Neutronic Assessments towards a Novel First Wall Design for a Stellarator Fusion Reactor with Dual Coolant Lithium Lead Breeding Blanket

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Abstract: The Stellarator Power Plant Studies Prospective R&D Work Package in the Eurofusion Programme was settled to bring the stellarator engineering to maturity, so that stellarators and particularly the HELIAS (HELical-axis Advanced Stellarator) configuration could be a possible alternative to tokamaks. However, its complex geometry makes designing a Breeding Blanket (BB) that fully satisfies the requirements for such a HELIAS configuration, which is a difficult task. Taking advantage of the acquired experience in BB design for DEMO tokamak, CIEMAT is leading the development of a Dual Coolant Lithium Lead (DCLL) BB for a HELIAS configuration. To answer the specific HELIAS challenges, new and advanced solutions have been proposed, such as the use of fully detached First Wall (FW) based on liquid metal Capillary Porous Systems (CPS). The proposed solutions have been studied in a simplified 1D model that can help to estimate the relative variations in Tritium Breeding Ratio (TBR) and displacement per atom (dpa) to verify their effectiveness in simplifying the BB integration and improving the machine availability while keeping the main BB nuclear functions (i.e., tritium breeding, heat extraction and shielding). This preliminary study demonstrates that the use of FW CPS would drastically reduce the radiation damage received by the blanket by 29% in some of the selected configurations along with a small decrease of 4.9% in TBR. This could even be improved to just a 3.8% TBR reduction by using a graphite reflector. Such an impact on the TBR is considered affordable, and the results presented, although preliminary in essence, have shown the existence of margins for further development of the FW CPS concept for HELIAS, as they have been not found, at least to date, to be significant showstoppers for the use of this technological solution.

Keywords: fusion; DCLL; breeding blanket; HELIAS; TBR; neutronic

1. Introduction

In the roadmap towards a commercial fusion power plant, the European efforts are focused on magnetic confinement devices, with two promising concepts: tokamaks and stellarators. While the development of the tokamak concept is more advanced worldwide under the technology and engineering aspects—with several big projects in sight (ITER [1], JT-60SA [2], Divertor Tokamak Test facility (DTT) [3], etc.) and most of the Eurofusion DEMO developments are also focused on the tokamak mainstream [4]—there is still a long way to bring Stellarator reactors to technological maturity.

Substantial progress has been made in the understanding of stellarator plasmas and important advances in the physical aspects have already been obtained, especially thanks to the operation of the Weldenstein 7-X (W7-X) stellarator [5]. This has led the Eurofusion community to define the HELIAS (HELical-axis Advanced Stellarator) [6] type stellarator development as one of its long term missions as an alternative to the European DEMO
All the related engineering and technological activities are included in the Eurofusion Horizon Europe Work Package Prospectives R&DT: Stellarator Power Plant Studies (WPPRD SPPS). Among these activities, and exploiting the large experience in BB design for DEMO tokamak [8–15], CIEMAT is leading the development of a Dual Coolant Lithium Lead (DCLL) Breeding Blanket (BB) for the HELIAS device [16]. Such a concept, which is detailed in Section 2, has high potentialities to answer the specific challenges posed by the complex HELIAS configuration.

Apart from the BB-specific design solutions explored to cope with the stellarator challenges, novel solutions have also been proposed to simplify the remote maintenance and integration of the BB segments. The solution proposed and evaluated here is the use of a fully detached First Wall (FW) based on liquid metal Capillary Porous Systems (CPS), as will be described in Section 3. This strategy could allow a reduction of the damage produced inside the BB, increasing the machine availability while keeping the tritium breeding performance required for a BB (among other criteria).

Different FW configurations have been implemented (Section 4) considering a simplified 1D approach. Then, the radiation transport simulations have been carried out by Monte Carlo code MCNP5 [17] to address the relative variations in Tritium Breeding Ratio (TBR) and displacement per atom (dpa) produced by each FW configuration. The preliminary results (Section 5) show that a compromise can be found between TBR and damage to the BB, and the use of CPS could simplify the BB integration in a stellarator device.

2. The Dual Coolant Lithium Lead BB Concept: Major Features and Specific Challenges for a HELIAS Device

One of the most demanding components of the future fusion power plants, whether tokamaks or stellarators, is the Breeding Blanket (BB), which has to fulfill a number of essential requirements to demonstrate the feasibility of fusion. One of the most important requirements (i) is that any large fusion device must generate its own tritium (T) fuel, since, being unstable and radioactive with a half-life of 12.32 years, it does not exist in nature in a sufficient quantity. This means that after the initial tritium loading, self-breeding of tritium is necessary to keep the DT fusion reactions and guarantee the self-sufficiency of the reactor.

