Effect on the Tritium Breeding Ratio for a distributed ICRF antenna in a DEMO reactor

A. Garcia[1, 2, 3, 4 a)] J-M Noterdaeme[1, 4] U. Fischer[2] J. Dies[3]

[1]*Max-Planck-Institut für Plasmaphysik (IPP), Garching, Germany*
[2]*Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*
[3]*Polytechnic University of Catalonia (UPC), Barcelona, Spain*
[4]*Department of Applied Physics, Ghent University, Ghent, Belgium*

[a)]albert.garcia.hp@gmail.com

Abstract. The paper reports results of MCNP-5 calculations to assess the effect on the Tritium Breeding Ratio (TBR) when integrating a distributed Ion Cyclotron Range of Frequencies (ICRF) antenna in the blanket of DEMO fusion power reactor. The calculations consider different parameters such as the ICRF covering ratio and the type of breeding blanket including the Helium Cooled Pebble Bed (HCPB) and the Helium Cooled Lithium Lead (HCLL) concepts. For an antenna with a full toroidal circumference of 360°, located poloidally at 40° with a poloidal extension of 1 m, the reduction of the TBR is -0.349% for the HCPB blanket and -0.532% for the HCLL blanket. The distributed ICRF antenna is thus shown to have only a marginal effect on the TBR of the DEMO reactor.

INTRODUCTION

A DEMO fusion power reactor [1] must be self-sufficient in the tritium supply. Hence, a net Tritium Breeding Ratio (TBR) greater than one is essential. Some margin is required to account tritium losses and uncertainties, thus typical design targets set the global TBR required in the range of 1.05 to 1.15 [2]. The integration of diagnostics, plasma heating components, etc. deteriorates the TBR due to the required replacement of breeder blanket parts by non-breeding materials or volumes. Recently, a new concept for the Ion Cyclotron Range of Frequencies (ICRF) antenna integrated within the blanket has been proposed [3] (see Fig. 1). In the ICRF point of view the antenna presents large advantages (low power density, no use of equatorial ports, better definition of the k-spectrum), but the impact on the TBR is less evident. It uses a large surface but, in contrast to a big port opening, it does not require a high volume at expenses of the blanket breeder. The biasing on the TBR is due to the combination of three effects:

1. Parasitic absorption of neutrons in the antenna
2. Moderation of neutrons affecting the neutron spectrum
3. A reduction of the total breeding blanket volume

The objective of this paper is to quantify this loss of TBR and thus to check if such an antenna is compliant with the TBR requirements of DEMO. The assessment has been performed for the European DEMO power reactor employing two types of breeder blanket concepts, the Helium Cooled Pebble Bed (HCPB) and the Helium Cooled Lithium Lead (HCLL) [4]). The calculations were done at KIT (Karlsruhe Institute of Technology) using the Monte Carlo N-Particle code MCNP, version 5 [5], and nuclear cross-section data from the Fusion Evaluated Nuclear Data Library (FENDL-2.1) [6].

Some design changes were considered to study their effect on the calculated TBR. In addition to the employed breeding blanket concepts which strongly affect the TBR, the covering ratio of the straps of the antenna has been varied to estimate the loss of TBR if the preliminary configuration of the antenna changes.

BLANKET

The European fusion technology programme considers two blanket development lines, the HCPB blanket with Lithium ceramics pebbles as breeder material and beryllium pebbles as neutron multiplier, and the HCLL blanket with the Pb-Li eutectic alloy acting both as breeder and neutron multiplier [7]. Both of them are considered in this paper.

The DEMO-tokamak is divided into 22.5° sectors (16 in total). For the in-vessel components (First Wall, Blanket and Manifold) each sector is composed by 2 inboard and 3 outboard segments [3]. The outboard segments consist of a Central Outboard Blanket Segment (COBS) between the toroidal field coils, a Right and a Left Outboard Blanket Segments (ROBS and LOBS respectively) each partly under a toroidal field coil. Both outboard and inboard segments contain 6 modules. Figure 1 shows the corresponding CAD model, requiring only 11.25º due to symmetry, into which the ICRF antenna has been integrated.

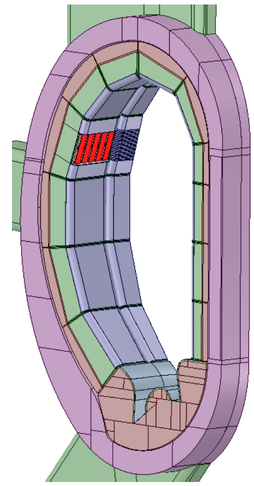


FIGURE 1. DEMO torus sector model with blanket modules and distributed antenna integrated (Faraday screen partially removed)

The model includes only the in-vessel components (breeding blanket modules with manifolds and shields, the vacuum vessel, the divertor and the ports). The First Wall of the blanket modules consist of 2mm tungsten followed by 25 mm cooled Eurofer. The breeding material consist of a homogeneous composition of 57% Beryllium (neutron multiplier) + 19% Li_4SiO_4 (ceramic breeder with ^{6}Li enriched up to at. 60%) + 15% EUROFER (cooling plates and stiffening grid) + 9% He (coolant). Behind the breeding zone a cooled Eurofer mixture is used for both the backplates of the blanket and the manifold. The model has been developed at KIT in the frame of the Power Plant Physics and Technology Programme (PPPT) under EFDA [8] but takes into account a recent update conducted in 2014 with the EUROfusion PPPT programme.

