WPPMI-CPR(17) 17355

P. Pereslavtsev et al.

Tritium breeding performance of a DEMO based on the Double Null divertor configuration

Preprint of Paper to be submitted for publication in Proceeding of
13th International Symposium on Fusion Nuclear Technology
(ISFNT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Tritium breeding performance of a DEMO based on the Double Null divertor configuration

Pavel Pereslavtsev[a*], Ulrich Fischer[a], Lei Lu[a],
Christian Bachmann[b], Gianfranco Federici[b] and Francesco Maviglia[b]

[a]Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
[b]EUROfusion – Programme Management Unit, Boltzmannstrasse 2, 85748 Garching, Germany

Different design modifications of a Double Null (DN) DEMO were analysed by means of 3D Monte Carlo calculations using the MCNP code to assess the effect of a DN divertor configuration and various in-vessel components (IVC) on the tritium breeding performance. A simplified DN DEMO model based on the HCPB breeder blanket concept was set up to this end. A Tritium Breeding Ratio (TBR) of 1.14 was obtained with this model without taking into account any auxiliary equipment such as limiters or port plugs. The inclusion of such design modifications results in a significant reduction of the TBR from 1.14 down to ~1.00. To compensate the loss of breeder space in the reactor either the integration of breeder materials in the divertor body or the enlargement of the available breeder zone could be considered. Both of these options can provide an increase of the TBR and ensure a sufficient margin for a DN DEMO with a HCPB breeder blanket. Meeting the TBR requirement with a Pb-Li based breeder blanket concept would be more challenging and require significant changes to the overall IVC configuration.

Keywords: Double Null DEMO, neutronics, TBR, breeder blanket

---

author's email: pavel.pereslavtsev@kit.edu

1. Introduction

The development of a conceptual design for a demonstration fusion power plant (DEMO) is a key priority of the current European fusion program [1]. The use of two divertors at the bottom and the top of the Tokamak, called a magnetic double-null (DN) configuration of the DEMO, has some attractive features compared to the single-null (SN) configuration [2]. In this case several advantages can be potentially achieved: an improved vertical stability of the plasma, a reduction of the heat flux to the lower divertor target plates and a reduction of the thermal loads to the first wall of the blankets. There are however certain deficiencies of the DN configuration, namely, a significant reduction of the tritium breeding capability due to the presence of the upper divertor and likely a certain loss of the overall efficiency of the plant.

Limiters and high heat flux panels might be requried for power handling and wall protection [3]. The limiters extrude the first wall and can consume a significant space that could otherwise be covered by the breeder blanket. This results in the reduction of the tritium breeding performance of the DEMO that should be assessed. The integration of auxiliary equipment, i.e. diagnostics and heating and current drive systems is primarily planned for the equatorial ports. The dimensions of the equatorial ports can affect the breeder zone volume and therefore reduce additionally the overall tritium breeding.

In this work the tritium breeding ratio (TBR) of a DN DEMO with different in-vessel components (IVCs) was assessed by means of 3D Monte Carlo calculations using the MCNP code. The work aims at quantifying limitations for the integration of non-breeding in-vessel components and the identification of a DEMO IVC design suitable to meet the tritium breeding requirement.

2. Double null DEMO model

2.1 DN DEMO CAD model

The DN DEMO reactor was developed using a system code [2] and its geometry was defined using CATIA V5 [4]. On this basis, a 20° torus sector model was created for numerical simulations, Fig.1. The model includes the plasma chamber, an upper divertor with a dome (1) and outer upper target (2), an upper port limiter (3), a possible extension of the vacuum vessel (4), an equatorial port limiter (5), a banana-shaped space for the insertion of the breeder blankets and manifolds (6), the vacuum vessel (VV) (7), a lower divertor (8) and its dome(9), VV ports, and toroidal and poloidal magnetic field coils. The upper port limiter penetrates the central outboard blanket segment and has a cross-section of 100 x 100 cm (toroidal x poloidal) size. The equatorial port has a cross-section of 100 x 200 cm (toroidal x poloidal).