For such purpose, the BB is made by a T breeding Li compound that regenerates T by $^6\text{Li}(n, T)$ and $^7\text{Li}(n, n'T)$ reactions. In the case of the Dual Coolant Lithium Lead (DCLL) BB concept, the breeder material is lithium–lead (PbLi) in the eutectic composition: 84.3% Pb and 15.7% Li [18]. In addition, as $^6\text{Li}$ has an exothermic reaction with neutrons and the $^6\text{Li}(n, T)$ reaction has a much more efficient cross section in a wider neutron energy range than $^7\text{Li}(n, n'T)$ reaction, the breeder is enriched to 90% in $^6\text{Li}$.

Inside the Li compound PbLi, the Pb acts as a neutron multiplier, which is needed to breed tritium with a margin to compensate the losses due to Li burn-up, retention in materials, T decay, etc. [19,20].

The measure for the tritium breeding performance of the plant is the Tritium Breeding Ratio (TBR), which is defined as the ratio between the tritium atoms produced in the breeder per second an the atoms of tritium burned in the D-T fusion reactions per second inside the plasma.

For the European DEMO, the TBR target has been set to $TBR \geq 1.15$ ([21,22]). Such 15% of margin takes into account the previously mentioned losses, the uncertainties in the cross-sections data and in the modeling (approximately a 5%) and a 10% extra margin due to non-breeding coverage areas (for example due to penetrations and ports for heating and current drive systems, diagnostics, limiters, etc.).

Another essential function of the BB (ii) is the heat extraction. The BB must absorb the largest (~80%) part of the fusion energy carried by neutrons from the fusion reactions
and deposited in the surrounding structures. In a reactor of about 2 GW of fusion power, the blanket system has to extract about 1900 MW. The conversion of this energy with adequate thermodynamic efficiencies requires that the coolants are at high temperature and pressure. In the case of the DCLL, the coolants are Helium (He) and PbLi. The He is used to cool the FW, while the PbLi is the self-coolant of the breeder itself since it flows at high velocity.

In addition (iii), along with the Vacuum Vessel (VV), the BB can integrate a radiation shield system that must effectively contribute to protect various components from nuclear radiation (e.g., superconducting magnets, the VV itself and other equipment outside the reactor). In the DCLL BB concept, both the structural steel (Eurofer [23,24]) and the PbLi breeder act as shielding for the systems located behind the blanket. In fact, there are several shielding requirements established to ensure the functionality and integrity of the superconducting coils, which refer to avoiding the extinction of the field (quenching) and maintaining the superconducting state of the coils and therefore the confinement of the plasma.

In a HELIAS configuration, the engineering challenges to implement an efficient BB, already difficult in DEMO tokamak, are here extreme, due to both the additional complexity of such a 3D configuration in terms of modeling and analyses and also to physical constraints, as it can be observed in Figure 1.

![Figure 1. CAD models and neutron source intensities (overlapped to the models) of DEMO tokamak (a,b) [25,26] vs. HELIAS stellarator (c,d) [27,28]. Both the geometry and the neutronic responses are three-dimensional in the stellarator configuration. As an example, the different neutron sources (in red to blue scale) have been overlapped to the models to show that in the tokamak configuration there is radial–poloidal variation (b), but toroidal symmetry in neutron emission (a), while in stellarator the variation is not only radial–poloidal (d) as in tokamaks, but also toroidal (c).](image_url)

In fact, the complex geometry of the vessel and the limited space availability between the plasma and the coils make it difficult to implement the currently available tokamak-oriented BB designs.

Therefore, new BB designs based on the existing Dual Coolant Lithium Lead (DCLL) BB concept developed for DEMO tokamak have been explored, re-adapting them to the 3D geometry of HELIAS and trying to answer the additional challenges that this complex configuration brings. Since in the DCLL BB concept the PbLi breeder is liquid, it could be
potentially easier to adapt the BB to the HELIAS complex shape, comparing with solid BB concepts. Furthermore, it can be also drained before the maintenance operations. Given that in a stellarator configuration there is less space available for ports (between coils) and hence for the maintenance operations, the capability of draining the blanket would be very useful to reduce the weight and loads, facilitating kinematics and operations for the extraction of the BB segments. From previous analyses on the EU DEMO DCLL [29], we found that the draining and refilling of large multi-module BB segments could take less than two minutes, and thus not being an issue from the point of view of the availability of the machine.

