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*Article*

# 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 among 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 an HELIAS configuration 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, as the use of fully detached First Wall (FW) based on liquid metal Capillary Porous Systems (CPS). These 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 to simplify the BB integration, improve 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 reduce the radiation damage received by the blanket without compromising its tritium breeding performance.

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

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## 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], 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 understanding stellarator plasmas and important advancements have been already obtained on the physics aspects, especially thanks to the operation of the Weldenstein 7-X (W7-X) stellarator [5]. This has lead the Eurofusion community to define the HELIAS (HELical-axis Advanced Stellarator) [6] type stellarator development as one of its long term missions (Mission 8 within the European roadmap towards fusion [7]), as an alternative to the main DEMO tokamak line. All the related engineering and technological activities are included in the Work Package Prospectives R&D: Stellarator Power Plant Studies (WPPRD SPPS).

Among these activities, and exploiting previous experience in BB design for DEMO tokamak [4], CIEMAT is leading the development of a Dual Coolant Lithium Lead (DCLL) Breeding Blanket (BB) for the HELIAS device. Such concept, which details are given 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 been proposed also to simplify the remote maintenance and integration of the BB

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segments. The solution here explored and assessed is the use of 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 to the BB, increasing the availability of the machine 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 [8] 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) shows 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 component of the future fusion power plants, being tokamaks or stellarators, is the Breeding blanket (BB), which has to fulfill a number of requirements essential to demonstrate the viability of fusion. One of the most important requirement (i) is that any large fusion device must generate its own tritium (T) fuel, as it does not exist in nature in any appreciable quantity.

For such purpose, the BB is made by Li compound T breeding material that regenerates T by $^6Li(n,T)$ and $^7Li(n,n'T)$ reactions. In the case of the Dual Coolant Lithium Lead (DCLL) BB concept the breeder material is PbLi in the eutectic composition: 84.3% Pb and 15.7% Li [9]. In addition, as $^6Li$ has an exothermic reaction with neutrons and the $^6Li(n,T)$ reaction has a much more efficient cross section in a wider neutron energy range than $^7Li(n,n'T)$ reaction, the breeder is enriched to 90% in $^6Li$.

Inside the Li compound PbLi, the Pb acts as 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 [10,11].

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 DEMO tokamak device, the TBR target has been settled to TBR $\geq$ 1.15 ([12,13]). Such 15% of margin takes into account the previously mentioned losses, the uncertainties in the cross-sections data and in the modelling (approximately a 5%) and a 10% extra margin due to non-breeding coverage areas (for example due to penetrations and ports with Heating & Current Drive systems, Neutral Beam Injectors, limiters, etc.).

Another essential function of the BB (ii) is the heat extraction. The BB must absorb the largest ($\sim$ 80%) part of the fusion energy transported by neutrons from the plasma and deposited volumetrically in the surrounding in-vessel structures. In a reactor of about 2 $GW$ of fusion power, the blanket system has to extract about 1900 $MW$ of nuclear power. Conversion of this energy at adequate thermodynamic efficiencies requires that the coolants are at high temperature and pressure. In the case of the DCLL the coolants are the He for the FW and the PbLi that, flowing at high velocity, is self-cooling.

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) and the PbLi breeder act as shielding for the systems located behind it. In fact, there are several shielding requirements established to ensure functionality and integrity of the superconducting coils, which refers 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 3D configuration in term of modelling and analyses and also to physical constraints.

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

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Therefore, new BB designs based on the existing Dual Coolant Lithium Lead (DCLL) BB concept developed for DEMO tokamak [14–18], have been explored re-adapting it 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, reducing its weight and hence the kinematic problems of moving big and heavy segments.

The design of a BB has to satisfy the previous requirements for the efficiency and viability of the reactor, but also in compliance with ensuring the BB integrability in the machine together with its durability and maintenance to increase the reactor availability. In fact, this will be an important economic factor [19], implying that the durability and maintenance of the blanket must be oriented to maximise 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 programme. In HELIAS device there is still not a foreseen operation plan, so as preliminary assumption the same schedule considered for DEMO is supposed [20].