The VV has 5 cm thick SS316 steel walls and its interior is filled with a homogenized mixture of 60% SS316 steel and 40 % water. The toroidal magnetic field coils (TFC) are enclosed in a steel casing of 5 cm thickness. Both divertors are modeled as three layers facing the plasma and a cassette body. The first layer is a 5 mm thick tungsten armor [5], the second one is the 15 mm thick layer filled with a homogenized mixture of 39.5% W, 17% CuCrZr, 13.5% Cu and 30% water followed by 44 mm thick layer filled with the 60% steel plus 40% water mixture. The cassette body is modelled as 30% SS316 steel and 70% water homogeneous mixture. The main DN DEMO parameters are given in the Table 1 [4].

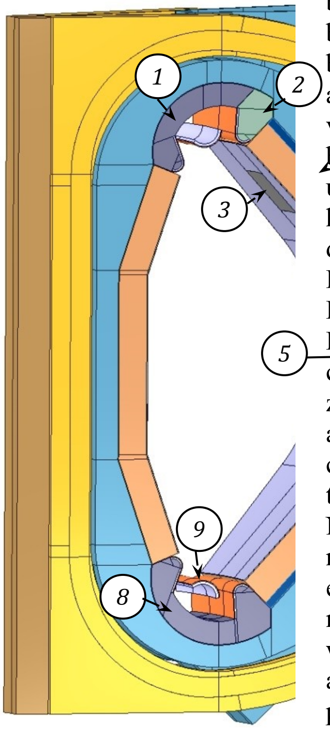

Fig. 1. 20° poloidal segment of the DN DEMO CAD model.

Table 2. Main parameters of the DN DEMO reactor.

Major radius, (m)	
Minor radius, (m)	
Plasma elongation	
Plasma triangularity	
Fusion power, (MW)	20
Net electric power, (MW)	5

2.2 DN DEMO model for neutronic simulations

The DN DEMO CAD model was converted into the MCNP geometry model using the McCad conversion tool [6]. The generation of the final DEMO geometry model suitable for the neutronic analyses was performed already on the MCNP platform. To this end the breeder blanket zone, Fig. 1, was modified to simulate a simplified DEMO blanket configuration. A 2 mm thick tungsten protecting layer and 25 mm thick first wall (FW) were introduced in the breeder blanket zone. The breeder zone (BZ) of the blanket was approximated by a single volume defined by the breeder module walls and uniformly filled with a homogeneous mixture derived from the specific DEMO blanket design: HCPB, WCLL, HCLL or DCLL. The corresponding breeder zone radial thicknesses and material compositions are given in the Tables 2 and 3 [7]. Note that such a model neglects heterogeneity effects and non-uniform material distributions which can significantly affect the TBR prediction. Thus only trends can be obtained.

In case of the HCPB DEMO the ^{6}Li

enrichment in lithium was 60%, in other concepts the ^{6}Li enrichment was assumed to be 90%. The breeder blanket zone was followed by a back plate of 30 mm thick for all concepts. The back supporting structure (BSS) or manifold was modelled also as a homogeneous mixture with the material composition given in the Table 3.

Table 2. The main geometry parameters of the breeder blankets in different DEMO concepts [7].

	HCPB	WCLL
BZ: IB/OB	23/52	47/80
BSS: IB/OB	58/70	26/45

Table 3. Homogenized material compositions (% vol.) derived for the different DEMO blanket concepts [7].