DISTRIBUTED ANTENNA

While the detailed configuration of the antenna is still being defined, the following assumptions were made to calculate the effect on the TBR.

The antenna is a toroidal 360° ring array of straps embedded in a poloidal module of the blanket and with its Faraday screen flush with the First Wall (FW). The straps will be placed inside a slot in the module as can be seen in Fig. 1 and Fig. 2. The slot measures 100 cm poloidally and 20 cm deep. Inside, the ring array of 20 cm-width straps is located (toroidal direction) with a separation by 6 cm between straps, and the thickness of the straps is 2 cm [9]. As can be seen in Fig. 2 the antenna is not filling all the space in the slot.

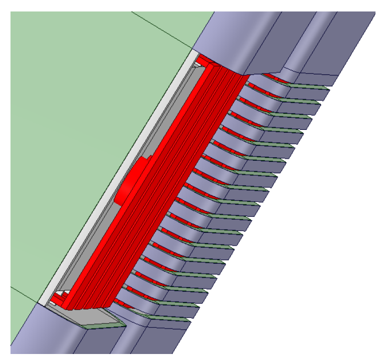


FIGURE 2. Antenna (Faraday Screen partially removed

For the material of the antenna, the same material is used as for stiffening the blanket (Eurofer). Alternatively, due to its position near the plasma, tungsten may be required, although the presence of a Faraday screen may alleviate this. For the time being the feeding lines through the blanket have been neglected. For the Faraday screen the same material as the FW has been used (2 mm of tungsten and 25 mm of He-cooled Eurofer). Tentative poloidal dimensions of the Faraday screen were chosen to be 4.2 cm of FW alternating with 1.5 cm of open space. In Fig. 1 the antenna integrated in the blanket can be seen, with the Left Outboard Blanket Segment (LOBS) and half of the Central Outboard Blanket Segment (COBS) shown. In the COBS the Faraday screen has been removed for a more illustrative picture.

CALCULATIONS

As noted above, the DEMO model developed at KIT for the HCPB blanket was used as basis model. The CAD model of the ICRF antenna was integrated into this model using the SpaceClaim software [10]. The resulting CAD geometry model was then converted into MCNP geometry using KIT's McCad interface [11]. Accounting for the symmetry of a DEMO reactor a 11.25° torus sector was used for the calculations, which were carried out using the MCNP-5 code and the FENDL-2.1 nuclear data library. The track length estimator was used to calculate the TBR. Typically 100 million neutron source histories were tracked in a MCNP run to get sufficient statistics.

Table 1 shows the neutron balance and the effect on the TBR of the considered cases. Although the antenna takes up 360° around the torus, the breeding volume removed is small, so it is the loss of TBR.

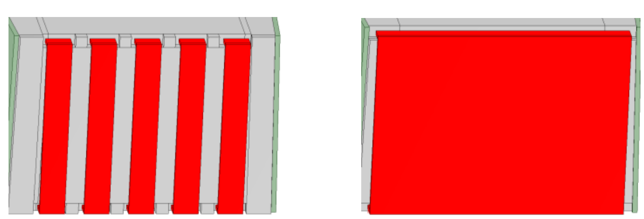
TABLE 1. Results of the MCNP-5 calculations for a DEMO with HCPB blanket

	Without antenna	**With antenna**	**Variation (%)**
Breeding volume per blanket segment (m^3)	23.890	23.638	-1.055%
Net multiplication	1.613	1.609	-0.248%
Total capture (per source neutron)	1.609	1.605	-0.249%
Capture in breeding material (per source neutron)	1.321	1.316	-0.379%
Tritium Breeding Ratio	1.145	1.141	-0.349%

As one can see from the table, the effect of the antenna on the neutron multiplication and the TBR is only marginal. This is mainly due to the fact that the breeder volume is not reduced very much. With the assumed HCPB breeder blanket, the relative reduction of the TBR is lower than the reduced breeding volume. With such low impact on the TBR, together with the fact that the antenna does not need to be placed in a port, it enhances the attractiveness of the ICRF and makes possible to combine ICRF with other heating methods or diagnostics that do use the equatorial ports. An interesting comparison for these results is with an equivalent void opening in the equatorial port. Taking 16 ports with 1 m x 2 m openings (32 m^2 in total) the loss of TBR in an HCBP blanket is 10% [2]. The effect of the complete ICRF antenna (total area of ~67 m^2) is thus equivalent to a single void opening of 1.40 m^2 in the equatorial port.

