCI; Right) longitudinal alumina mock-ups produced by casting.

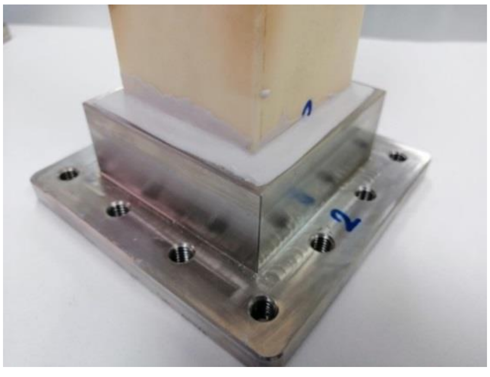

FIG. 7. Prototype assembly of the squared sectioned alumina tube and the steel flange with a white ceramic cement, before being submitted to mechanical stability tests at high temperature.

2.3. The DCLL Tritium Extraction System

One of the main functions of the breeding blanket is the tritium regeneration via neutronic reactions with the lithium compounds. Thus, the design of a breeding blanket cannot be understood without the definition of the Tritium Extraction and Removal System (TERS). An intrinsic characteristic of the DCLL blanket, when compared with the other liquid metal concepts, is the high velocity of the liquid metal. An immediate consequence is that the tritium concentration in the liquid at the exit of the blanket segment is rather low, meaning that the tritium partial pressure is about two orders of magnitude lower than the expected one in other blanket concepts [22]. From the point of view of safety, it can be an advantage since the permeation of tritium to the secondary coolant is reduced. However, the low tritium content complicates the recovery process needed to reach the self-sufficiency of the reactor, which gives special importance to the TERS.

Along with the evolution of the LT-DCLL design, the TERS design has been adapted to comply with the requirements of minimum extraction efficiency as function of the operational blanket outputs. The technology selected for the tritium extraction was the permeation against vacuum, PAV [23], based on the permeation of tritium through a membrane across a channel containing the flowing liquid metal. The outer side of the channel is subjected to vacuum favoring a pressure gradient at both sides of the permeable membrane. A first TERS design was proposed for the DEMO 2014 layout consisting of 16 sectors [23] that was later updated to meet the 18-sector configuration of DEMO [7] following the DCLL designs of 2015 and 2017.

A schematic view of the integration of the TERS into the reactor is shown in FIG. 8. The PbLi loop (red line) connects the breeding blanket (dark grey) with other subsystems (heat exchanger, purification, etc.). The TERS (blue box) is located in the loop immediately downwards the blanket. The system is connected through a bypass just in case there is no need to pass the liquid metal through the TERS (during the commissioning phase, maintenance procedures, etc.). The whole amount of PbLi mass flow is spread differently in several loops to manage the PbLi coming from the outboard and the inboard segments of the blanket. The figure shows a configuration based on one PbLi loop for each sector; however, the distribution of the liquid metal has been changing with the DCLL-DEMO designs to accommodate the total mass flow into an acceptable number of loops.

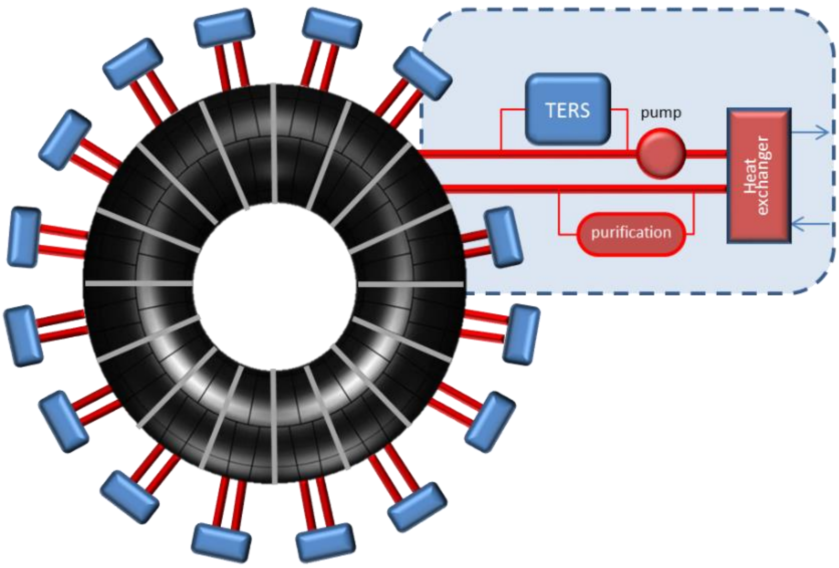

FIG. 8. Toroidal section view of the DCLL DEMO showing the 16 sectors (grey) and the PbLi loops (red). A detail of only one of the PbLi loops, including its main components (TERS - blue, heat exchanger, purification), is shown

Coming from the blanket, in the TERS, the PbLi passes through the PAV for tritium extraction, as shown in the P&ID of FIG. 9. A dedicated vacuum system is in charge of achieving an efficient extraction. It is composed of a rough vacuum pump (RVP) and a high vacuum pump (HVP) connected in series with the PAV. The tritium is extracted in one single step and is directly routed to the Tritium Plant. Additionally, a Getter System is included as a support to store the extracted tritium prior to its transport to the Tritium Plant in case of need.

