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Rationale and Method for design of DEMO WCLL Breeding Blanket Poloidal Segmentation

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Abstract

One of the most critical components in the design of DEMO Power Plant is the Breeding Blanket (BB). Currently, four candidates are investigated as options for DEMO. One of these is the Water Coolant Lithium Lead (WCLL) Breeding Blanket (BB). A new WCLL BB concept design has been proposed and investigated in 2015. The first activity driving the BB design was the definition of the poloidal segmentation. Current trend in breeding blanket designs is based on the multi module box approach, which has advantages in terms of manufacturing, in reducing the global stress and strain during the start-up and the shut-down phases and during operation, because the favourable thermal expansions; and in simplifying the First Wall (FW) layout and integration. Nevertheless, drawbacks are identified, such as the reduction of Tritium Breeding Ratio (TBR), the constraints in manifold and in Back Supporting Structure (BSS) design and integration because the limited space available. The present work concerns a method that, starting from these constraints, defines and optimizes some of the main design drivers for the selection of the segmentation of the WCLL BB. The method by definition is based just on geometrical parameters because it is used as first step of the design when any analysis and detailed data are available. It is based on the definition of Figures Of Merits (FOM), consisting in numerical parameters, such as the ratio between the modules volume and the overall volume of segment assigned, the approximation between the real profile of the modules and the theoretical one, the form factor of the modules, the ratio between the module thickness at the mid-plane and the segment thickness at the same position. The FOM support the choice among different options. In particular two different solutions of poloidal segmentation have been compared and, according to the proposed method, the best one was chosen for the design of WCLL BB.

"Keywords: Conceptual Design, DEMO Breeding Blanket, Water Cooled Lithium Lead, Poloidal Segmentation, Figure of Merits"

1. Introduction

The first step of BB design consists on discretization of its dedicated volume. In particular the volume has to be divided in simple sectors and modules through toroidal and poloidal directions. Previous studies about the BB toroidal segmentation have been clarified how the blanket has to be segmented in toroidal direction. The outcomes of these studies are integrated in the 2015 configuration of DEMO power plant [1]. The work focuses on a method that, starting from the outcomes of requirements, defines and optimizes some of the main design drivers for the selection of the BB segmentation. The method is based on geometrical parameters because it is used as first step of the design phase. Indeed at this stage, physical parameters characterizing the BB operation are not well defined and in any case difficult to be used, because requiring detailed design of the component (e.g. FW and BZ cooling systems design and layout, etc,). For instance, the interaction between plasma flux and FW shape (thermal charged particle heat loads, radiation heat loads, fast particle heat loads, disruption heat loads and erosion) in normal operation is a fundamental aspect to establish the optimization of the FW shape. Being the FW cooling system and the reference loads not well defined, these analyses will be addressed in the detailed design phase. The method is based on the definition of Figures Of Merits (FOM) consisting in numerical parameters, such as the ratio between the modules volume and the overall volume of segment assigned, the approximation between the real profile of the modules and the theoretical one, the form factor of the modules, the ratio between the module thickness at the mid-plane and the segment thickness at the same position.

2. DEMO Breeding Blanket segmentation design approach

To date the approach used in design of BB is based on Multi-Module Segment (MMS). In this concept (Fig. 1) pre-assembled blanket modules are mounted onto segmented vertical support structures that include the manifolds for distribution of the coolants and the breeder material [2]. During the maintenance activities the entire MMS is replaced thought the upper port. This approach is different from the ITER one [3], in which each modules is replaced separately. In this way most of the assembly activities are carried out outside the vessel reducing the number of handling units and consequently the BB maintenance time. These aspects contribute to an increasing of DEMO machine availability.

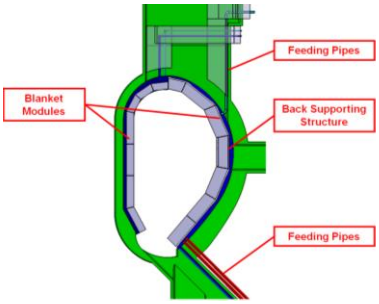

Fig. 1 DEMO BB Poloidal Segmentation

3. Breeding Blanket Poloidal Segmentation design method

The performances of DEMO BB are strongly dependents from the geometry of the entire blanket and its modules. In the initial stage of BB design, some choices have to be taken. In order to support the design team in an embryonal design stage a simple geometrical method have been developed. In particular the method evaluates some geometrical characteristics related to the main aspects of the BB design.

The geometrical characteristics of BB segmentation are evaluated through six figures of merits (FOMs).