In another calculation the covering ratio of the straps has been changed. The covering ratio of the straps is defined as the ratio between the surface of all the straps and the projected surface of the antenna slot. The covering ratio of the antenna studied is ~72%. Due to the U-shape of the FW, the maximum covering ratio with the current antenna-shape is ~94% (see Fig. 3-a). A third calculation with a ~49% covering ratio is done to complement the sensitivity analysis (see Fig. 3-b). Results are shown in Table 2. These results reveal that the covering ratio strongly affects the loss of TBR, but even in the worst case (94% covering ratio) the loss remains low with -0.437%.

In another calculation series, the HCPB blanket composition in the blanket modules has been replaced by a HCLL type mixture to study the antenna effect on the TBR for such a blanket mixture with different neutronics characteristics. Table 3 shows the neutron balance for this case. It is revealed that the effect for the HCLL mixture, with -0.532%, is greater than for the HCPB (-0.349%), but it is still low. This was actually expected since the use of the HCLL mixture results in a faster neutron spectrum and thus, as opposed to the HCPB mixture, results in an enhanced neutron out-scattering losses from the breeder and increased parasitic absorptions in the structure including the antenna.



(a) (b)

FIGURE 3. Covering ratio of the antenna straps: 49% (a) and 94% (b)

TABLE 2. Results for sensitivity analysis on the covering ratio of the antenna (DEMO HCPB)

	-	49% Covering Ratio		72% Covering Ratio		94% Covering Ratio	
	Without antenna	**With antenna**	**Variation**	**With antenna**	**Variation**	**With antenna**	**Variation**
Breeding volume per blanket segment (m^3)	23.890	23.641	-1.042%	23.638	-1.055%	23.637	-1.059%
Tritium Breeding Ratio	1.145	1.143	-0.175%	1.141	-0.349%	1.140	-0.437%

TABLE 3. Variation between the reactor with and without the antenna implemented for HCPB and HCLL blanket concepts

	HCPB	HCLL
Breeding volume per blanket segment (m^3)	-1.055%	-1.055%
Tritium Breeding Ratio	-0.349%	-0.532%

CONCLUSIONS

A quantification of the loss of TBR for a distributed antenna in a DEMO reactor has been performed in this paper based on Monte Carlo calculations. The ICRF distributed antenna was shown to have only a small effect on the tritium breeding performance of DEMO. For a DEMO with HCPB blanket, there is only a reduction 0.349% of the TBR. The TBR reduction strongly depends on the covering ratio of the antenna, but is always below 0.437%. The reduction is bigger for the HCLL blanket concept (0.532%) than for the HCPB (0.349%). The latter corresponds to an equivalent port opening on the equatorial plane of 1.4 m^2.

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.

REFERENCES

1. G. Federici, R. Kemp, D. Ward. C. Bachmann, T. Franke et al, *Overview of EU DEMO design activities*, Fus. Eng. Des. 89(2014), 882-889
2. U. Fischer, *Neutronics Requirements for a DEMO Fusion Power Plant, Fusion Eng. Design (2015)*-DOI: 10.1016/j.fusengdes.2015.02.029
3. G. Bosia, "*Low power density Ion Cyclotron Arrays for Fusion Reactors*" Fusion Engineering and Design, 92(2015), 8-15
4. U. Fischer, *Neutronics R&D Efforts in Support of the European Breeder Blanket Development Programme-DOI: 10.1088/0029-5515/49/6/065009*
5. X-5 Monte Carlo Team, MCNP-A General Monte Carlo N-Particle Transport Code (Version 5, Vol. I), Report LA-UR-03-1987, 24 April 2003 (Revised 10/3/05).
6. D.L. Aldama, A. Trkov, FENDL-2.1: update of an evaluated nuclear data library for fusion applications, Report INDC(NDS)-467, December 2004.
7. L.V. Boccaccini, *Design And Development of Demo Blanket Concepts in Europe*, 1st IAEA DEMO Programme Workshop, UCLA, 15-18 Oct. 2012
8. P. Pereslavtsev, et al., Neutronic analyses of the HCPB DEMO reactor using a consistent integral approach, Fusion Eng. Des. (2014), http://dx.doi.org/10.1016/j.fusengdes.2013.12.019
9. Ricardo Ragona, ERM/KMS Brussels, personal communication (2015)
10. 3D Modeling Software for Engineering SpaceClaim, http://www.spaceclaim.com
11. L. Lu, U. Fischer, P. Pereslavtsev, Improved Algorithm and Advanced Features for the CAD to MC Conversion Tool McCad, Fusion Eng. and Design 89(2014), 1885–1888.