The design of a BB has to satisfy the previous requirements for reactor efficiency and viability, but also complying with ensuring the BB integratability into the machine along with its durability and maintenance to increase the reactor availability. In fact, this will be an important economic factor [30], which implies that the durability and maintenance of the blanket must be oriented to maximize the availability of the machine.

Since the neutron wall load produced by the plasma within the reactor will lead to rapid material damage and degradation of the plasma facing components, it will be necessary to replace them as part of a scheduled maintenance program. In the HELIAS device, there is not yet a foreseen operation plan, so as a preliminary assumption the same schedule considered for DEMO is assumed [31,32].

DEMO would act (at least in its first phase of operation) as a “component test facility” for the BB assuming that operation will begin with a 20 dpa limit “starter” blanket installed in the tokamak that utilizes moderate-performance materials.

Hence, with respect to the radiation damage criteria, a conservative assumption of 20 dpa is adopted for the BB structural material as a limit to be ensured during the first phase operation (1.57 Full Power Year (FPY)). A second operation phase is expected considering more advanced materials that will be able to withstand up to 50 dpa during a longer irradiation time (4.43 FPY).

The availability of the machine is mainly conditioned by time-consuming maintenance operations in the reactor vessel. For example, the blanket system replacement will have to be accomplished fully remotely and under harsh environmental and radiation conditions.

Therefore, the in-vessel maintenance concept must provide for simplified and low-risk operations. For the DEMO BB maintenance, concepts such as the multi-module segments (MMS) are assumed to be the most favorable. The main feature of these concepts is the removal/replacement of large blanket segments through large upper maintenance ports. The number of ports and the ability to perform operations in parallel will influence the maintenance downtime.

Hence, in much complex HELIAS device, one of the main concerns from the engineering point of view is to select a BB segmentation and design that guarantee a viable and fast remote handling solution. The intricate geometry of a HELIAS device makes dealing with the blanket modules a hard task, due not only to their shape (which must be adapted to the Vacuum Vessel) but also to their size and weight.

As a consequence of previous studies [16] concerning the evaluation of the MHD resistance for different BB segmentations, it has been demonstrated [33] that a quasi-toroidal segmentation (instead than the poloidal one, used in DEMO) would be preferred to avoid the use of flow channel inserts (FCI) or coatings, and having strong impact on the simplification of the engineering BB design would be especially interesting to cope with the complex 3D stellarator configuration.

One of the main concerns of such toroidal segmentation is related to the RH, traditionally planned to be done by ports. Such a tokamak-oriented approach should be re-thought to be specifically planned for 3D stellarator machines in which the components (BB segments, ports, etc.) in a period rotate and what is vertical can be horizontal and what is concave/inboard/down, etc., could be then convex/outboard/upper, etc.

Additional to other Remote Handling possibilities already raised [33] as moving the coils to attach temporarily bigger ports, or opening the Vacuum Vessel [34,35], an attractive
solution for a faster Remote Maintenance could be the use of a detached First Wall decoupled physically and hydraulically from the Breeding Blanket cover box. In the past, and for the DEMO project, a finger solution was proposed and studied [26,36].

Another possibility, more attractive for the complex and changing shape of the plasma-facing last surface of a HELIAS device, could be the use of a detached First Wall based on a Capillary Porous System (CPS).

This new proposal could mitigate the complexity of the RH for a stellarator device and improve its availability, since the use of CPS could reduce the radiation damage to the blanket, which implies that big BB segments would be extracted from the ports just a few times (or never, as the damage is reduced sufficiently so as to not exceed the limit during the operation time); and the RH operations would be mainly reduced to the maintenance of the smaller CPS plates instead of complete BB segments. In addition, the CPS FW option would avoid the use of continuous Tungsten coating panels considered for traditional FW, which in stellarator 3D convex–concave twisting surfaces would be not easily manufactured.

Its characteristics, possible implementation in a HELIAS configuration and the neutronic assessment to verify its suitability to reduce the dpa in the BB while keeping an efficient TBR are exposed in Sections 3–5.

3. First Wall based on Capillary Porous System: Main Characteristics and Possible Implementation in HELIAS

An alternative solution to solid structural materials as Plasma Facing Components (PFC) is the use of liquid metals (LM). Having a self-renewable liquid PFC instead of a solid material presents several advantages, since surface erosion concerns are eliminated, as well as problems related to local thermal stresses encountered in solid FW structures produced by the heat flux incoming from the plasma. The unique properties of the LM have led to an intense research activity with the aim of achieving the implementation in a future fusion reactor. However, many aspects still remain unresolved and integration of these proposals into a realistic scenario may be challenging. Li, Sn, Li/Sn and Ga could be employed to this end, Li being the a very interesting option due to the plasma stability effects since it helps to decrease the wall recycling and avoid ELMs and disruptions [37]. Nonetheless, due to the uncertainties on the behavior of the two metals in the stellarator configuration, both Li and Sn have been considered in the simulations.