DEMO would act (at least in its first phase of operation) as a "component test facility" for the BB assuming that operation will commence with a 20 dpa limit "starter" blanket installed in the tokamak that utilises 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 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 favourable. 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.

For hence, in much complex HELIAS device, one of the main concerns under the engineering point of view is to select a BB segmentation and design which 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 [21] concerning the evaluation of the MHD resistance for different BB segmentations it has been demonstrated [22,23] that a quasi-toroidal segmentation (instead than the poloidal one, used in DEMO) would be preferred to avoid the use of FCI or coatings, and having strong impact on the simplification of the engineering BB design, especially interesting to cope with the complex 3D stellarator configuration.

One of the main concern of such toroidal segmentation is related to the RH, traditionally planned to be done by Ports. Such tokamak-oriented approach should be re-thought to be specifically planned for 3D stellarators machines in which the components (BB segments, Ports, etc.) in a periods 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 [22] as moving the coils to attach temporarily bigger ports, or opening the Vacuum Vessel [24,25], an attractive solution for a faster Remote Maintenance could be the use of a detached First Wall decoupled physically and hydraulically

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from the Breeding Blanket cover box. In the past, and for the DEMO project, a finger solution was proposed and studied [26–28].

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 Capillary Porous System (CPS) [23].

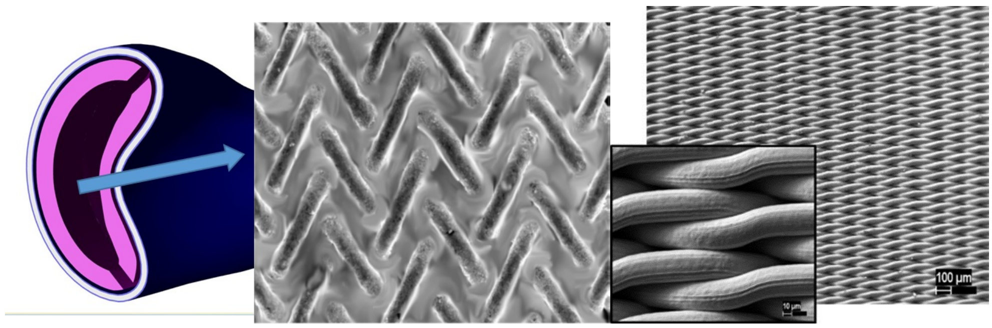
Its characteristics, possible implementation in a HELIAS configuration and the neutronic assessment to verify its suitability to reduce the dpa in the BB while keeping an efficient TBR are exposed in Sections 3 to 5.

## 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). A self-renewable liquid PFC presents several advantages against a solid material, such as the surface erosion concerns or the elimination of problems related to local thermal stresses encountered in solid FW structures produced by the heat flux incoming from the plasma. These properties have motivated intense research activity, with a variety of concepts, elements and proposals for practical 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, being the Li the most promising option due to the plasma stability effects [29].

In CPS concept a liquid metal pool is put into contact with a porous metallic mesh through which the LM can flow. Typical pore sizes are in the range of few microns and, although smaller pore radii would involve higher capillary holding forces, other undesired phenomena, such as viscosity-associated effects that hinder the refilling of the surface exposed to the plasma as well as other material-related compatibility issues such as corrosion, embrittlement or hydrogen solubility limit the design and final choice of materials [30].

As such solutions are being explored for the very extreme irradiation and thermal conditions of the divertor, withstanding heat fluxes of about 30 $MW/m^2$, they can be considered also for the more "relaxed" conditions of the FW, subjected typically to loads of the order of the $MW/m^2$. Additionally, the CPS FW could result in a structure easier adaptable to the complex geometry of a HELIAS device (Figure 1).




(a) (b)

**Figure 1.** Detachable FW Capillary Porous System option. **a**) Steel mesh wetted by Li in the Frascati tokamak (Figure. courtesy of Efremov Institute) [31]. **b**) SEM micrography of CPS plasma facing surface [32].