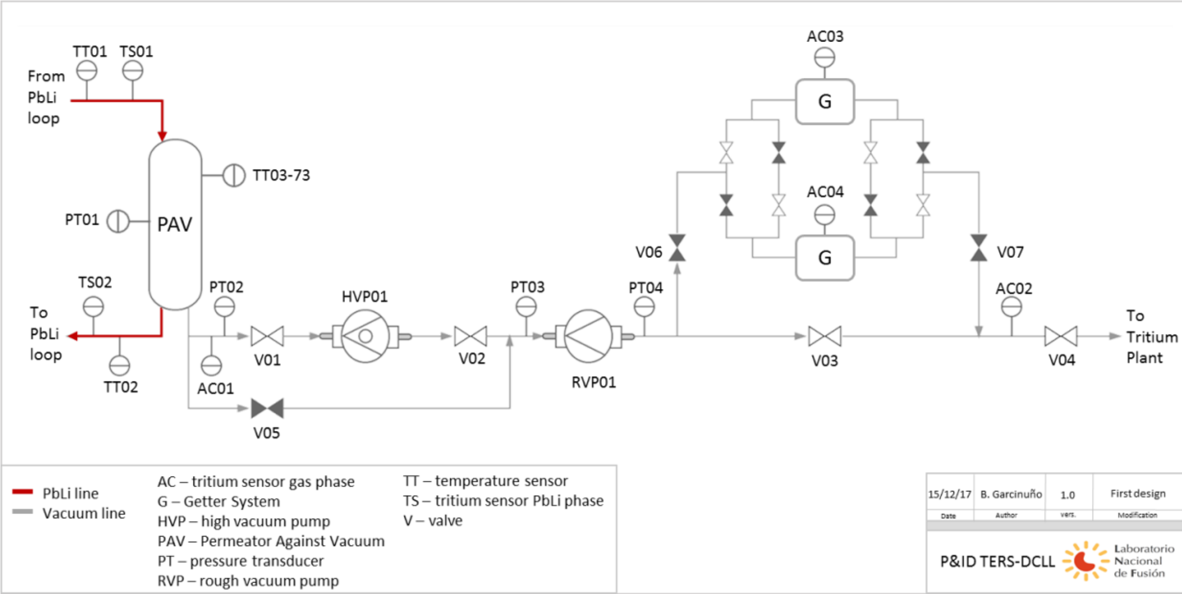

FIG. 9. P&ID of the Tritium Extraction and Removal System for the DCLL DEMO showing its main components: PAV; vacuum system; getter system; temperature sensors; pressure transducers; valves; tritium sensors in gas and PbLi phases.

The geometry and materials for the PAV design deserved a careful analysis and were chosen in order to optimize the extraction up to an 80% of efficiency. Geometrically, it should maximize the contact between PbLi and membrane assuring a uniform distribution of the liquid metal flow. The employed material should possess a high permeability to tritium and operate at high temperatures (550ºC), among others [23]. Within this context, a squared multi-channel component with vanadium, niobium or tantalum membranes was proposed. The component contains a series of alternated channels for flowing PbLi and vacuum (FIG. 10, left). A tritium transport model based on a diffusive limited regime was developed to optimize the geometrical characteristics of the PAV as function of the physical processes and the operational parameters [23]. The vacuum system required also special attention. It should provide enough pumping speed to achieve such a vacuum level capable to keep the pressure gradient at both sides of the membrane. The requirements were fixed as a function of the PAV efficiency and the tritium concentration in the PbLi. Considering the availability of commercial pumps, it was concluded that a dedicated R&D program is needed to improve actual pumps to be compatible with tritium and to provide the pumping speed needed. In this context, an upgraded diffusion pump was the concept proposed for the HVP, and a liquid ring pump for the RVP [7].

The final design of the TERS was made according to input data from DCLL blanket and PbLi loops, achieving a minimum extraction efficiency of the 80%. The design includes a consolidated P&ID diagram and considers all the TERS operational modes. Moreover, a CAD design of the TERS integrated in the DCLL PbLi loop was prepared, where the sizing of the components gives a realistic overview of the footprint in the reactor (FIG. 10, right). It is also included a preliminary definition of the instrumentation comprising temperature sensors, tritium concentration sensors, accountancy systems and pressure transducers.

