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Main Nuclear Responses of the DEMO Tokamak with Different In-Vessel Component Configurations

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Abstract: Research and development of the DEMOnstration power plant (DEMO) breeder blanket (BB) has been performed in recent years based on a predefined DEMO tritium breeding ratio (TBR) requirement, which determines a loss of wall surface due to non-breeding in-vessel components (IVCs) which consume plasma-facing wall surface and do not contribute to the breeding of tritium. The integration of different IVCs, such as plasma limiters, neutral beam injectors, electron cyclotron launchers and diagnostic systems, requires cut-outs in the BB, resulting in a loss of the breeder blanket volume, TBR and power generation, respectively. The neutronic analyses presented here have the goal of providing an assessment of the TBR losses associated with each IVC. Previously performed studies on this topic were carried out with simplified, homogenized BB geometry models. To address the effect of the detailed heterogeneous structure of the BBs on the TBR losses due to the inclusion of the IVCs in the tokamak, a series of blanket geometry models were developed for integration in the latest DEMO base model. The assessment was performed for both types of BBs currently developed within the EUROfusion project, the helium-cooled pebble bed (HCPB) and water-cooled lead–lithium (WCLL) concepts, and for the water-cooled lead and ceramic breeder (WLCB) hybrid BB concept. The neutronic simulations were performed using the MCNP6.2 Monte Carlo code with the Joint Evaluated Fission and Fusion File (JEFF) 3.3 data library. For each BB concept, a 22.5° toroidal sector of the DEMO tokamak was developed to assess the TBR and nuclear power generation in the breeder blankets. For the geometry models with the breeder blanket space filled only with blankets without considering IVCs, the results of the TBR calculations were 1.173, 1.150 and 1.140 for the HCPB, WCLL and WLCB BB concepts, respectively. The TBR impact of all IVCs and the losses of the power generation were estimated as a superposition of the individual effects.

Keywords: DEMO; TBR; breeder blanket; Monte Carlo; MCNP

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1. Introduction

The elaboration of the breeder blanket is one of the most challenging tasks within the EUROfusion DEMO project. This activity aims to elaborate on the technological schemes and solutions that can ensure the technical feasibility of the introduced technologies. Operation of the DEMO facility with a closed tritium fuel cycle is the most basic and, at the same time, the most challenging requirement adopted in the EUROfusion project [1]. A sufficient tritium breeding capacity of the breeder blanket that ensures the functioning of the DEMO closed tritium cycle is a prerequisite for acceptance of the blanket design into the project. This implies a blanket engineering layout that can provide sufficient tritium generation to realize the closed cycle and to cover natural tritium losses due to its inherent decay. Accepted in the project is a tritium breeding ratio (TBR) that is used to assess the potential of each breeder blanket concept to generate tritium in a sufficient amount for the DEMO facility.

A DEMO tokamak configuration, i.e., the type and number of auxiliary systems and equipment, is not yet fixed in the project. These so-called in-vessel components (IVCs) include different systems for plasma heating, diagnostic equipment and special limiter blocks that control the plasma stability. With the evolution of the DEMO project, the number and configuration of these systems change. Due to this uncertainty, the exact space available in the tokamak for the breeder blankets has yet to be finalized. This results in uncertainty about the requirements that have to be applied to the blanket breeding capability in the project. A solution adopted in the DEMO project for support and continuation of the blanket development assumes a qualification of the tritium generation in the breeder blanket with a basic value, TBR_{req}, indicating the TBR required to compensate all tritium losses in the fuel cycle and also to cover tritium production losses due to the arrangement of the auxiliary systems in the tokamak that consume the space available for the breeder blankets. The TBR_{req} is determined as $TBR_{req} = TBR_{target} + \Delta TBR$, where TBR_{target} is the routine tritium production in the DEMO tokamak with all in-vessel components installed. Respectively, ΔTBR should ideally account for all uncertainties associated with the insufficient information about the tokamak layout. As a common practice, the particular blanket design includes various simplifications that negatively affect the TBR, and therefore, the ΔTBR accounts for these kinds of effects as well. $TBR_{target} = 1.05$ is accepted in the EUROfusion as a DEMO project requirement [1,2].

The aim of this work is to present an assay of the ΔTBR and nuclear power losses coming from the allocations of the currently accepted auxiliary system components. This study was conducted to account for the effects on the TBR and power production of the diverse possible cut-outs in the blankets required for the arrangement of the IVCs. The numerical simulations were carried out with fully heterogeneous geometry models of the HCPB [3], WCLL [4] and WLCB [5] blanket concepts to provide feedback for designing groups with the indication of the TBR_{req} margins and losses of the power production due to IVCs that should be demonstrated before any blanket concept can be accepted in the DEMO project.