Moreover, and being 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 reduce also the number and size of ports. This fact could indirectly

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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.

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 in the different FW models.

## 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 [21], alternatives has been searched that, although being preliminary study, could bring valuable information about the neutronic performances of these new FW configurations. This first approximation comes in the way of a 1-dimensional spherical modelling of the HELIAS reactor.

The simplified 1D model consist of superimposed concentric spheres, where each sphere contains the composition of one specific material (Figureure 2). In this way, changing the composition and the thickness of the different spherical layers several FW configurations can be tested.

Despite 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 visualised through the MCAM (Monte Carlo Modelling Interface Program) tool SuperMC MCAM 5.2 Professional Version [33], an integrated interface program between commercial CAD software (here CATIAv5) and Monte Carlo radiation transport simulation codes.

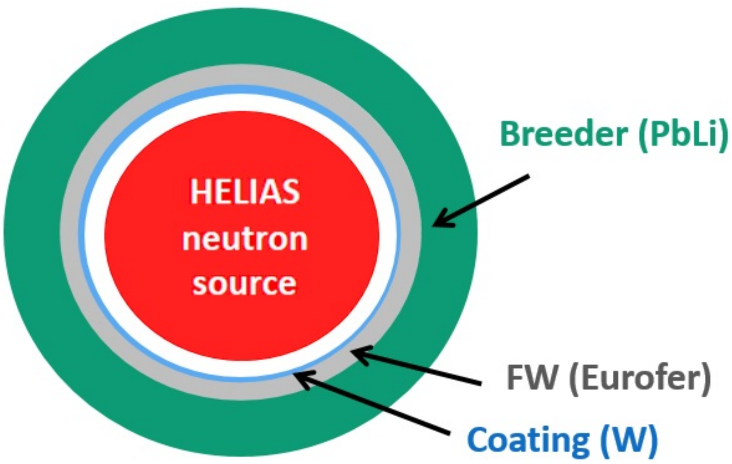


**Figure 2.** 1-Dimensional HELIAS spherical model. The configuration represented here corresponds to a couple FW and BB (dimensions not to scale).

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 [34] which has a prevalent homogenised BB (including the FW) but with four detailed DCLL blanket modules (Figureure 3a) with a separated W coating and Eurofer FW has been used. The neutron spectrum (Figureure 3b) 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

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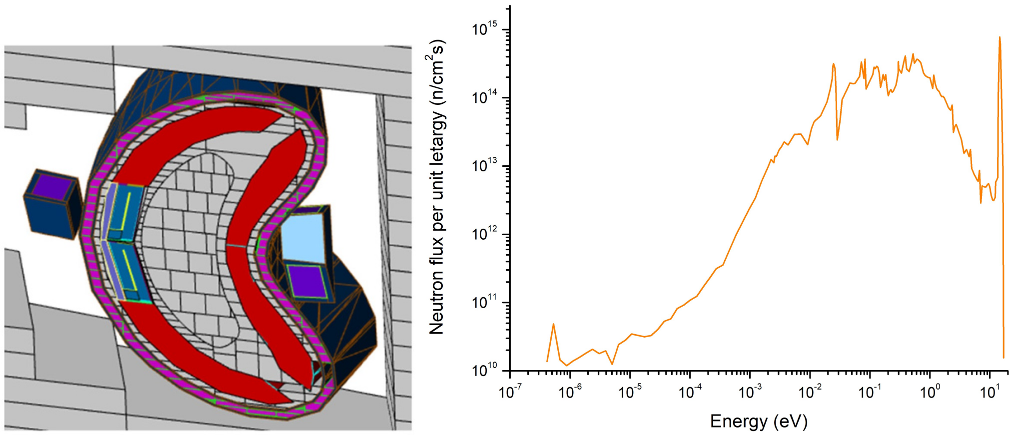
1-D concentric spheres simplified approach has been considered. The source in such model has been established to be spread homogeneously (with a radial distribution) inside the entire volume of the central sphere (in red, in Figureure 2), which represents the plasma, and emitting isotropically from such volume.