The CPS concept consists of a liquid metal reservoir in contact with a porous metallic mesh through which the LM can flow, with typical pore sizes in the range of a few microns. Although smaller pore radii would imply higher capillary holding forces, other undesired phenomena become relevant, such as viscosity-associated effects that hinder the refilling of the surface exposed to the plasma or some material compatibility issues, such as corrosion, embrittlement or hydrogen solubility, which limit the final material choice and design [38].

As such solutions are being explored for the very extreme irradiation and thermal conditions of the divertor, withstanding heat fluxes of about 30 MW/m², they can be considered also for the not so demanding conditions of the FW, subjected typically to loads of the order of the MW/m². Additionally, the CPS FW could result in a structure easier adaptable to the complex geometry of a HELIAS device (Figure 2).

Moreover, and the most important reason to be explored in such context, a detached FW with CPS architecture could imply that the BB could be not substituted during the entire lifetime of HELIAS, or fewer substitutions could be expected, leaving most of the Remote Handling operations to the (smaller) FW panels. This could also reduce the number and size of ports. This fact could indirectly impact positively on the TBR since the non-breeding area will be reduced. Hence, this would allow recovering at least partially the loss of TBR due to a detached FW concept.

The possibility to use a CPS FW concept has been tested under the neutronic point of view considering preliminary simplistic models to validate the concept with the purpose to simplify the Remote Maintenance of the BB, in the sense of reducing the damage to the BB
without compromising at unaffordable levels the T breeding capability of the blanket itself.

Figure 2. (a) Simplified HELIAS model in which the Plasma Facing surface could be fully covered by a FW CPS as proposed on the right. (b) Example of detachable FW Capillary Porous System option [39].

To this purpose, different models and materials for the FW substrate have been developed (Section 4) and studied (Section 5). A compromise has to be pursued between low damage to the BB and good tritium breeding performance. For that, dpa in the FW and the BB and the TBR values have been computed for each of the selected option.

Additionally, the use of reflectors (Section 5.1) behind the BB has been tested to recover part of the T lost with respect to the baseline due to the FW models previously implemented.

4. 1-Dimensional Approach: Simplified Neutronic Models for Scoping Studies

As there is not yet a complete 3D model of a HELIAS Stellarator sector with a full specific DCLL BB implemented [16], alternatives has been searched that, although being preliminary studies, could bring valuable information about the neutronic performances of these new FW configurations. This first approximation comes in the way of a one-dimensional spherical modeling of the HELIAS reactor.

The simplified 1D model consists of superimposed concentric spheres, where each sphere contains the composition of one specific material (Figure 3). In this way, by changing the composition and the thickness of the different spherical layers, several FW configurations can be tested.

Figure 3. One-dimensional HELIAS spherical model. The configuration represented here corresponds to a couple FW and BB (dimensions not to scale). Black dashed box details are shown in Section 4.1.
Although this is a simplified approach for the very complex stellarator reactor shaping and absolute results cannot be obtained or argued, this approach is helpful to address shortly in time relative differences of neutronic responses due to changes in the FW configuration.

The different FW models have been visualized through the MCAM (Monte Carlo Modelling Interface Program) tool SuperMC MCAM 5.2 Professional Version [40], an integrated interface program between commercial CAD software (here CATIAv5) and Monte Carlo radiation transport simulation codes.

In addition to the geometry, a representative neutron source is also needed for the MCNP neutronic analyses. To this purpose, a pre-existing simplified MCNP HELIAS DCLL BB model used for previous neutronic studies [28], which has a prevalent homogenized BB (including the FW) but with four detailed DCLL blanket modules (Figure 4a) with a separated W coating and Eurofer FW, has been used. The neutron spectrum (Figure 4b) obtained in a void cell at the front of the FW W coating of one of such BB modules has been used as the source term for the subsequent MCNP simulations in which the 1D concentric spheres simplified approach has been considered. The source in such a model has been established to be spread homogeneously (with a radial distribution) inside the entire volume of the central sphere (in red, in Figure 3), which represents the plasma, and emitting isotropically from such volume.

![Image](a)

**Figure 4.** (a) Neutronic model of a 36° sector of HELIAS, including four fully detailed DCLL modules [28]. The rest of the BB envelope, in red color, simulates in a simplified way all the different structures of the Blanket by considering just one homogenized composition. (b) Neutron flux per unit lethargy used as the neutron source in the 1D model.