2. DEMO Tokamak Layout

Similar to any nuclear facility, the operation of the DEMO fusion reactor is maintained and controlled by utilizing the dedicated auxiliary systems allocated in the tokamak. These systems do not contribute to the tritium production in the tokamak, and they consume space suitable for tritium breeding. These systems are designed to ensure the secure functioning of the complex fusion system by protecting the breeder blankets against plasma disruption through an arrangement of the limiters; feeding the plasma with atoms of deuterium and tritium; heating and maintaining the plasma through, for instance, neutral beam injectors and electron cyclotrons; and controlling the plasma stability through diagnostic systems arranged in cassettes. These auxiliary systems are supposed to be toroidally distributed over the tokamak to ensure the reliable operation of the facility.

The DEMO concept 2017 of the tokamak [6] includes 16 toroidal segments; each 22.5° big segment serves as an envelope to allocate a breeder blanket volume, a vacuum vessel, a divertor, an equatorial port and upper ports, toroidal magnetic field coils, poloidal field coils, a cryostat and a central solenoid [6]. For the computations, we adopted the same optional tokamak layout adopted in [2] that was suggested in the DEMO project to fulfill all DEMO system requirements. This DEMO layout, shown in Figure 1, includes the following systems:

- Four inboard mid-plane limiters (IMLs);
- A representation of diagnostic port plugs, the design of which is not yet available;
- Four outboard mid-plane limiters (OMLs);
- Eight upper-port limiters (ULs);
- Four outboard lower limiters (OLLs);
- Three neutral beam injector (NBI) systems;
- Nine electron cyclotron (EC) antennas.

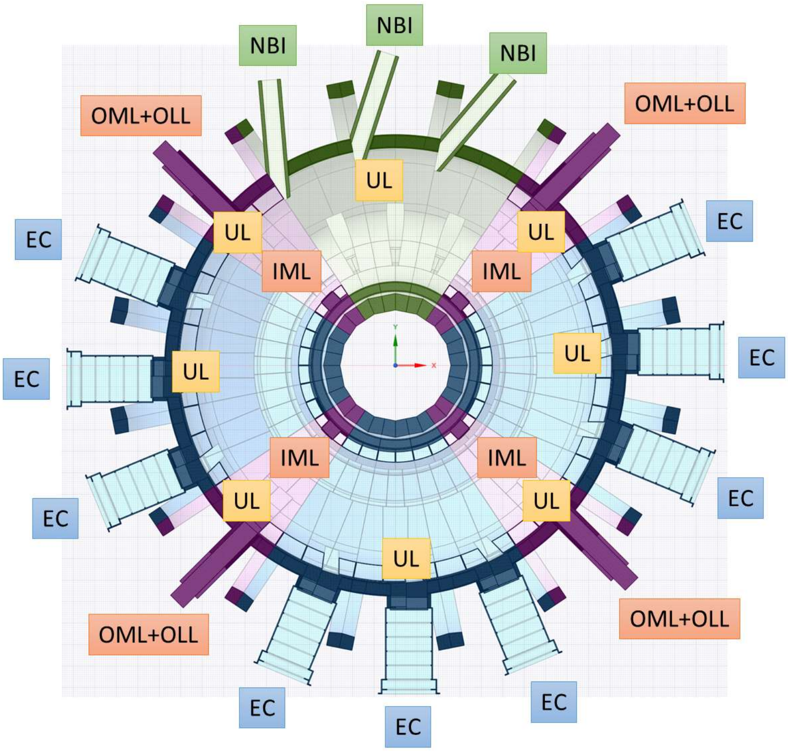


Figure 1. The scheme of the IVCs arrangement in the DEMO.