HCPB DEMO			
	Armour (2mm)	**FW (t=25mm)**	**Breeder module**
Eurofer		60.5	11
Be			37
Li_4SiO_4			13
Tungsten	100	0	
Void		39.5	8,
Void		0	28
HCLL DEMO			
	Armour (2mm)	**FW (t=25mm)**	**Breeder module**
Eurofer		70	13
Water			
PbLi			78
Tungsten	100		
Void		30	8
WCLL DEMO			
	Armour (2mm)	**FW (21mm)**	**Breeder module**
Eurofer		89,5	18
Water		10,5	1,
PbLi			80
Tungsten	100	0	
Void			
DCLL DEMO			
	Armour (2mm)	**FW (t=25mm)**	**Breeder module**
Eurofer		76	12
Water			
PbLi			73
Tungsten	100		
Void		24	15

3. Results of the neutronic simulations

The neutronics analyses comprised the assessment of the tritium breeding ratio (TBR) of the newly developed DN DEMO reactor. The calculations were carried out making use of the geometry model discussed above and the MCNP5-1.60 code [8] with nuclear data from the JEFF-3.2 library [9]. The toroidal fusion neutron plasma source was simulated making use of the specially developed source subroutine [10] linked to the MCNP executable. The results of the TBR calculations have a statistics that usually do not exceed <0.1%.

The majority of the simulations were performed with the homogeneous HCPB breeder mixture filled in the BZ. As a starting or "*basic configuration*" the following HCPB BZ radial thicknesses were applied: inboard (IB) side – 23 cm, outboard (OB) side – 52 cm [11]. The upper port limiter and equatorial port plug were replaced with the HCPB breeder zone mixture. No other modifications or IVCs were modeled. The MCNP geometry model used for the simulations is shown in the Fig. 2. The TBR for the HCPB DN DEMO model in the basic configuration was found to be TBR=1.14.

3.1. Pseudo SN configuration

The "pseudo" SN HCPB DEMO model was obtained by removing the upper divertor and replacing it with the extended IB and OB breeder zone. In this case the TBR increased to 1.24. The arrangement of the upper divertor in the DEMO, i.e. the transition from the SN to the DN configuration, leads to a significant reduction of the TBR: ΔTBR=-0.10.

Additional investigations were performed to assess the maximum TBR that can be reached in this pseudo SN configuration with homogenized breeder mixtures according to the different DEMO blanket concepts. To this end the BZ radial thickness in the outboard side of the HCPB DEMO was extended up to 80 cm. The maximum radial thickness of the BZ was estimated from the radial profiles calculated for the cumulative tritium production at the outboard side of the homogeneous HCPB and WCLL DEMO models, Fig. 2. The saturation in case of the HCPB DEMO configuration was achieved at a ~70 cm thick BZ. In case of the WCLL DEMO the saturation was found at a ~80 cm thick BZ. For the HCLL and DCLL SN concepts the same maximum breeder zone depth as for the WCLL reactor was assumed in the subsequent calculations. To get the maximum TBR, the radial thickness of the BZ was set at the same value inboard and outboard. The radial dimensions of the BSS were adjusted accordingly to keep its radial size not less than 30 cm. The TBR in case of the HCLL, WCLL and DCLL DEMO models was calculated as a sum of the tritium production in the BZ and the BSS, Table 4. The TBR results differ significantly from the reference ones obtained for the actual blanket designs [11-14] due to the assumed homogeneous and uniformly distributed breeder materials, no poloidal and toroidal gaps applied and very thick BZ in the IB side compared to the reference designs.

Table 4. The maximum TBRs for different DN DEMO blanket concepts in the pseudo SN configuration compared to the reference designs [11-14].

DN DEMO concept	TBR SN
HCPB	1.36
WCLL	1.24
HCLL	1.27
DCLL	1.27

3.2. Impact of the different IVCs on the TBR

In the following the modifications introduced sequentially in the DN DEMO design are discussed and a particular effect is assessed with the respect to the basic configuration as indicated in Fig. 3. These calculations were performed with the homogeneous HCPB breeder blanket mixture in the DN DEMO model.

The extension of the vacuum vessel towards plasma in the upper and lower part of the reactor (1) could serve as an additional option to increase the passive plasma vertical stability. Such extension results in a reduction of the BZ because the radial thickness of the BSS is assumed constant. The reduction of the TBR in this configuration relative to the basic configuration is ΔTBR=-0.03.