### 4.1. FW and BB Tested Configurations

The different BB+FW configurations analyzed are described here, considering just their modifications with respect to the baseline traditional configuration with coupled FW and BB.

Starting from the nearer to the farther from the plasma, the original configuration (v0), as shown in Figure 5a, consists of a first layer of 1 mm thickness representing the standard FW Tungsten (W) coating (light blue color in Figure 5a) a second layer of 2 cm representing the FW steel with a homogenized mixture of 77% Eurofer steel and 23% Helium (gray color); and a third one of 80 cm thickness representing the breeder zone made of the PbLi eutectic alloy, with 84.3% of Pb and 15.7% of Li, with 90% enrichment in $^6$Li (dark green).

The FW has been consequently modified adopting different materials or additional layers depending on the FW concept to explore.

In the case of a decoupled but more standard FW (v1), Figure 5b, as the case of the fingers concept considered for DEMO ([26,36]), the FW is made again by a W layer and a Eurofer + He layer, but such a FW is separated from the Eurofer structure of the BB.
In practice, the simplistic model has two layers of Eurofer: the first one belonging to the FW and the other to the BB, with a thickness of 2 cm also for the second one.

In the case of a FW with a CPS configuration, a metallic mesh of W embedded by a liquid metal has been considered. Both Li and Sn have been chosen, although as the quantity used in this model is limited to a thin mesh, no huge differences are expected on the impact on neutronic figures. The CPS FW (Figure 5c,d) is modeled by a 1 mm layer (violet color) consisting of a mixture of 50% W and 50% of the corresponding liquid metal. Attached to the W mesh there is another layer (orange) of variable thickness (from 1 to 5 cm) representing the substrate FW material for which we have chosen either W (mass density 19.25 g/cm$^3$) or carbon in the form of graphite (C) (mass density 2.23 g/cm$^3$) (v2–v8). The CPS can be again coupled (Figure 5c) or decoupled from the BB (Figure 5d), implying in such second case that the Eurofer layer (gray) is split into two Eurofer layers (gray), with the second one belonging to the BB and the first one to the FW.

![Figure 5](image_url)

**Figure 5.** Radial Schemes of the material layers’ sequence along the radial direction for the different FW configurations under analysis staring from the plasma: (a) traditional configuration with coupled FW and BB; (b) standard decoupled FW (like fingers); (c) coupled CPS FW configuration and (d) decoupled CPS FW configuration. For the sake of clarity, the layers’ radial dimension is not in scale. The layers contained in the red rectangle represent those belonging to the detached FW; when it is not present, it means that the FW would be integrated with the BB sharing the Eurofer wall.

The volume of the breeder zone is conserved for all the cases under study, so TBR variations due to changes in the breeder volume are neglected in such initial studies and only variations due to changes in the FW configuration are computed. Additional layers (when needed) and thickness variations are implemented to the geometry in a consistent manner with this constrain, i.e., increasing the total thickness of the FW and BB towards the core, which means that the Scrape Off Layer (SOL) space requirements in a HELIAS configuration are not considered on a first approach.

5. Neutronic Performance of the Different FW Configurations

The neutronic analyses are focused on the assessment of the TBR and DPA. The first parameter addresses the tritium breeding performance and the second one accounts for radiation damage received by the different materials providing information regarding the components’ replacement and maintenance, and thus, related to the availability of the machine.

For that, particle transport Monte Carlo simulations through MCNP5v1.6 Monte Carlo code [17] using the JEFF 3.2 nuclear data library [41] have been performed.
DPA values have been primarily calculated for the entire radial zone from the FW to the end of the BB, with special attention to the values achieved in the Eurofer layer belonging to the BB, in order to verify how much reduction a CPS FW concept could produce, and hence, if potentially the BB could withstand the whole operation time foreseen for the machine (6 FPY extrapolated from the DEMO schedule [31,32]).

The different radial profiles of the DPA from the W coating/mesh to the end of the BB are shown in Figure 6 and a summary of the results just inside the BB Eurofer are given in Table 1. It is observed that the radiation damage received by the structural Eurofer in the blanket is significantly reduced by changing the FW configuration, and the achieved DPA levels are lower compared to the baseline configuration.

Table 1. TBR and DPA at the Eurofer in blanket values for different FW configurations and their relative variations with respect to the baseline.