The tritium breeding performance of the DEMO primarily depends on the coverage of the space around the plasma with the breeder blankets. Any cut-out in the breeder blanket reduces the useful volume for tritium generation and, hence, complex layouts of the NBI and EC systems arranged outside the tokamak do not affect tritium breeding generation in the blankets. The DEMO tokamak schematic layout shown in Figure 1 supposes an unsymmetrical arrangement of the IVCs. Typically, an approach in the DEMO-related neutronic simulations implies modeling and utilization of one toroidal segment (for example, 22.5°), assuming a tokamak symmetry. A propagation of the results to the 360° tokamak is simulated by the introduction of reflecting boundaries in the geometry model. A logical distortion introduced with such simplification compared to the modeling based on the realistic DEMO tokamak configuration was studied in [2]. The possible effect of a neutron inter-streaming between IVCs in the realistic tokamak layout was found to be negligible. The approach adopted in this work that utilizes geometry models of 22.5° size toroidal segments with the reflecting boundaries to simulate the whole tokamak enables satisfactory global assessments of various effects. The computations were performed as follows: for each segment of 22.5° toroidal size, a separate geometry model was created according to the IVCs arrangement presented in Figure 1; the TBR_{req} was calculated based on symmetrical replications of this segment in the tokamak; the final reduction of the TBR due to the adaptation of all IVCs presented in Figure 1 was calculated as a superposition of the results obtained for separate IVCs.

3. Geometry Models with IVC

3.1. Breeder Blankets Models

3.1.1. HCPB Breeder Blanket Layout

The HCPB blanket design [3], which incorporates a Single Module Segmentation (SMS), aligns with the dimensions of the breeder blanket space outlined in the generic DEMO model described previously. Enclosed within a U-shaped FW of 25 mm thickness is the blanket, featuring a substantial 150 mm thick back supporting wall (BSW), as illustrated in Figure 2a. The inner volume of the blanket is partitioned into two segments by a separating EUROFER 97 steel wall composed of a breeder zone (BZ) and a manifold. The manifold comprises two large collectors for Helium coolant and a smaller collector positioned behind the separating wall to collect purge gas. The combination of the BSW and the gas collectors constitutes the back supporting structure (BSS) of the HCPB blanket. The BZ is composed of breeder units arranged in a hexagonal lattice, forming an arrangement of PINs. Radial central tubes of the breeder units extend into the manifold region, reinforcing the BZ. The breeder ceramic annular layer is encompassed by $Be_{12}Ti$ blocks, creating a hexagonal structure, as depicted in Figure 2a. Within the cylindrical annular volume between the central feed, a He pipe (Ø = 14 mm) and a separating pipe (Ø = 84 mm) and breeder ceramic pebbles (Li_4SiO_4 + 35% mol + Li_2TiO_3, 60% ^{6}Li enrichment) with a 64% Helium volume fraction are placed. An annular gap for the outlet He coolant is formed by pressure (outer Ø = 94 mm, inner Ø = 86 mm) and separating tubes, each with 2 mm thick walls. To enhance neutron multiplication, a $Be_{12}Ti$ annular insert (Ø = 52 mm, length = 127 mm) is strategically placed in the front part of the breeder ceramic layer, as depicted in Figure 2a. All the structural components of the HCPB blanket are constructed using EUROFER 97 steel.

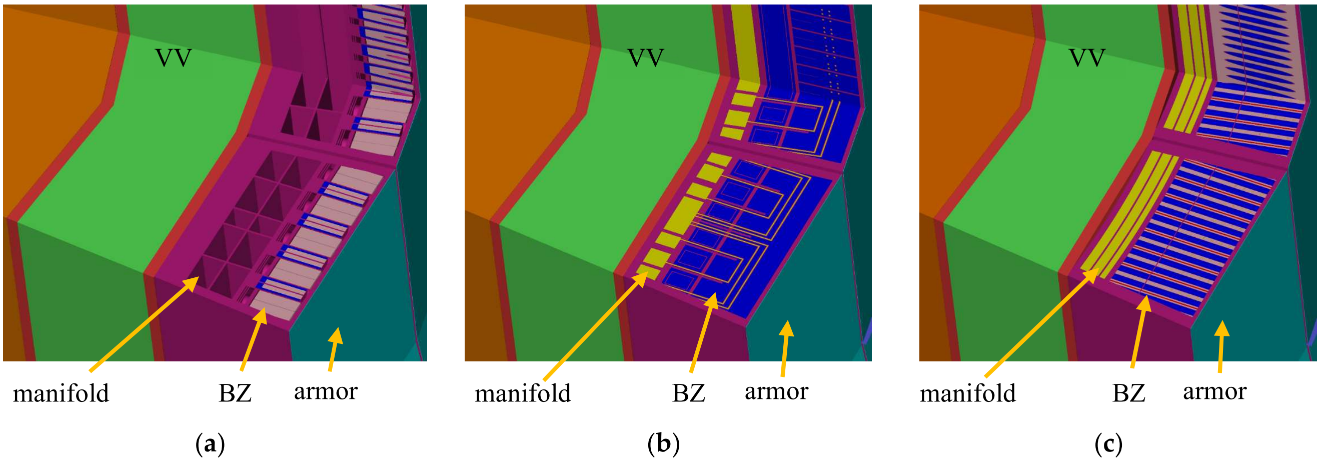


Figure 2. Horizontal and vertical 3D slice of inboard side of the HCPB (**a**), WCLL (**b**), and WCLB (**c**) DEMO geometry model.