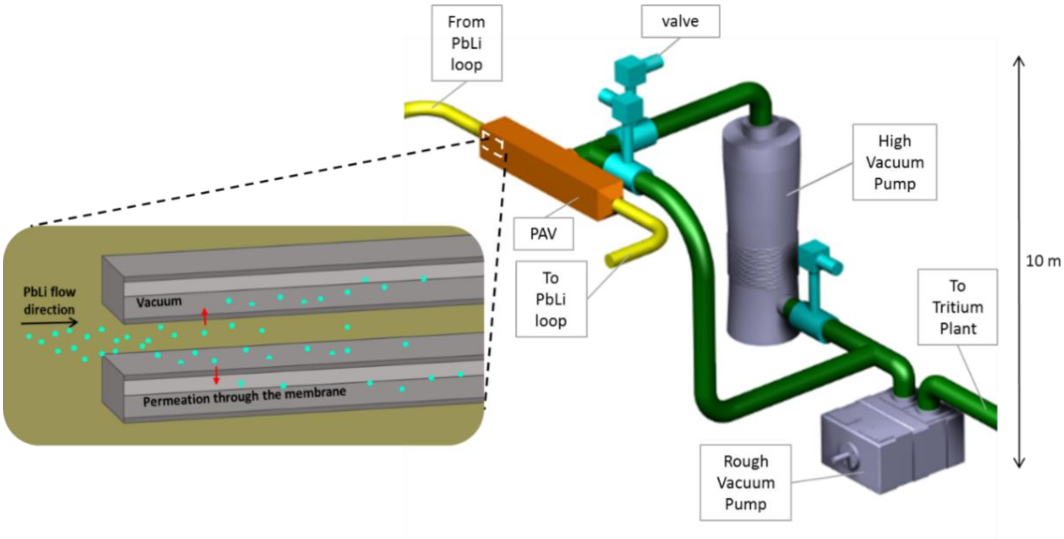

FIG. 10. Schematic view of the working principle of PAV (left) and 3D design of the TERS (right)

2.4. Tritium transport modelling

Tritium transport models at system level allow estimating important quantities for the blanket design such as tritium inventories in the different regions and permeation rates from the PbLi to the He flow and to the environment. These kinds of models are based on process flow diagrams (PFDs), in which each component represents one subsystem. *FIG. 11* depicts the most external PFD used for the DCLL tritium transport model at system level. Apart from the blanket itself, it includes the main ancillary systems: the PbLi and He piping, the TERS in the PbLi loop, the Coolant Purification System (CPS) in the He loop and the Heat Exchangers (HX) in both loops. PbLi and He flow rates are appropriately scaled at the entrance and exit of the blanket, considering the total number of loops in the real system.

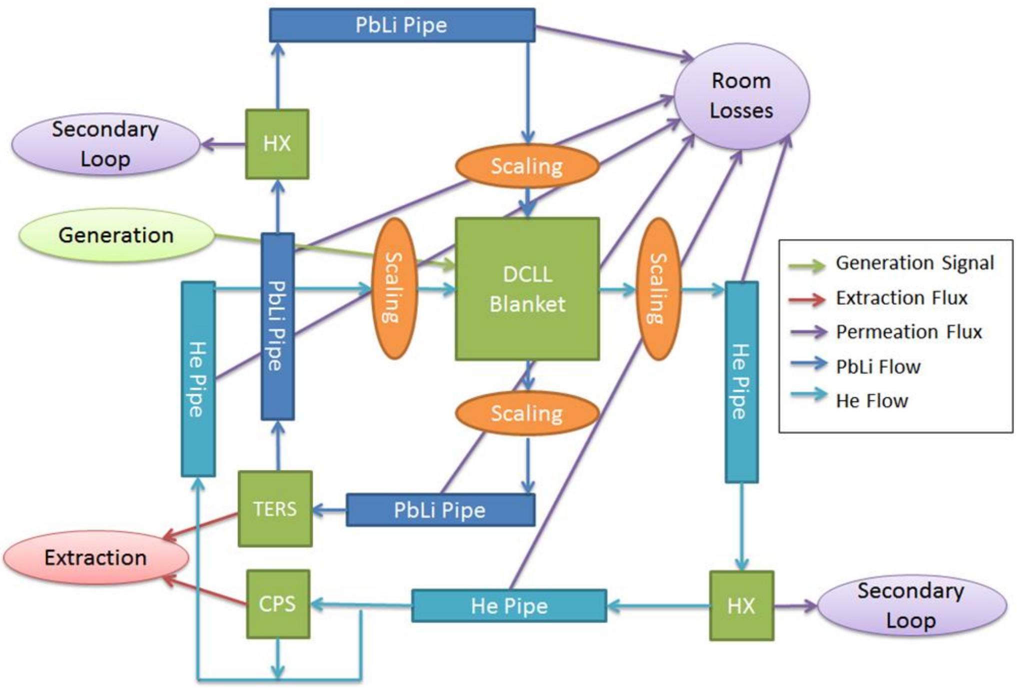

FIG. 11. External Process Flow Diagram of the system level tritium transport model including the blanket and the ancillary systems used to model the blanket and the ancillary systems

The model has been developed using the object-oriented simulation platform EcosimPro [24]. The specifics of the simulation strategies are the same than in previous models of former DCLL designs [8]. In these past analyses, it was obtained that the high PbLi velocities that characterize the DCLL concept keep the permeation rate from PbLi to helium in low levels (~1 mg/day), especially in comparison with PbLi-based low velocity blankets [25]. Indeed, high mass flow rates increase the number of recirculations through the TERS per unit time, boosting tritium extraction in detriment of permeation losses. In the model, the TERS is considered to have a constant extraction efficiency of 80% [23].