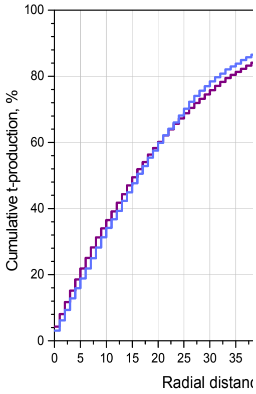

Fig. 2. Radial profiles of the cumulative tritium production in the BZs filled with homogeneous WCLL and HCPB breeder mixtures.

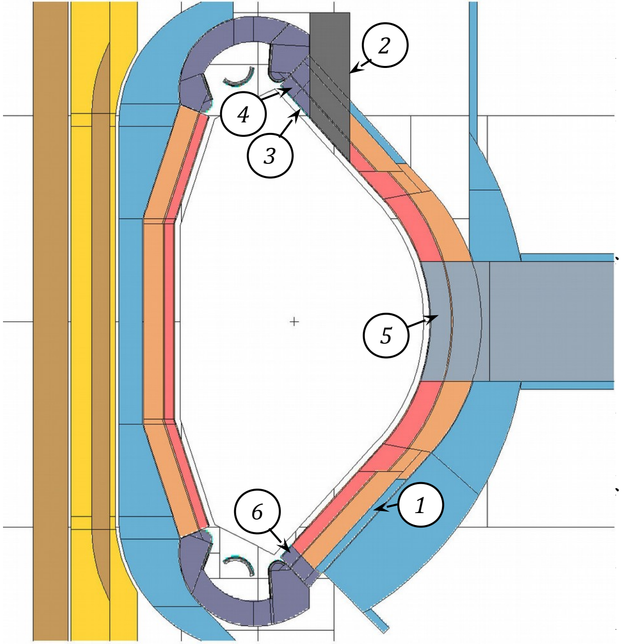

Fig. 3. A vertical cut of the DN HCPB MCNP model with integrated IVCs.

The effect of the port limiters was investigated using a geometry model shown in the Fig. 2. In this option 9 upper port limiters (2) were considered and the space between these limiters and the upper divertor was not considered to contribute to the tritium breeding. Both effects were assessed separately. The loss of the TBR due to the integration of the 9 upper port limiters results in the ΔTBR=-0.02. A replacement of the triangular piece in the vicinity of the limiter (3) with the steel-water mixture gives additional reduction ΔTBR=-0.01 in case of 9 limiters. These triangular parts are supposed to be implemented only several times in the torus depending on the number of limiters. The extensions of the upper (4) and lower divertors (6) by 40 cm in poloidal direction are assumed to be applied in the whole reactor. For the equatorial port two relative to the basic configuration was found to be ΔTBR=-0.13. The data shown in bold in the Table 3 are included in this result. For this DN HCPB DEMO configuration the resulting tritium breeding performance is TBR=1.01.

Table 5. Breakdown of the TBR losses calculated for the DN HCPB DEMO model due to inclusion of different IVCs.

Element of the design
Upper limiters -18
Triangular piece
Extension of the divertor cassette -upper -lower
18 equatorial ports -1x2 m -1x3 m
Extension of the vacuum vessel

For the DN DEMO configuration discussed above the assessment of the TBR was also performed for other breeder blanket compositions making use of the data given in the Tables 2 and 3. The results of the TBR calculations are presented in Table 6. The TBR requirement for DEMO including all non-breeding IVCs is TBR=1.05 for a heterogeneous representation of the blanket according to the engineering design [15]. The TBR results for the other breeder blanket mixtures in the DN DEMO model are lower than for the HCPB.

To compensate the loss of the breeder space in the reactor either the arrangement of breeder materials in the divertor bodies or the enlargement of the available breeder zone could be considered. Both of these options can provide a significant increase of the TBR and ensure a sufficient margin to the design goal of TBR=1.05 for the DN DEMO.