3.1.2. WCLL Breeder Blanket Layout

The design of the WCLL [4] blanket also utilizes the SMS segmentation approach. The blanket shell consists of a U-shaped first wall of 25 mm thickness and a massive back wall of 100 mm thickness that, in this case, represents the BSS. The blanket structure is composed of poloidally repeated and radially oriented breeding elements, as shown in Figure 2b. Water coolant inlet and outlet feeding manifolds for a feeding of the first wall and breeder zone are located ahead in the plasma direction of the back supporting structure (BSS). The PbLi manifold is next to the water one. The PbLi (90% ^{6}Li) liquid eutectic in the inlet and outlet channels are separated by square-formed steel pipes. The BZ is strengthened by vertical and horizontal stiffening plates that also affect the PbLi flow. The cooling of the BZ is provided by pressurized water (15.5 MPa) with 295 °C inlet and 328 °C outlet temperatures enclosed in double-wall U-shaped tubes of 13.5/8 mm (outer/inner) size, Figure 2b. The first wall contains 7×7 mm^2 square water-cooling channels repeated with a 13.5 mm step in the vertical direction. The EUROFER 97 steel is assumed to be a structural material in the WCLL blanket.

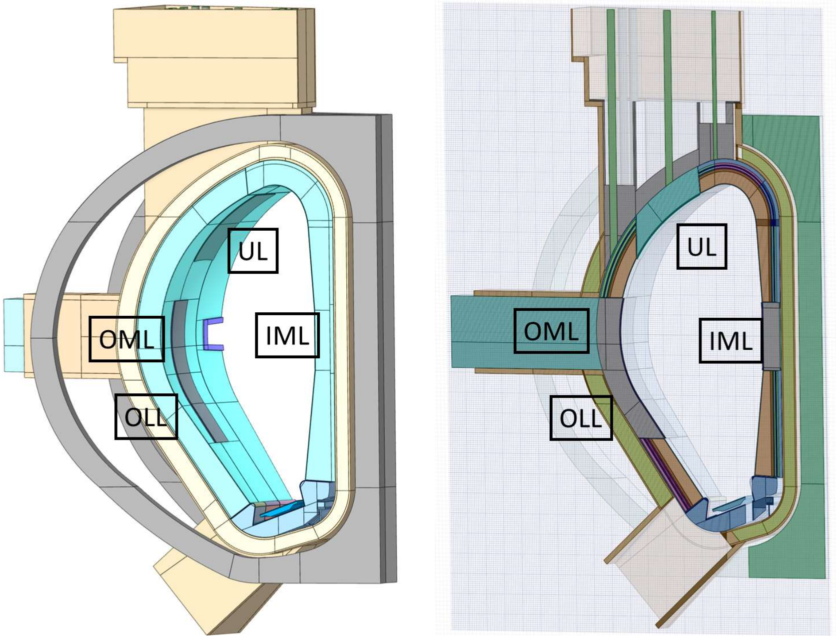
3.1.3. WCLB Breeder Blanket Layout

The WLCB concept design [5] assumes a blanket casing formed by the 25 mm thick first wall and the BSW of 50 mm thickness, as shown in Figure 2c. To ensure blanket integrity against a local coolant accident, the whole blanket structure is further reinforced: the side parts of the FW are 70 mm thick and there are vertical steel-plate connecting side walls that are 5 mm thick. To feed in the water coolant, a 180 mm thick layer is reserved for the manifold; it includes three chambers separated by steel plates. The basis of the BZ structure is a vertical unit repeated to fill the BZ space. Each unit of a 130 mm toroidal thickness includes a breeder ceramic vertical canister filled with breeder ceramic pebbles (Li_4SiO_4 + 35% mol. Li_2TiO_3), comprising a breeder volume with 64% volumetric fraction and vertical plates in a poloidal direction, as shown in Figure 2c. The ^{6}Li in lithium of the breeder ceramic is supposed to be enriched up to 90%. Two 6 mm thick cooling plates (a 4 mm water channel between 1 mm thick steel walls) are attached at both sides of the breeder canister. The space between the canisters is filled with molten lead. Circulation of the molten lead in a poloidal direction is not considered in this concept. Water pressurized at 15.5 MPa is used for the first wall and breeder-zone cooling with 295 °C inlet and 328 °C outlet temperatures.