(a) (b)

**Figure 3.** (**a**) Neutronic model of a 36° sector of HELIAS, including the four fully detailed DCLL modules. The rest (in red) represents the homogenised composition of the BB structure. **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 analysed 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 Figureure 4a, consist of a first layer of 1 mm thickness representing the standard FW Tungsten coating (light blue colour in Figureure 4a), with pure W composition; a second layer of 2 cm representing the FW steel with a homogenised mixture of 77% Eurofer steel and 23% Helium (grey colour); 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 $^6Li$ (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**), Figureure 4b, as the case of the fingers concept considered for DEMO ([26,27]), the FW is made again by a W layer and a Eurofer + He layer, but such FW is separated from the Eurofer structure of the BB. In practice, the simplistic model has 2 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 (Figureure 4c-4d) is modelled by a 1 mm layer (violet colour) 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 or C (**v2-v8**). The CPS can be again coupled (Figureure 4c) or decoupled from the BB (Figureure 4d), implying in such second case that the Eurofer layer (grey) is split in 2 Eurofer layers (grey) with the second one belonging to the BB and the first one to the FW.

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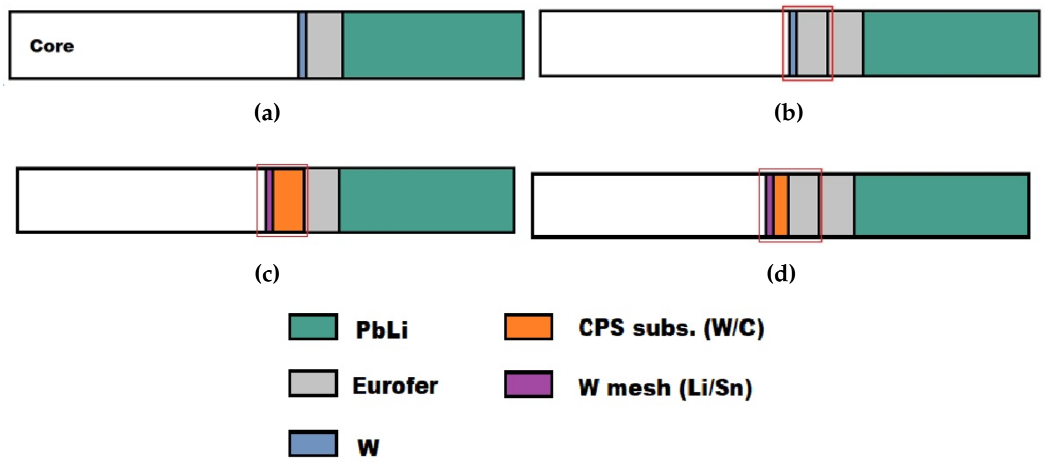


**Figure 4.** Schemes of the material layers along the radial direction for the different FW configurations under analysis: (**a**) Traditional configuration with coupled FW and BB. (**b**) Standard decoupled FW (like fingers). (**c**) Coupled CPS FW configuration. (**d**) Decoupled CPS FW configuration.

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 it is not considered on a first approach the Scrape Off Layer (SOL) space requirements in a HELIAS configuration.

## 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 for 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 [8] using JEFF 3.2 nuclear data library [35] have been performed.

DPA values have been primary calculated for the entire radial zone from the FW to the end of the BB but 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 DEMO schedule [20]).

The different radial profiles of the DPA from the W coating/mesh to the end of the BB are shown in Figureure 5 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 achieved DPA levels are lower compared to the baseline configuration.

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.

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Additionally, the use of Carbon as substrate material instead than W is more effective for shielding as it can be seen for example 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 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 it will be shown later.

