Design of the Helium-Cooled Lithium-Lead Breeding Blanket in CEA: From TBM to DEMO

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The helium-cooled lithium-lead (HCLL) blanket concept is based on the use of helium as coolant and the eutectic Pb-16Li as neutron multiplier and breeder material. This concept was originally developed in CEA at the beginning of 2000: it is one of the two EU blanket concepts to be tested in ITER in the form of a test blanket module (TBM) and one of the four blanket concepts currently being considered for DEMO.

The ITER HCLL-TBM was designed as representative of a DEMO blanket concept developed at the end of power plant reactor studies; its design is based on the same components and relevant geometries but intended to maximize the “DEMO relevancy” in the ITER environment, which is characterized by different plasma loads and the presence of other in-vessel components. It will allow studying the same physical phenomena that drive the design of DEMO, reproducing, e.g., similar temperature fields in structure and functional materials and typical velocities of liquid breeder and coolant in order to validate the numerical tools used for DEMO design. However, the TBM design must comply with ITER operational constraints, i.e., not jeopardize the safety and availability of the machine and account for specific issues of integration in an equatorial port. In short, the TBM is a highly optimized component for the ITER environment that will provide crucial information for the development of the DEMO blanket in several key areas, but the overall performances of the DEMO blanket will not be addressed in TBM. On the other hand, given the tight schedule for the construction of the DEMO reactor, CEA approach is to share as much as possible the technological solutions used on the HCLL-TBM for the DEMO BB design in order to profit from the ITER experience and reuse technologies with the highest technology readiness level (TRL). It is therefore essential to assess which technologies and design features could be transported from TBM to DEMO and which will instead need to be adapted, modified or replaced.
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Abstract: The Helium Cooled Lithium Lead (HCLL) blanket concept was originally developed in CEA at the beginning of 2000: it is one of the two EU blanket concepts to be tested in ITER in the form of a Test Blanket Module (TBM) and one of the four blanket concepts currently being considered for DEMO. The TBM is a highly optimized component for the ITER environment that will provide crucial information for the development of the DEMO blanket, but its design needs to be adapted to the DEMO reactor. This paper provides an overview of the main HCLL-TBM design features and discusses the similarities and differences with the present design options of the corresponding DEMO Breeding Blanket modules. With respect to the TBM design, reduction of the steel content in the BZ is sought in order to maximize tritium breeding reactions. Considerable design efforts are needed is the design of the Back Supporting Structure that has to support the blanket modules inside the VV. Design activities in the form of neutronic, thermo-hydraulic and thermo-mechanical analyses are on-going in order to assess the different options. Design changes, on the other hand, will have an impact on the manufacturing and assembly sequences that are being developed for the HCLL-TBM. Due to the differences in joint configurations, thicknesses to be welded, heat dissipation and the various technical constraints related to the accessibility of the welding tools and implementation of non-destructive testing, the manufacturing procedure should be adapted and optimized for DEMO design. A preliminary assessment of what technologies could be transported from TBM to DEMO and which will instead need to be modified or replaced is provided in the paper. Finally, essential information expected from the HCLL-TBM program that will be needed to finalize the DEMO BB design is discussed.

1. Introduction

In the European Roadmap to the realization of fusion power, the development of the Breeding Blanket (BB) technology is acknowledged as one of the key issues that must be solved by the DEMO reactor, which is considered as the only step between ITER and a commercial fusion power plant [1]. The Breeding Blanket is one of the most sensible components in a fusion power reactor, having the functions of collecting the energy generated by the fusion reaction, regenerating the burnt tritium to insure the reactor’s self-sufficiency and protecting the Vacuum Vessel (VV) and other reactor components from plasma radiation. The choice of the breeding blanket technology will have a significant impact on the overall plant design, performance, availability, safety and environmental aspects, and in the end on the cost of electricity [2]. In the European “fast track” approach, selected BB technologies shall be tested in ITER in order to speed-up the development of DEMO.