3.2. Geometry Models with Integrated IVCs

3.2.1. Geometry Model with Integrated Limiters

The DEMO layout presented in Figure 1 assumes an arrangement of four toroidal segments, each of them including three limiters: IML, UL and OML [7,8]. The latter consists of two connected limiters: OML itself and an outboard lower limiter, OLL, as shown in Figure 3. The plasma limiters have different protrusions relative to the FW surface: 70 mm, 50 mm and 40 mm for OML, UL and IML, respectively [2]. An optional simplified structure is adopted in all limiters: plasma-facing tungsten armor of 10 mm thickness, followed by a 20 mm thick homogeneous mixture of W (39.42%), CuCrZr (18.4%), Cu (9.38%), water (32.8%) and then a 30 mm thick EUROFER 97 steel layer. Behind this complex structure, a 700 mm thick shield block and finally a 30 mm thick EUROFER 97 plate are arranged to prevent a neutron leakage. The shielding block is filled with a simplified homogeneous material composed of 70% SS316L(N) steel + 30% water. The gaps of 10 mm thickness around the limiters are reserved in the models to allow their technological radial movement. A pipe forest for the cooling water is not presented in the geometry models of the limiters because this does not affect the breeding performances of the blankets and it makes the geometry models redundantly complex [9].



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

Figure 3. Integration of the IML, UL, OML + OLL in one toroidal segment on 3D (**a**) and 2D (**b**) plot.

3.2.2. The Geometry Model with the EC Launcher

The electron cyclotron (EC) is a complex device that serves as a plasma-heating driver. The external bulky equipment of the EC has no effect on the tritium breeding processes in the blankets, and therefore only part of the EC intersecting blankets and vacuum vessel was included in the geometry models, as shown in Figure 4. The EC model adopted for the simulations includes only the massive shielding part with channels for the electron beams close to the blanket and vacuum vessel [2,8]. The size and the shape of the cutout in the blanket and vacuum vessel required for the electron beams are important for the tritium breeding. A simplified cutout was reserved for the integration of the EC in the DEMO tokamak, as shown in Figure 4a. Also shown in Figure 4 is the part of the EC introduced in the model (Figure 4a) and its integration in the DEMO toroidal sector (Figure 4b). The shape of the cut-out for the integration of the EC was made almost rectangular to avoid sophisticated necklines in the first blanket wall (Figure 4b). SS316L(N) steel was mostly used for the integrated part of the EC. Two different 22.5° toroidal segments are anticipated in the tokamak layout shown in Figure 1: a segment with EC and UL and a segment with EC only.

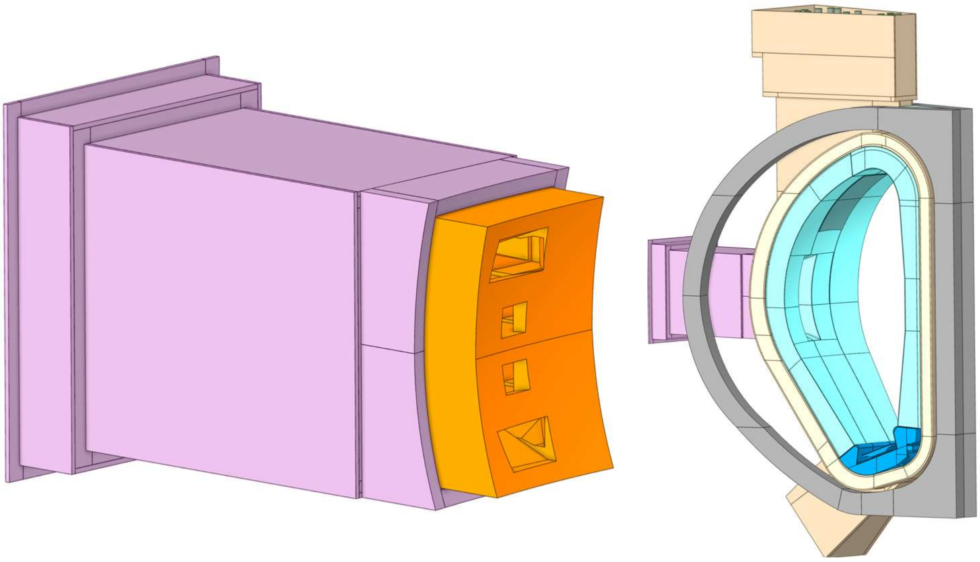

(**a**) (**b**)

Figure 4. The integration of the EC system (**a**) with DEMO toroidal segment (**b**).