Nevertheless, the previous system level model did not consider the quasi-stagnant PbLi flows that MHD interactions create in the Hartmann gap in between the channels walls and the FCI (FIG. 5). Since the alumina, used for the FCI, is an effective permeation barrier [26][27], only the tritium generated inside the gap is susceptible of permeating to the He circuit. Therefore, this relatively small volume of PbLi has a crucial impact on the mass transfer. In order to better understand this impact, an auxiliary 3D finite volume mass transfer calculation of the PbLi gap region has been performed using the velocity profiles obtained in the MHD analyses (FIG. 12). The Hartmann gap accumulates higher tritium concentrations while the tritium generated in the side gap is very effectively removed by the side flow. This result is in agreement with previous analyses that considered SiC FCI with low conductivity [28].

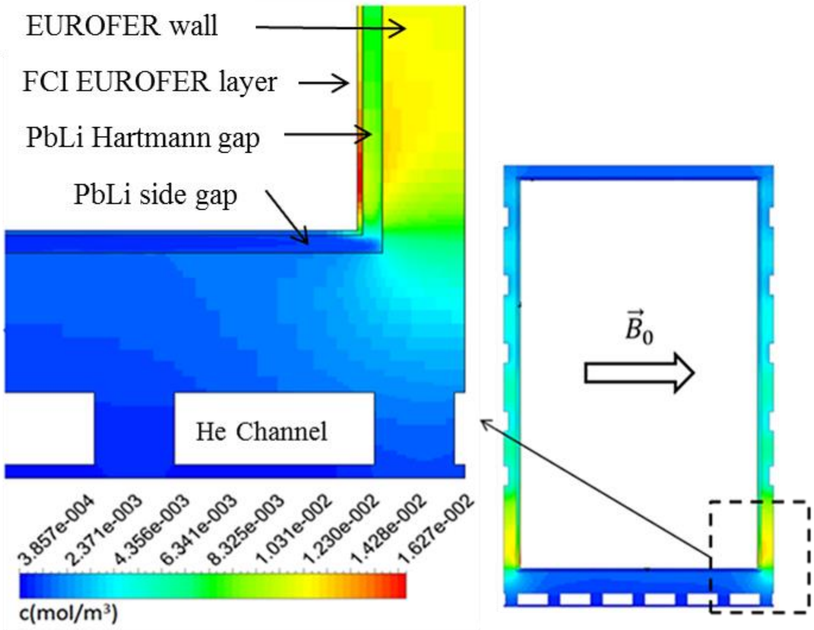

FIG. 12. Tritium concentration contours in the mid-section of the DCLL front channel gap

The results of the 3D analysis of the gap flow have been introduced in the global system level model in two different ways: On the one hand, the PbLi flow rate through the Hartmann gap and side gap has been adjusted to match the predictions of the MHD analyses. On the other hand, 3D results have been used for deriving mass transfer coefficients between the side gap and the Hartmann gap through the corners of the channel. Moreover, surface correction factors have been deduced to account the shape of the He cooling channels following a methodology similar to the one used in [29].

FIG. 13 depicts some of the results of the DCLL system level model. The generation pulses of the DEMO machine cause the oscillations of the output variables. Three different model assumptions are compared: one model in which the flow is evenly distributed between the side and Hartmann gaps (blue curve), one model including the uneven flow distribution between both gaps due to the MHD interactions (red curve) and one model that includes also 3D correction parameters (surface correction factors and mass transfer coefficients through the gap corners).

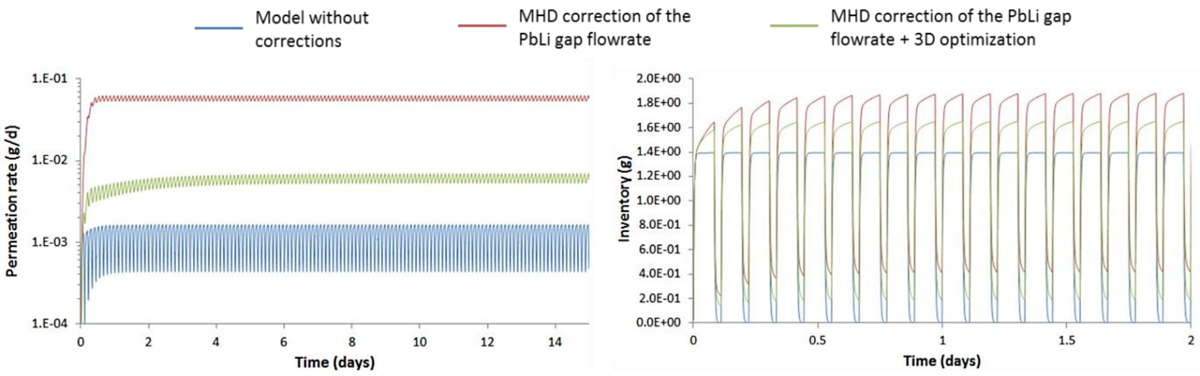

FIG. 13. (left) Total permeation rate from PbLi to He inside the blanket. (right) Total tritium inventory inside the PbLi

