Neutronics Investigations for Helical DEMO Reactor FFHR-d1*)

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(Received 12 December 2011 / Accepted 30 May 2012)

Radiation shielding and tritium breeding performances of the helical DEMO reactor FFHR-d1 have been investigated for the present proposed reactor component configuration. Since the core plasma position shifts to inboard side of the torus, the total thickness of the inboard breeding blanket and radiation shield of FFHR-d1 is limited to ~70 cm. To simulate the geometric features of the helical reactor, three-dimensional neutronics calculation model consisted of ~4,000 cells have been prepared for the neutron and gamma-ray transport calculations using the MCNP code. It has been confirmed that the present radiation shield configuration with WC (tungsten carbide) and FS (ferritic steel) + B_4C layers would provide sufficient shielding performance for the helical coils. The tritium breeding ratio (TBR) of 1.08 has been obtained with a Flibe+Be/FS breeding blanket for the present component configuration of FFHR-d1.

Keywords: helical reactor, DEMO, FFHR-d1, neutronics, tritium breeding ratio, radiation shield

DOI: 10.1585/pfr.7.2405132

1. Inroduction

The conceptual design activity for the helical DEMO reactor FFHR-d1 has been conducted aiming for an early realization and demonstration of a helical type power reactor [1]. The reactor component configurations and plasma parameters in the FFHR-d1 design are especially based on extrapolations from those of the present Large Helical Devise (LHD) in National Institute for Fusion Science.

From the neutronics point of view, the minimum blanket space for achievement of sufficient radiation shielding and tritium breeding performances is one of key parameters in the first step of the reactor design. Since the core plasma position in FFHR-d1 shifts to the inboard side of the torus as in LHD [2], the blanket space must be smallest at the inboard side. On the other hand, the blanket space at the outboard side could be significantly thick. This condition is considerably different from the previous designs of FFHR2, in which the uniform blanket space of ~1.0 m is assumed for the neutron wall loading of 1.5 MW/m^2 [3]. Therefore, neutronics investigations for the design window analysis have been performed using a simple torus calculation model simulating the thin inboard blanket space and thick outboard blanket space [4]. The results of the investigations indicate that the minimum inboard blanket space of ~70 cm would be achieved with a WC (tungsten carbide) radiation shield for the neutron wall loading of 1.5 MW/m^2. Since a blanket space of > 1.0 m could be assumed at the outboard side, a fully covered tritium breeding ratio (TBR), i.e. a TBR without neutron leakage through divertor and heating ports, would be ~1.3 for a Flibe cooled liquid blanket system [1]. These neurtonics results have been involved in the decision of the design parameters of FFHR-d1 [5].

In the second step of the design activity of FFHR-d1, three-dimensional neutronics calculations have been started for more accurate investigations of radiation shielding and tritium breeding performances especially by simulating the neutron leakage through openings for diverter pumping. The present paper describes the method and results of three-dimensional neutronics investigations for a present proposed configuration of FFHR-d1.

2. Neutronics Calculation

A three-dimensional calculation model of FFHR-d1 has been prepared by using the neutronics calculation system for helical reactors which has been developed in the previous design activity of FFHR2 [6]. The cross section drawings shown in Figs. 1 (a)-(c) have been prepared for the present investigations. The cross sections of the helical shaped components, i.e helical coils, tritium breeding blanket, radiation shield etc., have been divided into small rectangular pieces. Three-dimensional helical component shapes are generated by rotating those small rectangular pieces according to numerical equations defining the helical lines in the reactor. Vertices of cells for neuronics calculations have been calculated at every 4.5 degrees in the toroidal direction. The input file for the MCNP5 neutron and gamma-ray transport code [7] is generated from the vertices of the cells. Based on results of the neutronics investigations, the dimensions and configurations will be modified and optimized in the design activity.

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*) This article is based on the presentation at the 21st International Toki Conference (ITC21).

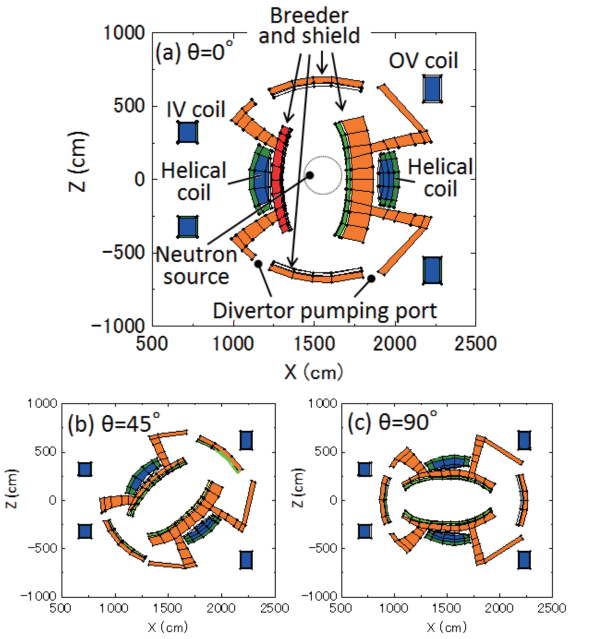

Fig. 1 Cross sections of three-dimensional calculation model for MCNP neutron and gamma-ray transport code. (IV and OV coils: inner and outer vertical field coils).