3.2.3. The Geometry Model with the Integrated NBI Port

The NBI system design for the DEMO presented in Figure 5b is huge, and most of the system is far away (up to 25 m) from a plasma chamber and the breeder blankets. The tritium breeding process in the blankets is, therefore, only affected by an NBI duct penetrating the vacuum vessel and the blankets shown in purple in Figure 5b. For the present simulations, only the NBI duct was included in the geometry models (Figure 5a). The empty duct block cutting the vacuum vessel and blanket is made of SS316L(N) steel and it has walls of 20 cm thickness. Several geometry models of the 22.5° tokamak toroidal segments were developed for various combinations of the NBI duct and other IVCs (see Figure 1) [8].

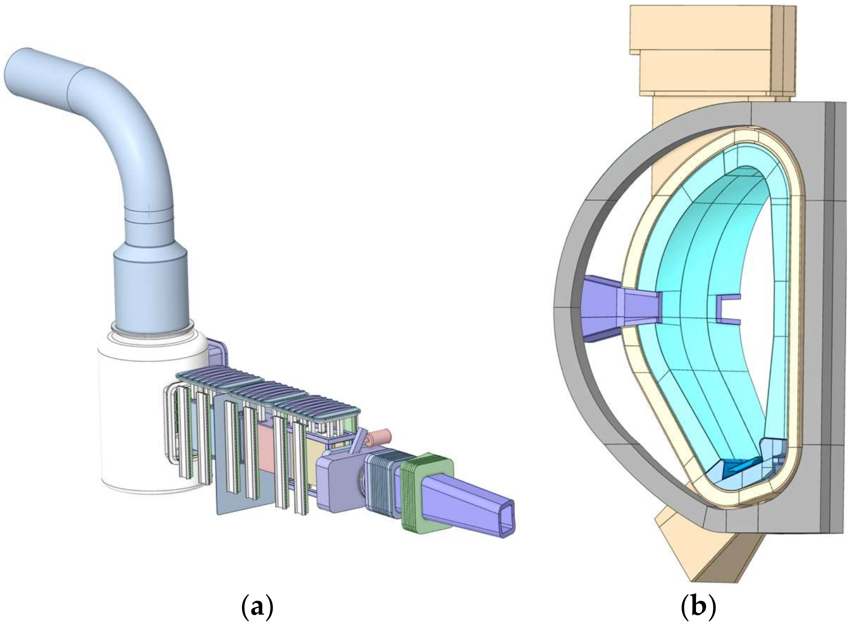


Figure 5. The NBI system (**a**) and ducts integration in the DEMO tokamak (**b**).

3.3. Geometry Models for Neutronic Simulations

The separate geometry models developed for the different toroidal DEMO segments were converted into MCNP geometry representations making use of SuperMC code [10]. The DEMO tokamak layout shown in Figure 1 assumes an arrangement of the same IVCs in different toroidal locations. This means that the geometry models for these IVCs are also identical. To facilitate the modeling process, a modular approach was implemented in all MCNP geometry models. To accommodate a specific IVC in the MCNP geometry, an empty module (envelope) was reserved that should be later filled with the geometry structure corresponding this IVC. This allows a quick development of the sequence of the MCNP geometry models for various tokamak toroidal segments without repetitions of the modeling efforts. Additionally, this method enables even small geometry changes in various envelopes without perturbing the rest of the geometry. Finally, a set of the standing alone MCNP geometry models was developed to assess individual effect to the DEMO tritium generation capacity coming from integration of the different IVCs.

Shown in Figure 6 are examples of the MCNP geometry models used for the simulations. As was mentioned above, all the MCNP geometry models of the 22.5° DEMO toroidal segments include reflecting boundaries to simulate the tokamak symmetry. The material assignments were performed in the MCNP input decks, making use of the reference data for different DEMO blanket concepts [3–5]: the VV shell of 6 cm thickness was made of the SS316L(N) steel and the VV interior volume was filled with a material mixture of 60% SS316L(N) steel and 40% water (200 °C, 3.1 MPa). The ports walls were assumed to also be made of SS316L(N) steel. All the models also include toroidal field coils that, nevertheless, have no effect on the tritium generation in the breeder blankets.