Different blanket concepts have been considered in the past as potential candidates for a commercial fusion power reactor [3]. The Helium Cooled Lithium Lead (HCLL) blanket concept was developed in CEA at the beginning of 2000 [4]. It uses the low activation ferritic/martensitic steel EUROFER as structural material, the eutectic Pb–15.7Li as breeder, neutron multiplier and tritium carrier and He as coolant with inlet/outlet temperature of 300/500 °C and 8 MPa pressure. It is one of the two EU blanket concepts to be tested in ITER in the form of a Test Blanket Module (TBM) [5] and is currently being developed within the EUROfusion Consortium activities [6] by a team of several European fusion laboratories under the technical coordination of CEA.
A brief presentation of the HCLL-TBM design is provided in chapter 2: given the tight schedule for the construction of the DEMO reactor, CEA approach is to share as much as possible the technological solutions used on the HCLL-TBM for the DEMO BB design in order to re-use technologies with the highest Technology Readiness Level (TRL). In particular, design changes discussed in chapter 3 could strongly impact manufacturing techniques and assembly sequences of the blanket. It is therefore essential to assess which design choices could be transported from TBM to DEMO and which will instead need to be developed, modified or replaced as discussed in chapter 4. Finally, chapter 5 discusses the essential information expected from the HCLL-TBM program that will be needed to finalize the DEMO BB modules. This paper is focused on in-vessel components: the discussion of the related blanket auxiliary systems (Tritium Extraction System, Coolant Purification System, PbLi loop …) as well as other ex-vessel components is outside the scope of this paper.

2. HCLL-TBM design features and relevance for the design of DEMO BB.

The ITER HCLL-TBM was designed as representative of a DEMO blanket concept developed at the end of the Power Plant Conceptual Studies (PPCS): its design is based on the same components and relevant geometries and intended to maximize the “DEMO relevancy” in the ITER environment [7]. It consists of a steel box formed by a U-shaped plate (first wall and side walls – FW/SW), closed on its sides by cover plates (lateral CAPs), and on its back by 5 successive parallel plates (backplates – BP) constituting the coolant manifolds (Fig. 1). The manifolds chambers are rigidified by a system of Stiffening Rods in order to withstand the internal He pressure during normal operation. Similarly, in case of accidental pressurization due to in-box LOCA, the box is internally stiffened by radial–poloidal and radial–toroidal plates (SP) constituting the stiffening grid (SG). The grid defines an array of internal cells for the breeder units (BUs) where the eutectic PbLi flows around parallel horizontal cooling plates (CPs) connected to a BU back plate ensuring the insert rigidity. The CPs are needed to remove the heat generated by the neutrons interacting with the breeder and the metallic structures. All the plates, except the back plates constituting the manifolds, have internal coolant channels with a rectangular section. The HCLL-TBM design is being finalized by the European DA F4E in view of the Preliminary Design Review phase, but the essential features are already frozen [8].

The TBM has been designed to reproduce as much as possible the operating conditions of a DEMO BB module in order to study the same physical phenomena that will drive the design of DEMO. He cooling channels sections and lengths, for example, have been determined in order to obtain the same thermodynamic parameters expected in DEMO. Mass flows have been determined in order to reach similar temperature fields in structural and functional materials. The liquid breeder flow scheme and velocities are typical of a DEMO BB module.
A successful TBM program in ITER will [9]:

- validate and calibrate the design tools and the database used in the blanket design process including neutronics, electromagnetics, heat transfer and hydraulics;
- demonstrate tritium breeding capability and verify on-line tritium recovery and control systems to ultimately enable the extrapolation to a full size blanket;
- provide essential information on nuclear licensing of BB components with regard in particular to structural integrity assessment and manufacturing techniques [10].
- demonstrate the integral performances of the HCLL BB concept in a fusion relevant environment.