The simulation of the tritium breeding in the divertors was performed with DN DEMO model for two breeder blanket material mixtures corresponding to the HCPB and the WCLL design. To this end the breeder zone was arranged in both divertors behind the 3 protecting layers described above. The inboard BZ radial thickness was implemented in the model. In this case an increase of the tritium breeding was found for both concepts: ΔTBR=0.05 and 0.04 for the HCPB and the WCLL mixtures, respectively. Such modifications would result in a TBR=1.06 for the HCPB and TBR=1.00 for the WCLL DN DEMO model.

Table 6. The TBR for the DN DEMO model with different breeder blanket material mixtures and the inclusion of auxiliary *IVCs.*

DN DEMO concept	
HCPB	
WCLL	
HCLL	
DCLL	

The model used in the simulations assumes an arrangement of domes (9) in front of the divertors, Fig. 1. The removal of the domes that shield the divertor cassettes would enhance the tritium generation. In this case the gain of the total TBR in the HCPB and the WCLL DN DEMO models can reach ΔTBR=~0.01.

3.3. Modification of the breeder zone radial thickness.

An additional option that can increase the TBR is a conservative enlargement of the breeder zone radial depth. This option could be reasonably applied if the tritium generation along the radial coordinate in the breeder zone is not saturated for the accepted blanket dimensions (Table 2). The tritium generation in the BZ based on the use of liquid PbLi metal indicates a saturation at ~80 cm radial distance from the FW, Fig.2. Therefore an increase of the BZ in the outboard side does not give a significant effect to the TBR. The increase of the radial build of the tokamak can provide an additional gain of the TBR in the inboard side. In case of the HCPB the breeder zone can be more extended to reach the TBR saturation. An additional study was performed to assess the effect of increasing the HCPB breeder zone as compared to the basic DN configuration. Shown in the Fig. 4 are the changes of the TBR due to the variation of the breeder zone radial dimension.

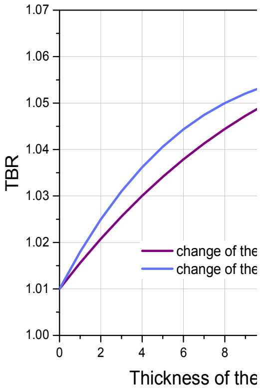

Fig. 4. Effect on the TBR of the HCPB breeder zones (IB and OB) radial extension with respect to the BZ thickness in the basic configuration (IB: 23cm, OB: 52cm)

The effect of the BZ enlargement was investigated separately for inboard and outboard sides of the HCPB DEMO. The increase of the breeder zone depth by +17 cm increases the ΔTBR=+0.05 both in the IB and OB sides respectively. The strong effect found for the IB side of the HCPB DEMO results from the small radial thickness of the IB breeder zone: 23 cm compared to the 52 cm at the OB side. In this case the effect of the BZ radial extension is ~2%/cm of the total TBR in the BZ and it is much stronger compared to the ~0.5%/cm at the OB side. With such modification the total gain was found to be ΔTBR=+0.10. Assuming the lowest TBR=1.01 obtained for the HCPB DN DEMO model (Table 6), this option can achieve a TBR=1.11, the breeding in the divertors being not included. In case of the option with the tritium breeding in the divertors of the HCPB DEMO the TBR could reach TBR=1.16.