These parameters take into account some critical aspects about the design of the BB modules. In other words the FOMs are used to characterize the performance of BB taking into account the poloidal segmentation.

It should be noted that the method can be applied in initial stage of the design of BB when not much information and data are available. The design method consists of three main phases Fig. 2:

- Input data and assumptions definition
- Design Solutions modelling
- Evaluation of best design solution

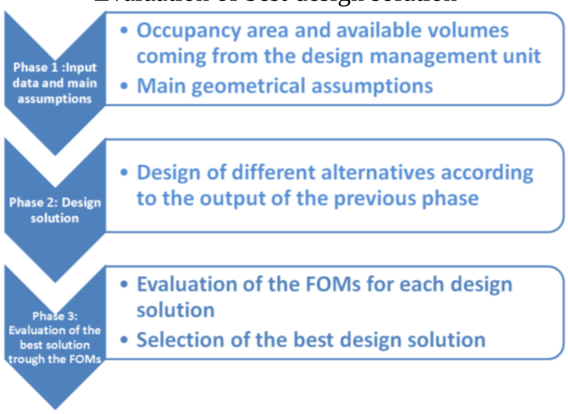

Fig. 2 Flow path of BB poloidal segmentation design method

3.1. Phase 1: Input data and geometrical assumption definition

The initial phase of the method consists in a collection of the design constraints coming from the design management unit and from previous studies. In this phase the constraints are collected and summarized, and their consistency is evaluated according to the preliminary requirements of the system. It is clear that in the case of DEMO BB, this check is limited by the project complexity. However, the consistency check can guarantee the quality of the design processes, when a relevant numbers of design teams with different skills and know-how interact and exchange data one another.

In this phase, the design team defines also some geometrical assumptions as the basis for development of all BB poloidal segmentation design solutions.

3.2. Phase 2: Design solutions definition and modelling

The second phase of the method focuses on the development of different design solutions compliant with the requirements [4] and assumptions coming from the previous phase. During this phase all ideas of the designers become sketch and tri-dimensional models. These data will represent the input for the design teams once the detailed design of each module of the BB MMS will be developed.

3.3. Phase 3: Evaluation of the best solution through the Figures of Merits

As aforementioned the method is based on definition of some FOMs. The evaluation of the best solution is done calculating the values of the FOMs for each design solution. Each FOM takes into account aspects related to the BB poloidal segmentation (tritium breeding ratio, module shape complexity, approximation of plasma chamber, etc.). In Tab. 1 are listed the FOMs defined and their characteristics. In particular, the FOMs classified as "*Integral*" are related to the entire MMS while the others, "*Local*", concern the single modules. The first parameter "N" is the number of the modules for each MMS, a high value of this parameter increases the complexity of design. The FOM "a" (Tab. 1) consists in a ratio between the module (from 1 to N) and the overall segment volume [1]. "*s*" is the volume of each module and "*S*" is the volume of the bounding box of the entire sector [1]. This parameter is strictly related to the Tritium Breeding Ratio (TBR), in the sense that represents a filling rate of the BB sector assigned volume.

The parameter "b" represents a measure of the approximation between theoretical inner profile of the BB sector [1] (labelled in Fig. 3) and the real profile generated by the segmentation. In other words gives a measure of the plasma chamber approximation.

In Tab. 1 "$x_i - y_i$" is the distance between the two profiles (real and theoretical) calculated in three points for each module; on the extremities of the module (point A and B in Fig. 3) and in correspondence of minimum distance point (point C in Fig. 3). The value "*n*" is the number of total points on which the distance is calculated. The BB segmentation design with the lowest value of parameter *"b"* gives a better approximation of the plasma chamber.

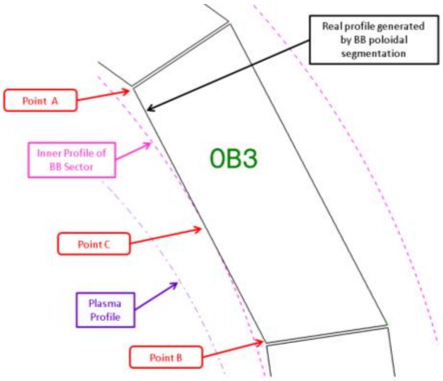

Fig. 3 Distance between the real and theoretical BB profiles on poloidal mid-plane of BB sector

The parameter "c" is related to the thickness of the modules, the manifold average area, the TBR and the electromagnetic forces depend from this parameter.