The HCLL-TBM design however cannot be directly transferred to the DEMO BB since the operating conditions and the integration constraints of the two machines will be very different:

- The heat flux and neutron wall load on the FW, and consequently the nuclear heating in the breeding zone, will be considerably lower than those of DEMO. The thermohydraulics of the cooling system will need to be optimized in DEMO, in particular with respect to the required coolant pumping power: this is not an issue in TBM, but in DEMO it will impact the overall efficiency of the plant.
- The neutron spectra in the TBM will (also) be determined by the composition and characteristics of adjacent components. This will affect the nuclear responses, and in particular the tritium production rates [11]. Of course, tritium « self-sufficiency» is not a concern in TBM or for the ITER machine.
- The shielding function will be provided by a separate shield component that will take the relay of the Vacuum Vessel inside the equatorial port (Fig. 1). The shield is composed by a succession of stainless steel plates and water compartments and is specific to the ITER machine.
- The TBM will have to comply with ITER operational constraints i.e. not jeopardize the safety and availability of the machine and be compatible with the Remote Handling (RH) procedures of ITER which foresee maintenance operations of the TBM and shield through the equatorial ports [12].

Overall, the TBM is a highly optimized component for the ITER environment that will provide crucial information for the development of the DEMO blanket in several key areas, but cannot be replicated in the DEMO BB: the operating conditions and performance objectives of the DEMO BB will need further development, optimization and modification of the original TBM design.

Fig. 2: HCLL DEMO BB reference design.
3. The HCLL DEMO BB design and development status.

The HCLL DEMO blanket is still in the conceptual development phase as the reactor baseline is still evolving. The present reference design is based on the Multi Module Segment approach: individual modules are attached on a thick steel structure (Back Supporting Structure - BSS) in order to form a single assembly that can be extracted as a whole from the VV upper port. The BSS also houses the coolant and PbLi distribution system and has no equivalent in the HCLL-TBM. The design of the modules on the other hand is based on the same design features of the HCLL-TBM the main difference being in the manifold zone that integrates the BSS. The Tie Rods serve in this case also as module attachment system (Fig. 2). It is already expected that this “TBM-like” design will need to be adapted to the loading conditions of the DEMO reactor, which are different for each module depending on the poloidal position. Design activities are for the moment focusing on the Outboard central blanket which is supposed to be the most critical\footnote{Modules near the top of the machine or next to the divertor can indeed experience very high transient heat fluxes that might require the use of specific («detached») FW panels. This issue is common to all blanket concepts for DEMO and is outside the scope of this paper, which only focuses on the BB modules.} [13].

Alternative design options are being investigated in order to maximize the performances of the concept with respect to the main blanket functions, i.e. maximizing the Tritium Breeding Ratio (TBR), increasing the shielding power and reducing the coolant pumping power. Each of these three objectives is related, directly or indirectly, to the volumes occupied by the breeder, steel and helium (respectively) inside the blanket module. The requirements are conflicting and optimal equilibrium must be found taking into account structural integrity criteria.

Initial nuclear analyses with the “TBM-like” reference configuration had shown an insufficient TBR (1.08, lower than the 1.1 target) but this was related to the use of the 2014 baseline (Table 1). Nonetheless the priority was given to maximizing the TBR by reducing steel content in the Breeding Zone. A new «optimized» design was developed by suppressing one He manifold and reducing the number of Cooling Plates from 3 to 2. In parallel to this optimized design, two alternative configurations (Table 1) have been investigated by suppressing the Vertical Stiffening Plates («advanced») and by using only Horizontal Stiffening Plates which also act as Cooling Plates («advanced +»). The new configurations show very promising TBR values [14]. The suppression of the VSP however must be weighted with an increase in stiffness (thickness or local stiffening elements) of the upper caps that must withstand the internal pressurization of the box in case of LOCA. Thermomechanical analyses are ongoing to validate this possibility (Fig. 3). The «advanced +» configuration shows a slightly lower TBR than the «advanced», but has the advantage of considerably simplifying the design of the module, leaving more space for the BSS. In addition to the problem of stiffening the caps, thermo-hydraulical analyses show a considerable increase of the pressure drops in the BZ that jeopardizes the advantages of this configuration [15]. Thicknesses of plates and channel geometry need to be optimized. Design studies are on-going to find the optimal compromise.