Including the quasi-stagnant volume of PbLi in the model (Hartmann gap) increases the permeation rate towards the He circuit by almost two orders of magnitude with respect to previous results. Considering the connection between the side gap and Hartmann gap mitigates this permeation raise. Nevertheless, even in the worst case obtained, permeation rates and tritium inventories are at least one order of magnitude below the values obtained with system level models for blankets with low PbLi velocity [30].

3. MAIN ISSUES OF THE LT-DCLL CONFIGURATION

The MMS configuration proposed for the LT-DCLL presents a number of drawbacks and benefits that have to be mentioned. In this paper we will focus on the main problems, since advantages are described in the numerous papers already published [5][11][13][15][20]. Thus, the main issues are the motivation for the new proposal presented in the next section 4.

Firstly, there are potential problems related to the geometry of the configuration, such as the liquid metal flow path inside the modules/segments. In this regard, there are a considerable number of turns, expansions and contractions of the fluid. Although they are produced in planes perpendicular to the magnetic field, they can promote important 3D MHD effects. This kind of MHD phenomena cannot be effectively mitigated with the use of electrical isolating components and should be avoided as much as possible [31]. The MMS approach has an important advantage, since the coolants (both the PbLi and He) can be distributed to the different modules in parallel, potentially diminishing the total pressure drop of the system. However, assuring a proper mass flow balance between the modules is a difficult task which, at the end, can affect the global pressure drop of the segments. Another geometrical issue arises due to the number of different fluids paths inside the blanket, assuring a heat transfer between them. This fact can diminish the overall outlet temperature of the segments, as was observed for the BSS circuits [15]. Besides, a recent work demonstrates, for a WCLL with a similar configuration than that of the LT-DCLL, that the thermomechanical performances of the MMS are worse than that for the SMS, particularly during disruptions [32]. This makes that not only the WCLL, but also the HCPB concept, have changed to a SMS configuration [33].

The heat removal performance of the LT-DCLL is also a point that has to be discussed. As already mentioned, the plant efficiency is limited (maximum around 35% [34]) due to the operational temperatures range of EUROFER (300 -550 ℃). In addition, the presence of the FCIs makes necessary a proper cooling of the walls in contact with the Hartmann gaps (radial stiffening grid), where the PbLi is almost stagnant (FIG. 5). This leads to He circuits longer and more complicated (higher pressure drop), having unfavorable effects on the PbLi outlet temperature that finally also penalize the plant efficiency. A large number of modules also implies a higher amount of welds, which undoubtedly has an impact on RAMI [35].

Finally, the geometry of a MMS approach necessarily entails a large amount of steel in the blanket segment, which in principle is not favorable for the TBR since the volume available for the breeding material is reduced. The value for the TBR for the LT-DCLL is adequate (higher than the limit of 1.1 [16]) and could be even increased, therefore absorbing possible losses due to heating systems and potential diagnostics installation. However, the introduction or modification of systems and components whose design is progressing [36], such as the divertor, the First Wall, the FCIs, etc… could seriously jeopardize the nuclear behavior of the LT-DCLL concept, since some neutronic criteria could be not fulfilled any more, as preliminary investigated in [13].

Pressure losses due to MHD have been estimated both in the internal DCLL circuits and the BSS channels. However, main contributions are expected to be located at the entrance and exit of the blanket segments, due to important expansion or contraction of the liquid metal path [37] even with the use of electrical isolation (3D effect).

The main objective of the FCI, initially proposed by Malang [38], is to mitigate some of the MHD problems. The concept of FCI studied for the European LT-DCLL is interesting and solves most of the issues related to electrical isolation inside the blankets, but when looking deeper into details it seems to introduce more limitations than possible gains:

- The original FCI selected for the LT-DCLL was the so-called sandwich concept [14]. This FCI is based on a ceramic component in between two steel jackets which protect the isolating component. However, it has been demonstrated that due to different expansion coefficients of the ceramic and the EUROFER, high thermal stresses can appear, giving place to thermomechanical problems and seriously compromising the integrity of the ceramic component [19]. Moreover, the electrically conducting steel layers reduce significantly the pressure reduction factor of the sandwich FCI.

- To accommodate the module deformation due to thermal gradients it was decided to set a gap of 2 mm between the steel walls and the FCI. However, this gap introduces an additional problem: it has an impact on the mass flow distribution between the PbLi bulk and the gaps (Hartmann and side), FIG. 5. In addition, the assembly of the FCI pieces inside the PbLi channels is not trivial and assuring a permanent gap of 2 mm is not possible without direct contact with the walls of the channels (again, thermal deformation can lead to high stresses on the ceramic).