<table>
<thead>
<tr>
<th>No.</th>
<th>FW Concept</th>
<th>FW Layers Configuration</th>
<th>BB Separate Structure</th>
<th>Tot Thickness before PbLi</th>
<th>DPA/FPY in BB</th>
<th>Δ (%)</th>
<th>TBR</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v0</td>
<td>Coupled Baseline</td>
<td>1 mm W + 2 cm Eurofer</td>
<td>2.1 cm</td>
<td>7.99</td>
<td>1.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v1</td>
<td>Decoupled fingers</td>
<td>1 mm W + 3.5 cm Eurofer</td>
<td>2 cm Eurofer</td>
<td>5.6 cm</td>
<td>6.58</td>
<td>−17.7%</td>
<td>1.02</td>
<td>−3.3%</td>
</tr>
<tr>
<td>v2</td>
<td>CPS *</td>
<td>2.5 cm W subs (Li) + 1 cm Eurofer</td>
<td>2 cm Eurofer</td>
<td>5.6 cm</td>
<td>5.59</td>
<td>−30.0%</td>
<td>0.831</td>
<td>−20.9%</td>
</tr>
<tr>
<td>v3</td>
<td>CPS *</td>
<td>2.5 cm W subs (Sn) + 1 cm Eurofer</td>
<td>2 cm Eurofer</td>
<td>5.6 cm</td>
<td>5.60</td>
<td>−29.9%</td>
<td>0.832</td>
<td>−20.8%</td>
</tr>
<tr>
<td>v4</td>
<td>CPS *</td>
<td>1 cm W subs + 2.5 cm Eurofer</td>
<td>2 cm Eurofer</td>
<td>5.6 cm</td>
<td>5.83</td>
<td>−27.0%</td>
<td>0.919</td>
<td>−12.5%</td>
</tr>
<tr>
<td>v5</td>
<td>CPS *</td>
<td>1 cm C subs + 2.5 cm Eurofer</td>
<td>2 cm Eurofer</td>
<td>5.6 cm</td>
<td>5.63</td>
<td>−29.6%</td>
<td>0.973</td>
<td>−7.3%</td>
</tr>
<tr>
<td>v6</td>
<td>CPS *</td>
<td>5 cm W subs</td>
<td>2 cm Eurofer</td>
<td>7.1 cm</td>
<td>4.55</td>
<td>−43.0%</td>
<td>0.669</td>
<td>−36.3%</td>
</tr>
<tr>
<td>v7</td>
<td>CPS *</td>
<td>3 cm C subs + 0.5 cm Eurofer</td>
<td>1 cm Eurofer</td>
<td>4.6 cm</td>
<td>5.67</td>
<td>−29.0%</td>
<td>0.999</td>
<td>−4.9%</td>
</tr>
<tr>
<td>v8</td>
<td>CPS *</td>
<td>4 cm C subs + 0.5 cm Eurofer</td>
<td>1 cm Eurofer</td>
<td>5.6 cm</td>
<td>5.04</td>
<td>−37.0%</td>
<td>0.964</td>
<td>−8.1%</td>
</tr>
</tbody>
</table>

* All the CPS configurations have 1 mm W matrix with embedded Li/Sn.

In particular, going from a traditional concept in which the FW and the BB are coupled (v0) to a decoupled finger FW (v1), which has in addition 3.5 cm of Eurofer in the FW, results in a beneficial effect for the protection of the blanket, reducing the damage received by a 17%.

This effect is increased when going to a CPS FW configuration (v2–v8), with damage reductions between 27% and 43%.

It has been noticed that when comparing the use of Li (v3) versus Sn (v4) as liquid metal in the CPS, no appreciable changes are observed (as expected) due to the fact that the quantity of the liquid metal is limited to a fraction in a tiny mesh.

Additionally, the use of carbon as substrate material instead of W is more effective for shielding as can be seen, for example, by looking at the differences among v4 and v5, with the same thickness used in both cases but giving lower DPA to the BB Eurofer when using a C instead of W substrate. Substituting the 1 cm W layer by C helps to increase the radiation damage protection of the BB and, at the same time, to keep an acceptable TBR value, as will be shown later.
The highest decrease in DPA value is achieved with the configuration v6, which consists of a CPS FW of 5 cm W (plus the 2 cm of Eurofer) producing 43% reduction in DPA, but being unaffordable under the TBR point of view (36% decrease in TBR).

Then, two additional configurations were simulated, consisting of a CPS with C substrate of variable thickness in front of a Eurofer layer (1.5 cm Eurofer layer shared as follows: 0.5 cm as FW support and 1 cm as BB structure). V7 considers a 3 cm C substrate, which gives a decrease of 29% in DPA at the blanket and just 4.9% reduction of the TBR. Increasing the thickness of the C substrate up to 4 cm (v8) increases the DPA reduction to 37% while keeping the TBR reduction to less than 10%.