The component that still requires considerable design efforts is however the BSS, being specific to the DEMO reactor. It has to accomplish several functions that are essential to the performances of the BB: support the deadweight of the modules, withstand the electromagnetic efforts due to plasma disruptions, act as manifold for the distribution of fluids and provide sufficient shielding for the VV. Moreover, to avoid interference with nearby components, the deformation of the segment assembly during operation must be limited. Once again, the requirements are conflicting, since shielding power and mechanical stiffness require high steel volume fraction, which would leave less space for the distribution of fluids, increasing the pressure drops. The first design of the BSS generalized the Tie Rods (TR) solution used in
TBMs to attach the modules to the BSS (Fig. 2). The Tie Rods acted also as internal stiffeners in the BSS. Preliminary analyses validated this solution w.r.t to mechanical design criteria [13], but the overall shielding power of the blanket was not satisfactory [16]. Alternative solutions that redistribute the steel amount more uniformly are being studied. Exploratory neutronic calculations have shown the potential of this solution in terms of shielding [14]. Thermo-hydraulic and thermo-mechanical analyses are on-going. It should be noted that, without the TR system, an alternative solution must be found to reinforce manifolds region. The attachment system of the module to the BSS must also be re-defined. Modification of the BSS and the attachment concept could therefore imply a major re-engineering of the module with respect to the «TBM-like» configuration whose impact cannot yet be assessed.

<table>
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<th>#MF</th>
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(*) CP = Cooling Plates, MF = Manifolds, VSP = Vertical Stiffening Plates

Table 1: TBR calculated for different blanket configurations

Fig. 3: Thermo-hydraulic and thermo-mechanical analysis of the «advanced» BB design.

4. Impact on selected manufacturing techniques and associated R&D.

The current «optimized» DEMO HCLL BB design has been developed with the aim of re-using most of the manufacturing techniques that are being developed for the corresponding HCLL-TBM in ITER. However, as discussed in the previous chapter, design changes might still be needed to improve the blanket performances or to comply with constraints imposed by the integration in the machine. A number of issues must in this case be checked, like accessibility of welding tools, distortions induced by the welding operations, Post Welding Heat treatments, Non Destructive Examination (NDE) and Reparation procedures. Also, issues related to the large-scale manufacturing of components required for DEMO must be considered, since TBM is a one-of-its-kind component: manufacturing techniques selected for TBM could prove economically not viable for DEMO.

Development and qualification of manufacturing processes for TBM are being carried out under contract by the European Domestic Agency Fusion For Energy (F4E) [17]. Two manufacturing processes of elementary TBM sub-components (FW, SCs, SPs, CPs), are being considered: the “aser weld + HIP” process and the two step HIP process (Fig. 4). Both could be used for the manufacturing of DEMO sub-components. The second one appears more suited for the higher yields required in DEMO, nonetheless mastering of geometries and defect
control needs to be improved, while effective NDE and reparation procedures have been developed for the first process.

Fig. 4: the YAG laser + HIP” process (right) and the two step HIP process (left) developed for the HCLL TBM.

With respect to the design options discussed in section 3, the main issues are the extent of the geometries and the thicknesses to be welded: expected induced distortion will be more important in DEMO than in TBM and must be controlled. For example, an alternative procedure has been defined for the assembly of the stiffening grid, performed by TIG welding. While in TBM the horizontal stiffening plates are assembled individually, inside the box, after completion of the vertical stiffening grid, a “comb”-system solution has been proposed for DEMO as shown in Fig. 5. The grid is in this case assembled outside the box, using YAG welding instead of TIG to reduce the distortions, and then welded to the box. The same distortion and accessibility problems exist in the manifold region, where the welding of the back plates will have to foresee bevels. To compensate for the presence of gap, it is then absolutely necessary to use “gap tolerant” welding processes (TIG + filler metal is an option).