- In the particular case of the LT-DCLL, the geometry of the module makes difficult to design a continuous FCI, with some gaps between the different FCI pieces. The impact of these gaps on the blanket performance has been investigated in [39], showing an increase in the overall pressure drop due to this gap and related to the loss of continuity. The results of this study are not comparable to DCLL conditions, but the effect is expected to be even more relevant.

- Other important MHD problem is expected in the connection between the BSS and the individual modules. In the LT-DCLL rectangular ducts connect the liquid metal channels inside the module with the hot/cold channels in the BSS (FIG. 1). Installing FCI in those ducts seems extremely difficult from the assembly point of view. Concerning the MHD in the BSS region, although the magnetic field is lower than in the breeder zone, it is still high enough to produce important MHD effects. In the LT-DCLL, and particularly for the IB segments, there are high flow rates in the PbLi manifolds (10-20 cm/s), making mandatory the use of FCI. However, the BSS supports the different modules through robust attachments that cross the PbLi channels, complicating the installation of FCI (FIG. 14).

One last point to be considered is that other species, apart from tritium, can be induced due to neutron irradiation. This can have an impact on the blanket performances, such as the case of helium produced in the PbLi due to the neutron reactions with ^{6}Li and ^{7}Li. In principle, thanks to the high velocity of the PbLi in the DCLL the helium atoms will be dissolved. However, in some situations the liquid metal circulates at low velocity, leading to the formation of He bubbles due to the low He solubility in PbLi [40]. These bubbles could be accumulated in the upper parts of the PbLi circuits, giving rise to hot spots and compromising the cooling performances. Although under DCLL conditions (high PbLi flow rates) the formation of He bubbles is less favorable, the He gas must be evacuated, and this point is especially difficult in a multi-module configuration. Presently, the strategy adopted to extract the He from the circulating PbLi is the installation of a dedicated tank (expansion/He relief) installed immediately after the TERS and in the highest level of the PbLi loop. In this He removal system, the velocity and pressure of the liquid metal are reduced so the He bubbles can be collected [41].

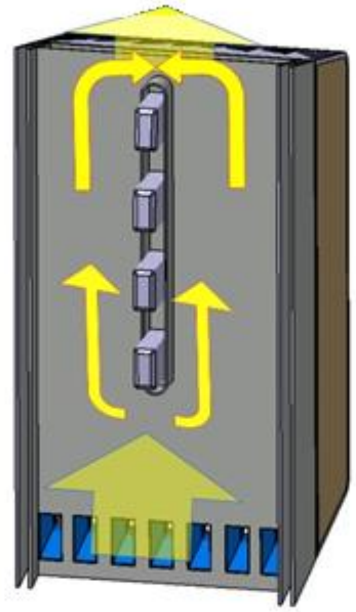

FIG. 14. Sketch of the PbLi circulation around the internal obstacles in one of the BSS manifolds.

4. PERSPECTIVES OF THE HT-DCLL AND CONCEPTUAL PROPOSAL

At the time that engineering design activities of the LT-DCLL were finishing, an extensive work to identify the best strategy to harmonize the ITER-TBM and the EU-DEMO BB Programs, including their associated R&D, was performed. An important conclusion was that a 'driver' blanket will be installed in DEMO that should be in line with the ITER TBM Program, which now considers the HCPB and WCLL blankets to cover all technologies (coolants, breeders) [42]. It seems advisable to develop, in parallel, alternative concepts for the long term, aiming at higher efficiencies. In that sense, although the feasibility of the DCLL has been demonstrated (main issues are related to corrosion and unknown MHD phenomena), it was decided that activities would focus more on the R&D of the concept, excluding all the integration tasks. Among others, these activities could explore different configurations for the FW, operational windows of the coolants, strategies for TBR enhancement... Thus, the efforts on the DCLL design have been lately concentrated on adapting the LT-DCLL to the needs of more advanced breeding blankets, taking as basis the already developed DCLL concept. Therefore, the activities are focused on optimizing the DCLL in terms of plant net efficiency, proposing solutions to solve the issues encountered during the period 2014-2018.

The first approach to increase the plant net efficiency has been working at higher temperatures (700 – 800 °C). This change has quite important consequences, not only in the materials development but also on the different blanket subsystems. Therefore, a comprehensive program has to be developed. Some of the most important points to be solved are:

- The structural material: usually, all the blanket designs consider the structural material as the container of the liquid metal, which involves the well-known problems of creep, corrosion and MHD phenomena.

- Corrosion of materials: anti-corrosion barriers are mandatory, not only in the blanket but also in the piping system, and probably in major components such as the heat exchanger.

- Larger temperature gradients are expected in the steel, which enhance the permeation through the structures. However, the velocity of the liquid metal would depend on the segment configuration of the blanket. This could lead to larger velocities in the PbLi, which could reduce the impact on tritium permeation, although the MHD pressure drop will limit the allowable PbLi velocity scale.