As anticipated, such modified FW could also have a strong impact on the achievable TBR. The fulfillment of the TBR target (which is around 1.1–1.15 for DEMO ([21,22])) is essential, otherwise the design has to be modified to demonstrate the reactor self-sufficiency. Thus, the impact of the different FW concepts on the achieved TBR has also been computed. Nevertheless, due to the simplicity of the model, just relative estimations can be provided and absolute values cannot be extrapolated.

Table 1 shows the TBR values, as well as their relative variations, together with the DPA values at the BB Eurofer of different FW configurations. As the DPA values on the Eurofer blanket layer decrease (for example, up to a 43% dpa decrease in the v6 CPS configuration, with a W substrate of 5 cm), such a decrease also occurs in the TBR values, dropping to TBR levels that are unaffordable in most of the cases (36% TBR decrease in such configuration).

From Table 1, there are four cases showing a decrease of less than 10% in TBR that could be considered as they may could satisfy the necessary requirements. Among them, there are three configurations that achieve a considerable radiation damage reduction (around 30%). Below is a resume of these.

- CPS FW with 1 mm W mesh embedded with Li/Sn on a substrate of 1 cm of C and 4.5 cm of Eurofer (i.e., 2.5 cm CPS, 2 cm BB) (v5): produces a reduction of 29.6% in the DPA level and 7.3% TBR decrease (total thickness before PbLi: 5.6 cm).
• CPS FW with 1 mm W mesh embedded with Li/Sn on a substrate of 3 cm of C and 1.5 cm of Eurofer (i.e., 0.5 cm CPS, 1 cm BB) (v7): results in a reduction of 29.0% in the DPA level and 4.9% TBR decrease (total thickness before PbLi: 4.6 cm).

• CPS FW with 1 mm W mesh embedded with Li/Sn on a substrate of 4 cm of C and 1.5 cm of Eurofer (i.e., 0.5 cm CPS, 1 cm BB) (v8): generating a reduction of 37.0% in the DPA level and 8.1% TBR decrease (total thickness in front of the PbLi: 5.6 cm).

Hence, the best combination of materials and thickness is achieved by version v7 producing strong dpa reduction but reduced TBR impact.

In the past [28], for the simplified DCLL HELIAS extrapolated from DEMO tokamak and not optimized to the stellarator configuration, the produced TBR was calculated to be around 1.24. Thus, a 5% of TBR reduction, as resulting from v7, could still be affordable, being the values still higher than the DEMO TBR target, $TBR \geq 1.15$ [22] (to be still established, since the TBR target is machine-dependent).

### 5.1. TBR Enhancement through Reflectors

Considering the possibilities offered by the previously described CPS FW configurations, versions v7 and v8 have been selected for further assessment implementing improved designs to reach higher TBR.

An additional 2 cm carbon layer (in the form of graphite) has been introduced behind the breeder (Figure 7a) and in the middle (Figure 7b) for back-scattering purposes (as C is known to be a good neutron moderator and reflector) in order to enhance the Tritium breeding performance. Acting as a neutron reflector, the C plate would scatter part of the neutrons back to the breeder zone (the PbLi), increasing the possibility of the occurrence of T production reactions. The results of the modifications are provided in Table 2.

![Figure 7](image_url)

**Figure 7.** Schematic of the model with additional reflector layers (a) behind the breeder and (b) inside and behind the breeder.

In particular, v8a is the modified configuration v8 with a reflector at the back. For such configurations, the reduction in TBR passes from 8.1% to 7.3%, which implies an increase of 0.9% in the tritium breeding performance due to the C reflector.

Moreover, four additional modifications have been applied to v7 configuration (CPS with W mesh on 3 cm C substrate and 0.5 cm Eurofer). In one of them (v7b), the effect of breeder volume loss on the TBR has been addressed by increasing the FW thickness at the expense of the breeder zone instead of occupying the space of the SOL. The total thickness from the FW surface to the back BB was kept at 82.1 cm (being 1 mm W + 2 cm Eurofer + 80 cm PbLi in v0, while 1 mm + 3 cm + 1.5 cm (total 4.6 cm) W/C/Eurofer + 77.5 cm PbLi in v7b). Such PbLi volume reduction is computed to be a 2.9% breeder volume loss while the TBR loss compared with v7 is 0.4% (from −4.9% to −5.3%).
When the 2 cm carbon reflector is added in the back (v7c) (keeping the rest of layers fixed as in v7b), a slight increase in the TBR (+0.6%) is observed (Table 2), recovering more than the previous loss due to the breeder volume reduction.