4. Conclusion

Different IVC configurations of a DEMO with double-null (DN) divertor configuration were assessed with respect to the tritium breeding performance. To this end a simplified 3D MCNP model suitable for parametric studies was developed. The breeder zone (BZ) of the blankets was modelled as a single volume filled with a homogenized material mixture according to the four different breeder blanket concepts. The inclusion of the upper divertor in the reactor design (DN configuration) results in a significant loss of the total tritium production by ~8% due to the replacement of the breeder zone with the non-breeding divertor structure. For a simplified DN DEMO configuration based on the HCPB blanket concept a TBR of 1.14 was found without inclusion of any auxiliary equipment such as limiters or port plugs. The introduction in this DN configuration of 9 upper port limiters and 18 equatorial port plugs for auxiliary systems led to the significant reduction of the tritium breeding to TBR=1.01. This indicates the need for further design modifications to compensate the loss of the breeder space in the reactor in particular given that the HCPB concept has a superior breeding performance as compared to LiPb-based concepts. Such modifications could be either the arrangement of the breeder materials in divertor cassettes or the enlargement of the blanket BZ. Both options were studied on the basis of the DN HCPB DEMO and significant increases of the TBR were predicted: ΔTBR=+0.05 for the former option with breeder materials in both divertors, and ΔTBR=+0.10 for the latter one. The extension of the BZ radial depth in the outboard side does not provide significant gain for the PbLi based blankets because its dimensions had been chosen to be close to those showing saturation of the TBR. Some increase of the TBR can be achieved by the extension of the BZ in the inboard side. This option nevertheless requires a change of the machine radial build.

Meeting the TBR requirement in a DN DEMO with an HCLL, WCLL, or DCLL breeding blanket seems challenging and would certainly require more significant changes to the overall configuration of the IVCs.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This work was performed on the computational resource For HLR II funded by the Ministry of Science, Research and the Arts Baden-Württemberg and DFG ("Deutsche Forschungsgemeinschaft ").

References

[1] G. Federici et al., Overview of EU DEMO design activities, Fusion Engineering and Design, v. 89, Issues 7-8 (2014) 882-889.

[2] R. Wenninger et al, Power Handling and Plasma Protection Aspects that a affect the Design of the DEMO Divertor and First Wall, 26th IAEA Fusion Energy

Conference - IAEA CN-234, 2017

[3] F. Maviglia et al, Effect of engineering constraints on charged particle wall heat loads in DEMO, this conference.

[4] C. Gliss, https://idm.euro-fusion.org/?uid=2MTF89

[5] R. Villari, G. Mariano, G. Mazzone, Neutronic Analysis Report for Divertor Cassette and PFC 2015, EFDA_D_2MGK4L

[6] L. Lu, U. Fischer, P. Pereslavtsev, Improved algorithms and advanced features of CAD to MC conversion tool McCad, Fus. Eng. Design, v. 89, Issue 9-10, (2014) 1885

[7] A. Spagnuolo, Blanket Material Composition for Neutronics, https://idm.euro-fusion.org/?uid=2MU2ZL

[8] X-5 Monte Carlo Team, MCNP - A General Monte Carlo N-Particle Transport Code Overview and Theory (Version 5, Vol. I), Los Alamos National Laboratory, Report LA-UR-03-1987, 24 April 2003

[9] "JEFF-3.2", http://www.oecd-nea.org/dbdata/jeff, 2014

[10] C. Fausser et al., Tokamak D-T neutron source models for different plasma physics confinement modes, Fusion Engineering and Design 87 (2012)787-792.

[11] P. Pereslavtsev, U. Fischer, F. Hernandez, L. Lu, Neutronic analyses for the optimization of the advanced HCPB breeder blanket design for DEMO, Fusion Engineering and Design, 2017, in press

[12] Jean-Charles, Jaboulay, Giacomo Aiello, Julien Aubert, Alexandro Morin, Marc Troisne, Nuclear analysis of the HCLL blanket for the European DEMO, Fusion Engineering and Design, 2017, in press

[13] A. Del Nevo et al., WCLL breeding blanket design and integration for DEMO 2015: status and perspectives, Fusion Engineering and Design, 2017, in press

[14] Iole Palermo, David Rapisarda, Ivan Fernandez-Berceruelo and Angel Ibarra, Optimization process for the design of the DCLL blanket for the European DEMOnstration fusion reactor according to its nuclear performances, Nucl. Fusion 57 (2017) 076011

[15] U. Fischer, Ch. Bachmann, I. Palermo, P. Pereslavtsev, R. Villari, Neutronics requirements for a DEMO fusion power plant, Fus. Eng. Design, v. 98-99 (2015) 2134