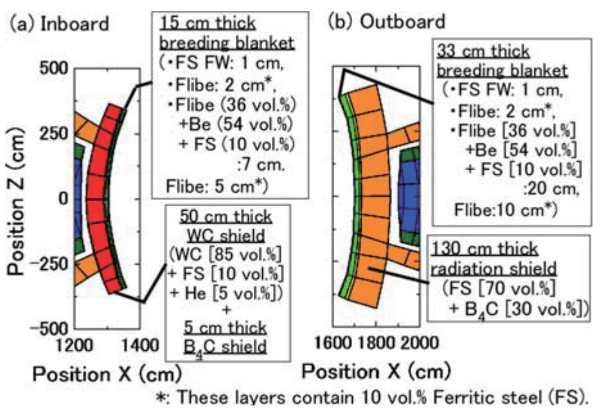

Fig. 2 Layer thicknesses and compositions in inboard and outboard breeding blanket and radiation shield.

The breeding blanket in the calculation consists of four layers of ferritic steel first wall, Flibe coolant layer, Flibe+Be layer and second Flibe coolant layer. The thicknesses of the blanket layers are shown in Fig. 2. The thicknesses of the Flibe+Be layer and second Flibe coolant layer are increased at the outboard side and decreased at the inboard side of the torus. At the back side of the breeder blanket, radiation shielding layers are placed. For the outboard side, compositions of the shielding layer are 70 vol. % ferritic steel (FS) and 30 vol. % B_4C, and the thickness is ~130 cm. For the inboard side, a 50 cm thick WC layer and a 5 cm B_4C layer are placed for shielding. The thicknesses of the FS+B_4C and WC shielding layers are changing gradually with the poloidal rotation. Ring shaped poloidal coils (IV and OV coils: inner and

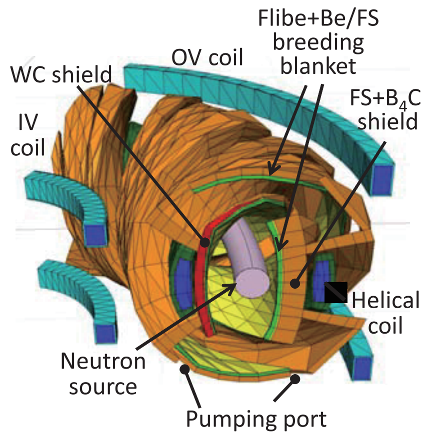

Fig. 3 Three-dimensional drawing of calculation model.

outer vertical field coils) are also included in the calculation model for investigation of a radiation shielding performance in the future studies. The total number of cells input for the MCNP transport calculations is ~ 4,000 (Fig. 3). A uniform torus shaped 14.1 MeV mono-energetic neutron source was assumed in the present investigation. The JENDL-3.3 nuclear data library was used in the present investigations [8].

Understanding of a neutron flux distribution in FFHR-d1 and investigation of a tritium breeding performance of a Flibe+Be/FS blanket have been performed in the present study.

3. Results and Discussion

Figure 4 shows an example of a calculated fast neutron (> 0.1 MeV) flux distribution. The fusion power of the FFHR-d1 is 3 GW and the averaged neutron wall loading is assumed to be 1.5 MW/m^2 [1]. The distribution indicates that the breeding blanket and radiation shielding layers attenuate direct neutrons from the core plasma effectively (Arrows (a) in Fig. 4). The maximum fast neutron flux in the superconducting winding region of the helical coil was ~ 2×10^{10} n/cm^2/s at the inboard side. This result indicates that the present proposed radiation shield configuration using the WC layer at the inboard side would satisfy the design target of neutron shielding for the helical coils of FFHR-d1 [5].

The distribution also indicates that the neutron flux at the back side of the helical coils is higher than that inside of the coils. While the back side of the helical coil is covered with a ~ 30 cm thick stainless steel coil case at the present model, more detailed analyses of neutron flux and nuclear heating inside of the coil, i.e. superconducting winding region, are required in the future studies. Since a large space is available around the back side of the helical coils, significant improvement and optimization of the shielding will be possible.