- The definition of the TERS, which in this new concept has to operate at a higher temperature. This should have a positive impact on the extraction efficiency, which in the case of PAV increases with temperature. However, it could also increase the corrosion of the membrane, so dedicated experimental programs to study the compatibility with the PbLi at high temperature will be required.

- The development of a heat exchanger for high temperature. In this regard some studies can be found in literature (e.g. [43][44]).

Another important point is the segment definition. As explained, the LT-DCLL was conceived as a multi-module component, where different blanket modules were attached to a common BSS. This arrangement was mainly motivated by the use of the EUROFER as structural material, since having a complete ‘banana’ (or single module) segment as in previous DCLL concepts (e.g. [38][45]) would imply a large route for the liquid metal, which has to maintain the temperature between 300 and 550 °C. This short operational window, together with the large path through the segment (typically > 10 m length), means that the velocity of the PbLi has to be really high, of the order of dm/s. The direct implication is the rising of MHD phenomena, causing important pressure drops and, in addition, an enhancement of the corrosion rate [46]. Thus, the multi-module distribution resulted in a better solution for the LT-DCLL: the velocity of PbLi is one/two orders of magnitude lower (depending on the channel location), and therefore MHD effects are diminished; corrosion is not a critical point; and the different modules can be cooled in parallel, reducing the total pressure drop.

For a high temperature blanket, from now on HT-DCLL, it seems advisable going back to a single-module approach, trying to diminish the liquid metal velocity thanks to a unique route along the poloidal direction. One important advantage is that the temperatures of the blanket can be substantially modified: not only the operational window can be enlarged for an improved efficiency, the lower temperature can also be increased up to 400 °C, avoiding the embrittlement of the material [47]. In addition, the velocity of the liquid metal can be moderate and only one turn can be expected (even none turns), considerably reducing the MHD effects, which will be dominated by the contribution of the channels curvature along the poloidal direction. In this case, the geometry of the single-module is much simpler than having 8-10 modules, which is also beneficial to introduce components for electrical isolation. Finally, another potential advantage is the possible enhancement of the TBR due to the reduced amount of steel in the module, since the poloidal continuity in the breeder volume is assured when having one unique box. Note that in a multi-module configuration there are, typically, 8-10 modules with a separation of 20 mm between them and a thickness of the plate around 25-30 mm. The single-module approach is also beneficial for RAMI, since the amount of components (modules, circuits…) is reduced and the number of welds decreases as well.

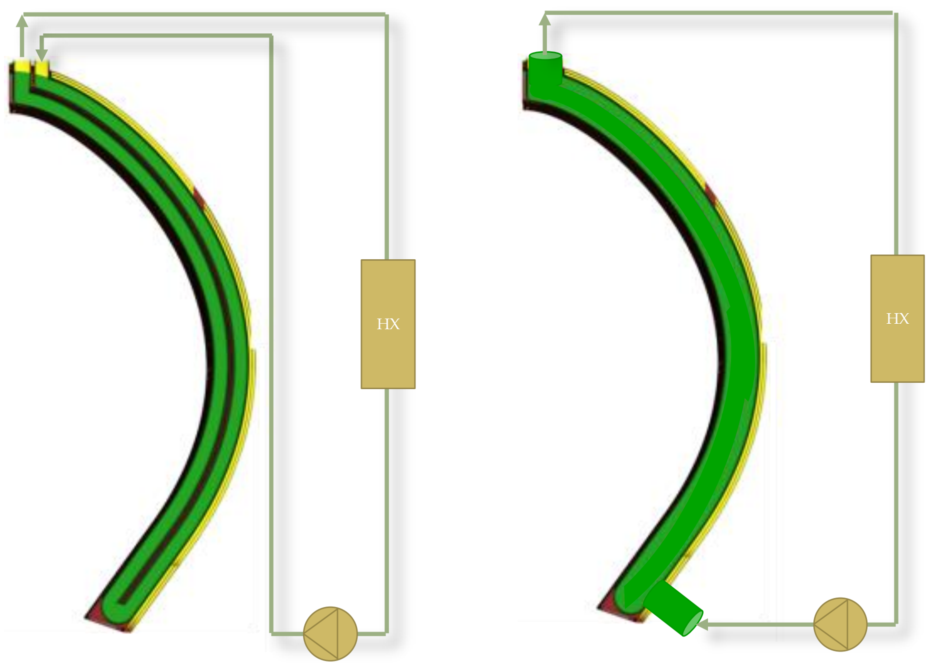

FIG. 15. Schematics showing the possibilities to route the liquid metal in a single-module design.