Moreover, this parameter gives a measure of how much space is available for the BSS and represents the filling rate of each module. In detail the value "t_i" is the thickness of each module and "T_i" represents the distance between the inner and outer profile of BB bounding box sector [1] (Fig. 4).

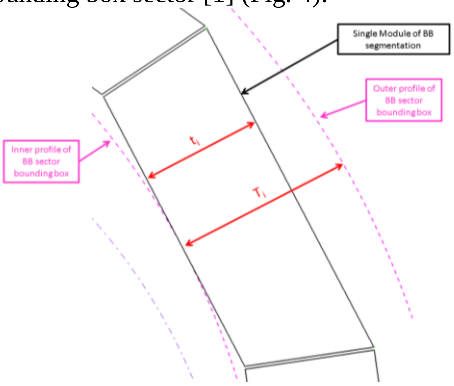

Fig. 4 Thicknesses of BB modules and BB sector on poloidal mid-plane of BB sector

The parameter "d" states a factor form of each module. The value is calculated as a ratio between the two diagonal of a poloidal section of each module. In others words if the form factors of the modules are similar their shape will be similar. The shape of the module has a relevant impact on the manufacturing issues of the breeding blanket. In Tab. 1 the values "DM_i" and "Dm_i" are respectively the major and minor diagonal of each module.

The last parameter "e" is the average length of the modules, this parameter is related to the TBR and to the manufacturing issues.

As we can observe the FOMs take into account the aspects related mainly to TBR, the approximation of the plasma chamber, the modularity of the blanket and the manufacturing issues.

Tab. 1 Figure of Merits characteristics

FOMs	**Connection with BB features**	**Type**
N	--	--
$a = \frac{\sum(s_i)}{S}$ $i = 1,..N$	TBR related parameter Filling rate	Integral
$b = \frac{\sum(x_i - y_i)}{n}$ $i = 1,..n$	Approximation of plasma chamber	Integral
$c_i = \sum \frac{t_i}{T_i}$ $i = 1,..N$	BSS and manifold average thickness TBR related parameter	Local
$d_i = \frac{\sum \frac{DM_i}{Dm_i}}{N}$ $i = 1,..N$	Modularity of the blanket Manufacturing	Local
$e = \frac{L}{N}$	Manufacturing	Integral

4. Case Study: Design of Poloidal Segmentation of WCLL Breeding Blanket

The geometrical method provided has been applied and tested on design of the WCLL BB poloidal segmentation.

4.1. PHASE 1: Main assumption and input data for WCLL BB segmentation

In the first phase, starting from the 3d model provided by Eurofusion Programme Management Unit PMU [1] the available working domains of WCLL BB have been identified. Moreover some driven assumptions in design of poloidal segmentation have been collected from previous studies [5] and checked to be consistent with the high level requirements to date available [4].

The main assumptions defined are listed below:

- ✓ the height of the modules shall be lower than 3000mm;
- ✓ First Wall and Back Plate of the modules shall be straight and parallel;
- ✓ the angles between the upper and lower walls of the modules should be greater than 90°;
- ✓ the radial dimension of the outboard modules varies between 800mm and 900mm;
- ✓ the radial dimension of the inboard modules is set to 550mm;
- ✓ radial space behind the modules shall be greater than 200 mm;
- ✓ distance between modules is set to 20 mm, assuming parallel the upper and lower walls between two modules;
- ✓ the number of modules shall be minimized as much as possible;
- ✓ the relationship between the Tritium Breeding Ratio (TBR) trend and the geometrical constraints shall be evaluated;
- ✓ the facing plasma surface of the modules shall be as much as possible tangent to theoretical inner surface of BB design [1];
- ✓ the fitting between the plasma geometry and the discretized geometry of the modules first walls shall be evaluated.

4.2. Phase 2: 3D model of WCLL BB poloidal segmentation

Phase two of design concerned the 3d modelling of WCLL BB poloidal segmentation. In particular two design solutions for poloidal segmentation of the inboard and outboard BB segments have been modelled. The two solutions have been generated through a parametric approach. A master model of WCLL BB poloidal segmentation has been created. One of the objectives was to develop efficiently to manage CAD model in view of the likely changes in WCLL BB structure required during the conceptual design activities on DEMO [6]. The two solutions with dimension and main geometrical characteristics are shown in Fig. 5.