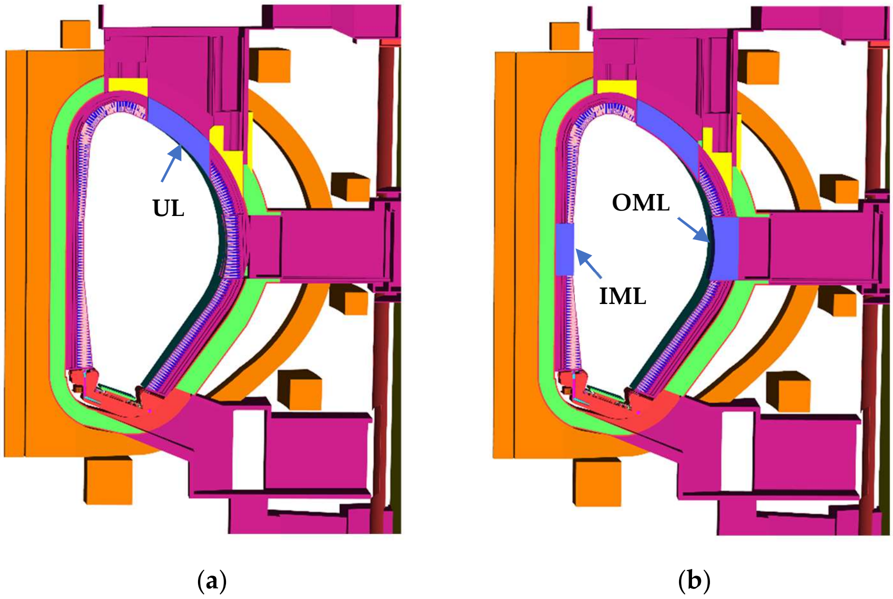


Figure 6. Cuts of the 22.5° MCNP geometry models for the HCPB DEMO: UL (**a**) and integration of IML, UL and OML without OLL (**b**).

4. Results of the Neutronic Simulations

The particle transport simulations were carried out, making use of the geometry models for different DEMO tokamak toroidal segments presented above and MCNP6.2 [11] code with nuclear data from the JEFF-3.3 library [12]. The explicit plasma neutron source description was introduced in the MCNP input deck, making use of the model developed in [13]. The statistical uncertainty of the MCNP nuclear responses for the TBR did not exceed 0.01%. For the geometry models with the breeder blanket space filled only with the blankets, the results of the TBR calculations were 1.173, 1.150 and 1.140 for the HCPB, WCLL and WLCB BB concepts, respectively.

The approach adopted in this study for the DEMO tritium breeding performance assessment in respect to the inclusion of the IVCs was to estimate a relative variation of the TBR given as a percentage. For each DEMO blanket concept, a starting point for the assessments was the tokamak configuration without any IVCs included. The calculations with the set of various DEMO toroidal segment configurations allowed us to assess the TBR reduction caused by separate IVCs arranged in the tokamak. Assuming that the effect from every IVC is independent, the global TBR reduction for the layout presented in Figure 1 was calculated as a superposition of the individual results. As was mentioned above, this approach was proven to be valid for such kinds of assessments.

The results of the simulations with different optional tokamak configurations are presented in Table 1. The results obtained in the previous study [2] with the inclusion of the breeder blankets filled with the representative homogeneous material mixture are given in Table 1 for a comparison. The effect of the detailed heterogeneous representation of the breeder blankets compared to the homogeneous one did not exceed 0.5%, and therefore the former approach can also be used to perform quick assessments of the relative TBR deviations in the DEMO tokamak. The inclusion of the various limiters in the DEMO tokamak reduced the TBR by up to ~8%. The most significant effect on the TBR reduction ~4% came from the UL. The TBR losses due to the inclusion of the IVCs in the two main breeder blanket concepts (HCPB and WCLL) considered as the driver blankets in the DEMO were similar and were assessed to be ~10.5%. The results for the alternative blanket concept (WLCB) were slightly less, at ~9.3%. The study performed in [14] assuming only equatorial port cut-outs in the blanket assessed the TBR losses in the DEMO tokamak and found that they were no greater than 8.7%.

Table 1. TBR reduction rate for single port or limiter, and entire 360° model (units: %).