Shielding for the poloidal (IV and OV) coils will be one of next major issues in the neutronics design, since the

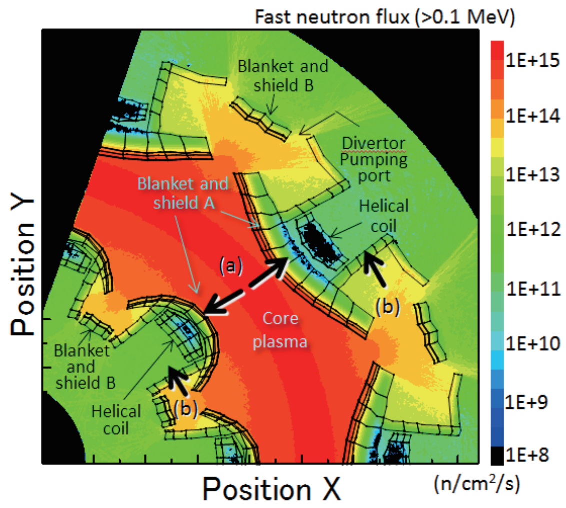

Fig. 4 Example of calculated fast neutron flux distribution in tentative FFHR-d1 model.

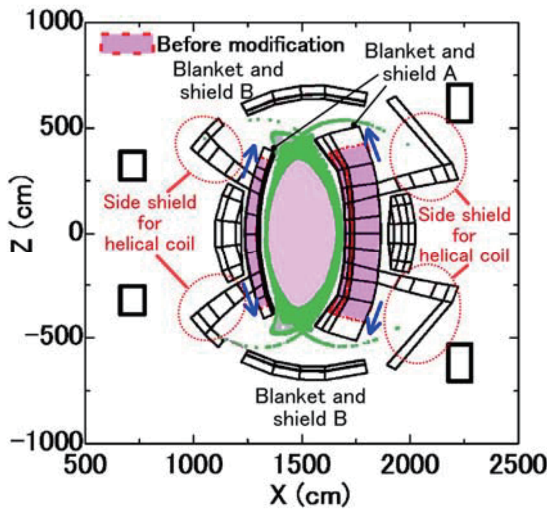

Fig. 5 Expansion of blanket layers for improvement of tritium breeding performance.

cross sections shown in Figs. 1 (b) and (c) indicate that neutron streaming through the divertor pumping ports would hit the coils. Improvement of shielding configuration and partial closure of the divertor ports are being investigated to protect the coils.

The tritium breeding performance in the present three-dimensional model has been investigated by calculating the reaction rates of ^{6}Li(n,α)T and ^{7}Li(n,nα)T reactions in the breeding blanket layers. The tritium breeding ratio (TBR) calculated in the previous investigations using a simple torus model, in which a core plasma was completely covered with breeding blanket layers and neutron leakage was not simulated, was 1.31 for the Flibe+Be/FS blanket system (fully covered TBR) [1]. In the first tentative three-dimensional model based on the cross section shown in Fig. 1, the calculated TBR was 0.96. After increasing the thickness of the second Flibe coolant layer in the outboard blanket from 10 cm to 20 cm, the TBR was 0.98. Therefore, these low TBRs are considered due to significant neutron leakage through openings between the blanket and shield A and B (Fig. 5). Improvement of the tritium breeding performance has been investigated by expanding the edges of the breeding blanket layers as shown in (Fig. 5). In the helical reactor configuration, the expansion of the blanket edges is limited by magnetic field lines coming out from the edge of the core plasma to the divertors [9]. The TBR increased to 1.08 after the modification of the blanket shape, while further accurate adjustment of the shapes is required. This result indicates that the FFHR-d1 design would achieve a sufficient tritium breeding performance with the Flibe+Be/FS blanket system, although the thin breeding blanket of 15 cm in thickness is installed at the inboard side.

Since FFHR-d1 provides a large blanket space at the outboard side, a thicker outboard breeding blanket could be installed. Moreover, additional breeding blanket layers could be installed around the side shields for the helical coils (Fig. 5). These two modifications would increase the tritium breeding performance considerably.

4. Conclusion

The neutronics investigations have been performed for the first tentative design of the helical DEMO reactor FFHR-d1. The three-dimensional calculation model for the MCNP neutron and gamma-ray transport code has been generated from the present proposed cross section drawings of FFHR-d1. The calculation model consists of ~4,000 cells to simulate the geometric features of the helical reactor.

The calculated neutron flux distribution indicates that direct neutrons from the core plasma are effectively attenuated by the present radiation shield configurations and accurate analyses of neutron transport around the back side of the helical coils would be important in the future design studies. The TBR obtained for the Flibe+Be/JLF-1 breeding blanket is 1.08 after the modification of the blanket dimensions. A sufficient tritium breeding performance would be achieved in FFHR-d1 with a thin inboard breeding blanket.

Improvement and optimization of the neutronics performances are being continued by using the three-dimensional neutronics calculation system. The further detailed analyses of neutron transport in the reactor are important to provide sufficient radiation shielding performances for all the helical and poloidal superconducting magnet systems. It is required to optimize the shield configurations by keeping the compatibility with the helical divertor design [9]. Investigations of neutronics performances for other breeding blanket systems with FLiNaK(LiF-NaF-KF), Li, Li-Pb etc. are also being performed in the FFHR-d1 design activity at present.

Acknowledgement

This study has been performed under the NIFS research program UFFF-021.

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