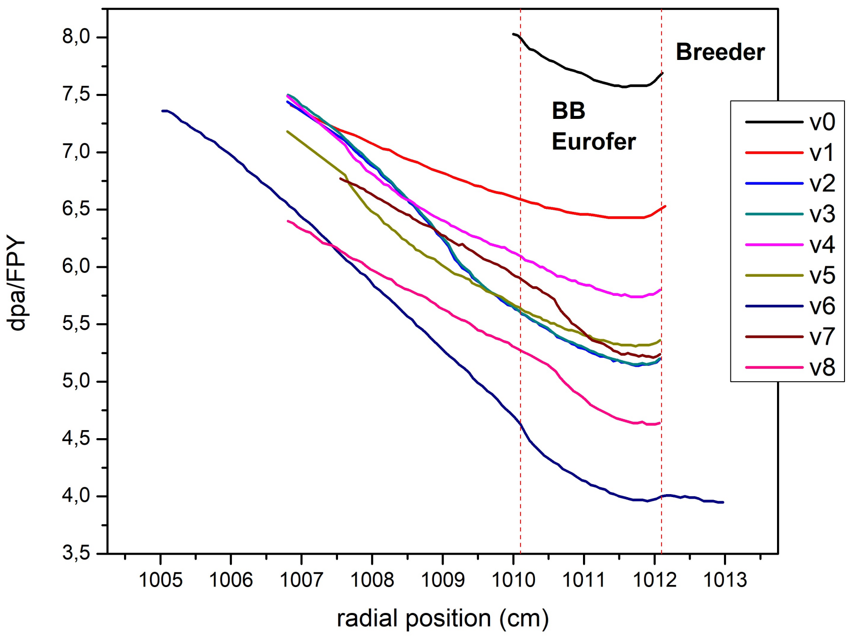


**Figure 5.** DPA radial profiles for different FW configurations.

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 tested, 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 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 have also a strong impact on the achievable TBR. The fulfilment of the TBR target (which is around 1.1-1.15 for DEMO ([12,13])) 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 been also 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 decrease also occurs to the TBR values, dropping to TBR levels that are unaffordable in most of the cases (36% TBR decrease in such configuration).

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

| N° | FW Concept | FW layers configuration | BB separate structure | Tot thickness before PbLi | DPA/FPY i |
|---|---|---|---|---|---|
| **v0** | Coupled Baseline | 1 mm W + 2 cm Eurofer | | 2.1 cm | **7.99** |
| **v1** | Decoupled fingers | 1 mm W + 3.5 cm Eurofer | 2 cm Eurofer | 5.6 cm | 6.58 |
| **v2** | CPS* | 2.5 cm W subs (Li) + 1 cm Eurofer | 2 cm Eurofer | 5.6 cm | 5.59 |
| **v3** | CPS* | 2.5 cm W subs (Sn) + 1 cm Eurofer | 2 cm Eurofer | 5.6 cm | 5.60 |
| **v4** | CPS* | 1 cm W subs + 2.5 cm Eurofer | 2 cm Eurofer | 5.6 cm | 5.83 |
| **v5** | CPS* | 1 cm C subs + 2.5 cm Eurofer | 2 cm Eurofer | 5.6 cm | 5.63 |
| **v6** | CPS* | 5 cm W subs | 2 cm Eurofer | 7.1 cm | 4.55 |
| **v7** | CPS* | 3 cm C subs + 0.5 cm Eurofer | 1 cm Eurofer | 4.6 cm | 5.67 |
| **v7** | CPS* | 4 cm C subs + 0.5 cm Eurofer | 1 cm Eurofer | 5.6 cm | 5.04 |

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

From Table 1, there are four cases showing a decrease 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 [34], for the simplified DCLL HELIAS extrapolated from DEMO tokamak and not optimised 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 be still affordable, being the values still higher than the DEMO TBR target, TBR $\geq$ 1.15 [13] (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 has been introduced behind the breeder (Figureure 6a) and in the middle (Figureure 6b) for back-scattering purpose (as C is known to be a good neutron moderator and reflector) in order to enhance the Tritium breeding performance. The results of the modifications are provided in Table 2.