	Homogeneous HCPB [2]		**Homogeneous WCLL** [2]		**Heterogeneous HCPB**		**Heterogeneous WCLL**		**Heterogeneous WLCB**	
	δTBR Single IVC	**δTBR 360° Tokamak**	**δTBR Single IVC**	**δTBR 360° Tokamak**	**δTBR Single IVC**	**δTBR 360° Tokamak**	**δTBR Single IVC**	**δTBR 360° Tokamak**	**δTBR Single IVC**	**δTBR 360° Tokamak**
EC	0.272	2.448	0.261	2.350	0.218	1.966	0.266	2.397	0.185	1.661
NBI	0.160	0.480	0.240	0.720	0.218	0.655	0.266	0.799	0.185	0.554
UL	0.612	4.896	0.499	3.990	0.517	4.135	0.440	3.522	0.503	4.022
IML	0.773	3.092	0.803	3.210	0.192	0.767	0.212	0.848	0.165	0.662
OML					0.373	1.492	0.386	1.544	0.299	1.196
OLL					0.373	1.492	0.386	1.544	0.299	1.196
Total in tokamak		**10.916**		**10.270**		**10.507**		**10.653**		**9.292**

Similarly, the reduction in the nuclear power generation in the breeder blankets due to the arrangement of the IVCs was assessed for all concepts (Table 2). The full 360° tokamak model was not developed to obtain the data presented in Table 2. Instead, the results obtained for the one toroidal segment were extrapolated to the full tokamak. Assuming that the breeder blanket volumes occupied by the cut-outs do not participate in the nuclear power generation, reductions of 6.4%, 6.16% and 5.86% were obtained for the full power production in the HCPB, WCLL and WLCB BB concepts, respectively. This could result in a 105 to 124 MW loss of power production in the DEMO with different blanket concepts [15].

Table 2. Power reduction rate for single port or limiter and entire 360° model. (units: %).

	Heterogeneous HCPB		**Heterogeneous WCLL**		**Heterogeneous WLCB**	
	δPower Single IVC	**δPower 360° Tokamak**	**δPower Single IVC**	**δPower 360° Tokamak**	**δPower Single IVC**	**δPower 360° Tokamak**
EC	0.135	1.211	0.118	1.062	0.112	1.008
NBI	0.135	0.404	0.118	0.354	0.112	0.336
UL	0.259	2.074	0.269	2.152	0.255	2.040
IML	0.187	0.748	0.151	0.604	0.160	0.640
OML	0.296	1.183	0.248	0.992	0.229	0.916
OLL	0.296	1.183	0.248	0.992	0.229	0.916
Total in tokamak		**6.40**		**6.16**		**5.86**

5. Conclusions

A complex assay of the tritium breeding capacities of the different DEMO concepts that included various IVCs in the tokamak was carried out to assess the individual effects of each IVC included in the DEMO design. To this end, a set of the MCNP geometry models of different 22.5° toroidal segment configurations was developed and dedicated MCNP simulations were performed to provide corresponding nuclear responses. All the geometry models used in the computations were developed to represent fully heterogeneous breeder blanket structures corresponding to the current status of the EUROfusion breeder blanket R&D program. Therefore, this method provided a very realistic assessment of the various effects of the DEMO tritium breeding capacity introduced in the tokamak through the arrangement of the IVCs. In spite of the optional tokamak layout, the results obtained can serve as a basis for strategic decisions about the value of the required TBR (TBR_{req}) adopted in the EUROfusion breeder blanket development program.

Compared to the reference breeder blanket models developed thus far within EUROfusion R&D work, the TBR reduction due to arrangement of the different IVCs is about 10.5% for both the HCPB and WCLL concepts and ~9.3% for the WLCB blanket.

If the TBR_{target} = 1.05 remains the hard limit in the DEMO project, only HCPB could marginally satisfy this criterion; both the WCLL and the WLCB concepts failed in this exercise. The calculations performed using the very detailed DEMO blanket models confirmed the previous suggestions to keep the TBR_{req} as high as possible, but no lower than $TBR_{req} \geq 1.17$. The previous assessment of the upper limit, $TBR_{req} = 1.15$ [14], appeared to be too low; it does not reflect a realistic tokamak layout and it could be considered as misleading in the EUROfusion DEMO project. If the TBR_{req} requirement is relaxed, i.e., the tritium supply can be provided by an industrial fission reactor, and the DEMO tritium fuel cycle is efficient and short, leading to a $TBR_{target} \approx 1.02$, all the considered breeder blanket concepts could be suitable for the DEMO project. The effect of the power losses associated with the arrangement of the IVCs up to 6.4% (or up to 124 MW) depending on the BB concepts should be also accounted for in the DEMO project. These results do not include any other assessments of the TBR_{req} uncertainty and the power production (for instance, inclusion of the uncertainty due to the nuclear data, simplifications accepted in the geometry models, etc.), and therefore its upper limit can be adjusted, respectively.

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