Thus, a conceptual design based on a single pass of the PbLi is proposed, as it is schematically presented in FIG. 15. The problem to solve is the issue with the EUROFER operative conditions. A simple solution is to thermally decouple the liquid metal from the structural container. Taking advantage of the R&D on ceramic elements for the LT-DCLL carried out during the last years, it seems feasible the use of a ceramic component to route the PbLi inside the box. Until now, all DCLL concepts are based on the use of a metallic structure which has the function of containing the breeder material, avoiding any leakage to the VV. As discussed, in the DCLL this implies an important issue associated to the MHD and corrosion. Thus, the first approach we have adopted is to route the liquid metal through long, robust ceramic channels which cover the entire length of the segment. Similar ideas were proposed in the US for the ARIES-AT, where SiCf/SiC was used as structural material for the blanket [48]. In the case here exposed, the ceramic does not have a structural function but helps to route the liquid metal inside the vertical segment.

In this HT-DCLL the steel is used as a secondary containment box and with structural function. Ceramic and EUROFER would be separated by an inert gas which fills the entire death volume in the segment, see a cross section (toroidal-radial) in FIG. 16. This configuration has some advantages. Firstly, there is enough space to allocate the different thermal expansion of the steel and the ceramic (one of the main problems with the use of FCI). Secondly, the liquid metal will never be in contact with the EUROFER, so corrosion and MHD phenomena will be strongly reduced. Thirdly, in case of in-box LOCA, the integrity of the structural box is not compromised. In the DCLL an in-box LOCA is produced when a helium channel, used to cool the steel structure, breaks and the helium at 8 MPa leaks into the segment interior pressurizing all the internal volume. To avoid any break of the steel box the integrity of the module mainly relies on the response of the internal stiffening grid. Thus, the design has to be reinforced by introducing more stiffeners and increasing their thickness, with the consequent reduction on the TBR. In the case of the HT-DCLL, helium only leaks to the inert gas, which in principle can accommodate the overpressure [49].

Concerning the first wall there are different approaches that can be followed to accept the high heat fluxes expected in DEMO. In principle, it has been demonstrated that for the LT-DCLL the integrated first wall could accommodate the majority of the heat flux by considering heat transfer enhancement (e.g. via turbulators) in zones where peaks are expected. However, another possibility is using a protecting (and replaceable) panel which covers the entire blanket surface. The helium manifolds could be located in the rear part of the segment (FIG. 16) to poloidally feed all the helium channels, with a potential reduction on the pressure drop when compared to the last LT-DCLL design.

Taking into account all these considerations, a first attempt has been done to produce a conceptual design of a HT-DCLL [49], and it will constitute the main design line in CIEMAT for the upcoming years.

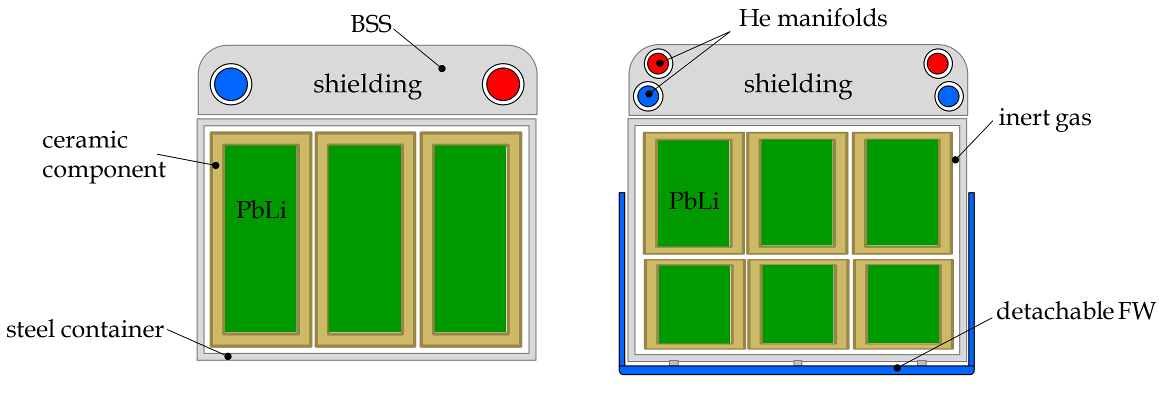

FIG. 16. Cross section of the high temperature breeding blanket showing the different alternatives that could be used for the routing of the different effluents. A detachable FW could be used (right figure), although an integrated FW is preferred (left figure).

5. SUMMARY

In this work we have presented a brief summary of the work performed on a low-temperature version of the Dual Coolant Lithium Lead breeding blanket during the period 2014-2018. Considering that the DCLL was not selected as a possible driver blanket for DEMO, the activities were re-oriented towards a more ambitious concept, where the DCLL could work at higher temperatures looking for larger plant efficiencies. A preliminary conceptual design of a HT-DCLL has been presented and some new ideas discussed. Among the advantages that the HT-DCLL presents, it is worth mentioning the simplicity of this single-module design, which will improve its RAMI performance. In addition, the risks associated to an in-box LOCA are reduced. In the next years a dedicated work program will be followed to reach a mature design, with its accompanying R&D.

ACKNOWLEDGEMENTS

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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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