Fig. 5: assembly of the stiffening grids proposed for DEMO and corresponding mock up (before welding).

Finally, the issue of defect assessment is central to the development and qualification of the welding process, also with respect to the “quality” of the welds required in nuclear components. Considering a range of full penetration butt welds with thicknesses between 6 mm and 100 mm, it is considered that 61% of the defects will be detected by radiographic testing. Ultrasonic testing under the same conditions would detect 53% of defects\(^2\). Phased array ultrasonic testing could improve defect detection, but such a gain has not been quantified by any study to date. The Time-of-Flight Diffraction (TOFD)technique (an ultrasonic testing technique based on the diffraction signals on the ends of discontinuities), on the other hand, offers a simple and interesting implementation: the percentage of defects which can be detected by ultrasonic testing in a weld is assessed to 82%, which means that it is the most sensitive volumetric testing method. All this options are currently being assessed.

5. Additional information expected from the TBM program with direct impact on the design of the BB.

As presented in §2, the TBM program will provide essential information related to the physics of a HCLL BB in a fusion environment that will allow to validate the modeling of physical

\(^2\) It is worth noting that the 53% of detected defects are not necessarily included in the 61% of defects detected by radiographic testing.
phenomena and thus improve the confidence in the predicted blanket performances. Major advances are expected, for example, in the field of tritium transport modelling tools [18] and nuclear data validation [19]. Both are essential issues to validate the tritium breeding capability of the concept and can thus lead, indirectly, to design changes.

More directly related to the design is the modeling of Magneto-Hydro-Dynamics (MHD) flows inside the blanket. Critical issues related to MHD interactions of the moving PbLi with the magnetic field are due to occurrence of increased pressure drops and special flow distributions [20]. The latter will modify the temperature distribution inside the module and can have positive (level temperatures, easing the design of the cooling system)) or negative effects (hot spots, affecting structural integrity by a decrease of the resistance limits of the material). A detailed knowledge of MHD phenomena is therefore required to finalize the design of the blanket.

More critical for the design of the DEMO BB is the development and validation of appropriate design criteria. In order to validate the thermo-mechanical performances of the blanket, the TBM has been designed to reproduce typical temperature and stress fields expected in the structural material EUROFER97, which has been developed specifically for fusion. However, because of the specificities of the fusion environment and the peculiarities of EUROFER97 mechanical properties, there is no single validated set of design rules available for the BB components [21]. Appropriate design criteria are in this case needed and development of the RCC-MRx nuclear Codes and Standards (C&S) [22] is underway in the framework of the TBM program [10]. The return of experience from the TBM licensing process will also provide essential feedback with respect to regulation requirements that will also impact the DEMO design. Issues related to the higher neutron fluence (neutron damage) and longer operating time (creep) in DEMO will however not be a concern for TBM and will have to be investigated in parallel.

6. Conclusions

The HCLL-TBM in ITER has been designed in order to be representative of the corresponding DEMO blanket, and will provide crucial information for the development of the DEMO blanket in several key areas, but its design is not meant to be directly replicated in DEMO. On the other hand, CEA approach is to keep the main design features of TBM in the DEMO BB design in order to profit from technologies with the highest possible TRL (in particular manufacturing techniques). Alternative design options are however being investigated that could significantly improve the performances of the blanket. They imply considerable modifications in the geometries, spacing and thicknesses of sub-components and consequently additional R&D on welding processes. Moreover, the design of the BSS, which is in its early development, might imply a major re-engineering of the module that has yet to be assessed. At the same time, the final design of the DEMO blanket will also depend on information expected from the TBM program. Validation of MHD modeling tools is essential to assess temperatures fields in the blanket which impact resistance limits of the material. Finally, appropriate design criteria are needed and development of the RCC-MRx nuclear Codes and Standards (C&S) has already begun in the framework of the TBM program.

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