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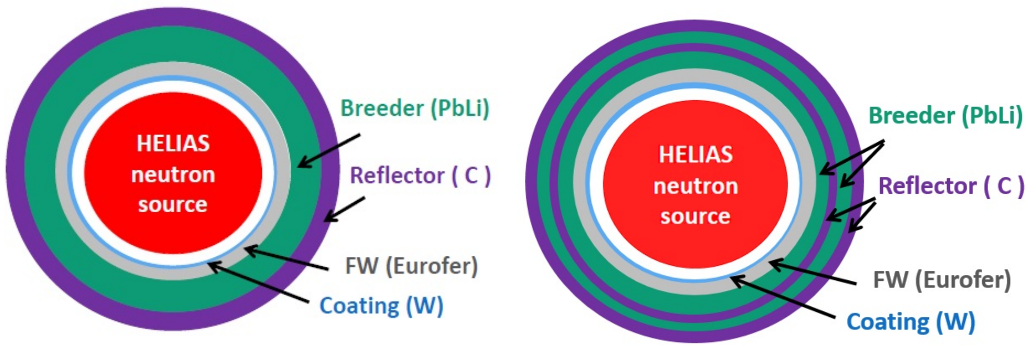


**(a)** **(b)**

**Figure 6.** 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 configuration the reduction in TBR pass 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 than occupying the space of the SOL. The total thickness from the FW surface to the back BB was kept at 82.1 cm (being 1mm W + 2cm Eurofer + 80cm PbLi in **v0**, while 1 mm + 3 cm + 1.5 cm (total 4.6cm) W/C/Eurofer + 77.5cm PbLi in **v7b**). Such PbLi volume reduction is computed to be a 2.9% breeder volume loss while the TBR loss comparing with **v7** is a 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 of 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 a 1.1% from **v7b** and 0.5% from **v7c**. In such configuration the breeder zone is split in 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) (Figureure 6b).

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

| N° | FW Concept | FW + BB and reflector configuration | TBR | Δ(%) over baseline | Δ(%) reflector effect |
|---|---|---|---|---|---|
| **v0** | Baseline | 1 mm W + 4 cm tot Eurofer | **1.050** | | |
| **v8** | CPS | 1 mm W + 4 cm C subs + 1.5 cm tot Eurofer | 0.964 | -8.1% | |
| **v8a** | CPS | + back reflector | 0.973 | -7.3% | 0.9% |
| **v7** | CPS | 1 mm W + 3 cm C subs + 1.5 cm tot Eurofer | 0.999 | -4.9% | |
| **v7b** | CPS | Keeping SOL thickness | 0.994 | -5.3% | |
| **v7c** | CPS | +2 cm back C reflector | 1.000 | -4.7% | 0.6% |
| **v7d** | CPS | +2 cm middle C reflector | 1.006 | -4.2% | 1.1% |
| **v7e** | CPS | +2 cm middle +2 cm back C reflectors | 1.010 | -3.8% | 1.5% |

Using both a back and a middle reflector (**v7e**) implies a positive contribution to the TBR of 1.5% comparing with **v7b**. Hence the total decrease from the baseline **v0** considering the loss due to the CPS

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FW thickness and the gain due to the two C reflectors is -3.8%, being tolerable under the neutronic point of view.

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 configuration will be further tested in a realistic framework, implementing the most promising ones in a 72º HELIAS 3D parameterised neutronic model.

## 6. Conclusions

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

Previous MHD analyses, focused on optimising the self-cooling breeder (PbLi) route according to reducing the MHD pressure-drop due to the coupling of the magnetic field and the metal-liquid path, concluded in a BB quasi-toroidal segmentation. Such configuration would minimise so much the pressure drop that the use of isolating systems (coatings, ceramic walls, Flow-channel inserts) could be fully avoided even in the zones with the highest magnetic field.

The use of a toroidal BB segmentation nonetheless would complicate the 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, that could be manageable through ports.

The use of a fully detached FW based on 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 its availability) without compromising at unaffordable levels its T breeding capability.

Such alternative has been tested considering a simplified 1D approach, but using a realistic neutron source distribution, which allows to address rapidly 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 substrate (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 RH solutions stellarator-oriented will be explored to impulse the progress of the general BB design activities.

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