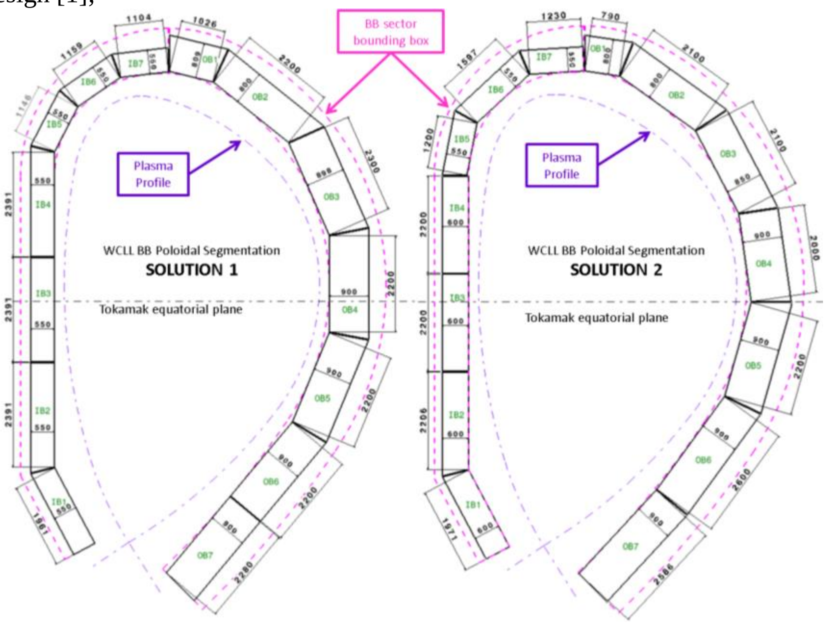

Fig. 5 Section on poloidal plane of WCLL BB Segmentation Solution 1 and Solution 2

4.3. Phase 3: Evaluation of the FOMs of WCLL BB segmentations

The last phase of development of WCLL poloidal segmentation concerned the evaluation of the best solution. In detail for each design solution the FOMs have been evaluated. The Values of the figures of merit obtained in both solutions are listed Tab. 2. As we can notes in Tab. 2 both solution have advantages and disadvantages form the FOMs value point of views.

Tab. 2 Results of FOMs evaluation for WCLL BB poloidal segmentation solutions 1 and 2

FOMs	Sol. 1 Inb.	Sol. 1 Outb.	Sol. 2 Inb.	Sol. 2 Outb.
N	7	7	7	7
$a = \frac{\sum(s_i)}{S}$ $i = 1,..N$	0.45	0.69	0.48	0.68
$b = \frac{\sum(x_i - \mathrm{y_i})}{n}$ $i = 1,..n$	10.9	32.4	14.32	27.4
$c_i = \sum \frac{t_i}{T_i}$ $i = 1,..N$	0.71	0.75	0.71	0.70
$d_i = \frac{\sum \frac{DM_i}{Dm_i}}{N}$ $i = 1,..N$	1.03	1.04	1.04	1.04
$e = \frac{L}{N}$	1800	2057	1517	2053

In particular the solution 1 is expected to have better performance in terms of TBR, available volume for the BSS and feeding manifold. Moreover, the two solutions seem to be similar from the manufacturing point of view while the solution 2 approximates better the plasma chamber. Taking into account these aspects the WCLL BB design team chose the solution 1 as reference solution for the future development of the WCLL BB design favouring the aspects related to TBR because the T self-sufficiency [1] is the most critical aspects in design of DEMO BB.

5. Conclusions

The work carried out focused on a geometrical method to support the designers in the initial stage of the design of DEMO BB. It is clear that the method cannot replace the skills and know-how of the designers but can support them in defining the starting point of the design activities. The method does not replace any analysis and study about the interaction between the plasma and the FW shape, neither makes an optimization in this sense, in other words the work focuses on a complementary point of view about the optimisation of the FW shape. These aspects such as detailed engineering analyses (thermal, thermo-hydraulic, structural, neutronic, etc.) are typical of a later design phase, once a rough geometrical design of the segmentation is provided. In this optic the work can support designers in defining of a reasonable starting point for the future development of BB design. Moreover the outcomes of the method can be considered robust for further optimizations. The method developed has been used for design of BB WCLL poloidal segmentation. The Solution 1 is expected to have better performance in terms of TBR, available volume for the BSS and feeding manifold. Moreover the two solutions seem to be similar from the manufacturing point of view while the solution 2 approximates better the plasma chamber. Currently the Solution 1 has been chosen as the reference solution for the development of WCLL BB design. The design team favoured the aspects related to TBR and filling rate because, at the moment, the requirements about the TBR is one of the most critical aspects in design of DEMO BB. It should be noted that the method does not pretend to solve any problems related to BB development but it is just a tool which supports the designers when major FW design requirements are still under investigation.

Acknowledgements

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