If the reflector of 2 cm C is added inside the breeder (v7d), the TBR increases 1.1% from v7b and 0.5% from v7c. In such a configuration, the breeder zone is split into 38.75 cm of PbLi in front and 38.75 cm PbLi behind (keeping the total thickness 77.5 cm PbLi, while increasing the PbLi breeder volume in a 0.19% from v7b having switched the PbLi second layer) (Figure 7b).

Using both a back and a middle reflector (v7e) implies a positive contribution to the TBR of 1.5% compared to v7b. Hence, the total decrease from the baseline v0 considering the loss due to the CPS FW thickness and the gain due to the two C reflectors is −3.8%, being tolerable under the neutronic point of view.

**Table 2.** TBR enhancement using carbon reflectors.

<table>
<thead>
<tr>
<th>No.</th>
<th>FW Concept</th>
<th>FW + BB and Reflector Configuration</th>
<th>TBR</th>
<th>Δ (%) over Baseline</th>
<th>Δ (%) Reflector Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>v0</td>
<td>Baseline</td>
<td>1 mm W + 4 cm total Eurofer</td>
<td>1.050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v8</td>
<td>CPS</td>
<td>1 mm W + 4 cm C subs + 1.5 cm total Eurofer</td>
<td>0.964</td>
<td>−8.1%</td>
<td></td>
</tr>
<tr>
<td>v8a</td>
<td>CPS</td>
<td>+ back reflector</td>
<td>0.973</td>
<td>−7.3%</td>
<td>0.9%</td>
</tr>
<tr>
<td>v7</td>
<td>CPS</td>
<td>1 mm W + 3 cm C subs + 1.5 cm total Eurofer</td>
<td>0.999</td>
<td>−4.9%</td>
<td></td>
</tr>
<tr>
<td>v7b</td>
<td>CPS</td>
<td>Keeping SOL thickness</td>
<td>0.994</td>
<td>−5.3%</td>
<td></td>
</tr>
<tr>
<td>v7c</td>
<td>CPS</td>
<td>+2 cm back C reflector</td>
<td>1.000</td>
<td>−4.7%</td>
<td>0.6%</td>
</tr>
<tr>
<td>v7d</td>
<td>CPS</td>
<td>+2 cm middle C reflector</td>
<td>1.006</td>
<td>−4.2%</td>
<td>1.1%</td>
</tr>
<tr>
<td>v7e</td>
<td>CPS</td>
<td>+2 cm middle +2 cm back C reflectors</td>
<td>1.010</td>
<td>−3.8%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

Such relative estimations are to be considered as scoping studies for the down-selection and viability of the pre-chosen FW configurations, and to determine if the aim of a detached FW CPS would be accomplished: to reduce damage to the BB in order to increase its lifetime, reducing the RH operations to small FW panels while keeping the T breeding self-sufficiency of the machine. In the future activities, such a configuration will be further tested in a realistic framework, implementing the most promising ones in a 72º HELIAS 3D parameterized neutronic model.

6. Conclusions

In order to solve the specific challenges that the HELIAS Stellarator complexity brings, new design solutions have been proposed to configure a viable Breeding Blanket design based on the DCLL concept.

Previous MHD analyses, concluded in a BB quasi-toroidal segmentation, would nonetheless complicate the traditional Remote Handling of the BB through ports. Such controversy motivated the search for a brand-new solution: the use of decoupled FW to switch the maintenance problem mainly to small FW panels, instead of entire BB segments, that could be manageable through ports.

The use of a fully detached FW based on a Capillary Porous System (CPS) decoupled from the BB has been settled with the purpose to simplify the Remote Maintenance of the BB. The objective was to reduce the BB damage (and increase the device availability) by introducing different FW substrates materials and thicknesses that could absorb the neutron damage and switching the maintenance operations from the heavy BB segments to just small FW detached panels.

Nonetheless, a compromise has to be achieved between reducing the BB damage and deplete its T breeding capability to unaffordable levels.

To this purpose, different FW configurations, materials and thicknesses have been tested.
Such alternatives have been tested considering a simplified 1D approach, but using a realistic neutron source distribution, which allows us to quickly address the relative variations of the TBR and DPA values in a number of FW configurations. Preliminary results confirmed that a compromise can be found between TBR losses and damage to the BB by adopting a combination of materials for the FW CPS and by using C-based reflectors.

A considerable dpa relative reduction has been achieved in some of the FW configurations that consider C substrates (around a 30% dpa reduction) together with a small TBR relative loss of 3.8%. The proposed configurations will be implemented and tested in 3D detailed neutronic models. Furthermore, other stellarator-oriented RH solutions will be explored to investigate the progress of the general BB design activities.

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