Proposal for the Method of Maintaining Breeder Blankets in the LHD-Type Helical Fusion Reactor FFHR*)

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A maintenance method for the breeder blanket of the LHD-type helical reactor FFHR was considered. A simple segmentation in a plane with a constant toroidal angle was proposed by utilizing the flexible arrangement capacity of the coolant path in the blanket module with a molten salt tritium breeder. Moreover, it was found that all blanket modules can be extracted by a combination of uniaxial movements and poloidal rotation without cutting of the coolant pipes inside the vacuum vessel.

Keywords: helical reactor, breeder blanket, maintenance, toroidal segmentation

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1. Introduction

The conceptual design of the LHD-type helical reactor FFHR-d1 [1] is being intensively studied. After the primary design parameters were determined using the systems code HELIOSCOPE [2], three-dimensional (3D) design and analysis of in-vessel components and the supporting structure of the superconducting magnet system were conducted [3, 4]. In parallel with these design activities, the construction and maintenance methods of these components are under review with the goal of enhancing design feasibility. Among the components, the divertor and breeder blanket are important because they need to be replaced periodically. In this paper, we focus on the method of replacing the breeder blanket because its 3D shape has been clearly defined. Section 2 gives an algebraic expression of the 3D shape of the breeder blanket. The segmentation method and required movement of each module in the replacement process are discussed in Section 3.

2. 3D Shape of the Breeder Blanket of the FFHR-d1

The breeder blanket of the FFHR-d1 is classified into two main parts: the part located at the bottom of the helical coils and the part that faces the separatrix of the magnetic surfaces. To ensure a continuous toroidal structure with smooth surfaces and a flexible response to the change in the design of the core plasma and the surrounding components, the shape of the breeder blanket was defined by a mathematical formula: a function of helical coil angle θ_c (which is defined by the function of toroidal angle ϕ as $\theta_c = -5\phi - 0.1\sin 5\phi$) in the plane normal to the tangent line to the guiding curve of the helical coil (here we define this plane as the ξ–η coordinate with its origin located at the current center of the helical coil as shown in Fig. 1). For the part located at the bottom of the helical coils, the shape of plasma-facing side is defined by a part of a parabola:

$$\xi = \xi_0 + \left\{ r_w \left[1 - f_w \cos\left(\theta_c - f_{mod} \sin 2\theta_c\right)\right] + r_{mod} \sin^6 \theta_c \right\} \left(\frac{\eta}{a_c}\right)^2 . \quad (1)$$

The range w_b and the thickness of the breeder blanket in the ξ direction (Δ_b) are also defined by a function of θ_c:

$$w_b = \eta_{max} = -\eta_{min} = w_{b0} + w_{b,add} \cos^6 \frac{\theta_c}{2}, \quad (2)$$

$$\Delta_b = \Delta_{b,in} + \Delta_{b,add} \cos^4 \frac{\theta_c}{2} + \Delta_{b,mod} \sin^4(\theta_c + \alpha_b \sin\theta_c), \quad (3)$$

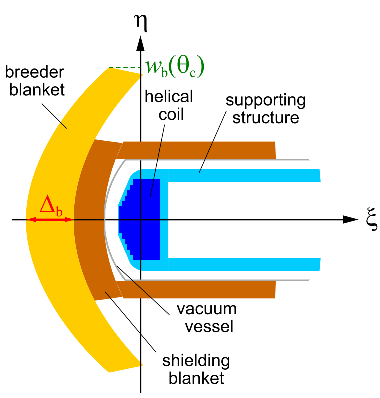

Fig. 1 Definition of the parameters that determine the shape of the breeder blanket in a plane normal to the helical coils.

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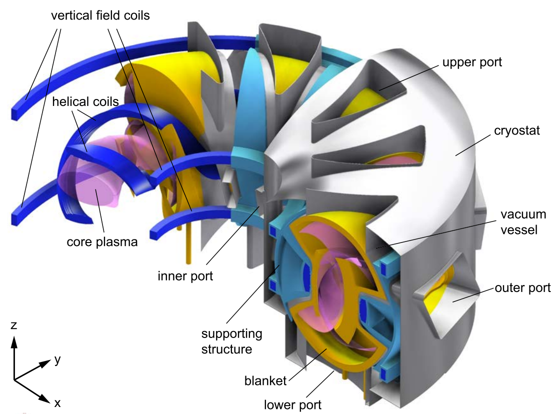

Fig. 2 LHD-type helical reactor FFHR-d1.

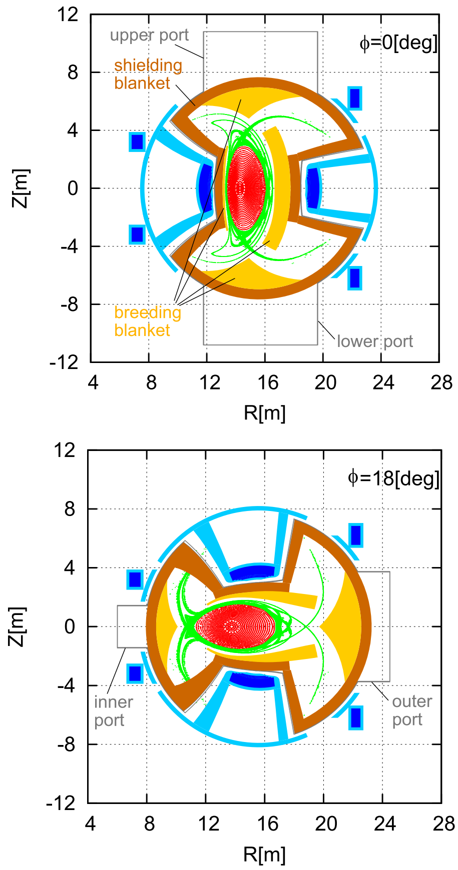

Fig. 3 Cross-sectional view of the FFHR-d1 reactor at $\phi = 0°$ (upper) and $\phi = 18°$ (lower).

where the parameters r_w, f_w, f_{mod}, r_{mod}, w_{b0}, $w_{b,add}$, $\Delta_{b,in}$, $\Delta_{b,add}$, $\Delta_{b,mod}$, and α_b are adjusted according to the plasma shape.

For the part facing the separatrix, the shape of the plasma-facing side is given as a part of Archimedes' spiral that starts from the point $(R_{geo} + a^* \cos\theta, a^* \sin\theta)$, where R_{geo} is the plasma's geometric center (14.4 m for the FFHR-d1) and $\theta = 5\phi$. Parameter a^* is selected according to the shape of the magnetic field lines.

The detailed shape of the port apertures is given in Ref. [3]. The upper and lower ports have a triangular shape and the inner and outer ports have a parallelogram shape as is shown in Fig. 2. Figure 3 shows the cross-sectional view of the FFHR-d1.

3. Consideration of the Segmentation and Method of Replacing the Breeder Blanket

The reduction of the time required for the replacement of the breeder blanket is quite important in terms of improving plant availability and radiation protection. Thus, we considered the segmentation method of replacing the breeder blankets, which enables each breeder blanket module to be replaced with the simplest movements possible. In general, the segmentation of the blanket system is closely linked to the inside arrangement of the coolant path. In this respect, the arrangement of the coolant path of the breeder blanket of the FFHR-d1 can be flexibly set without any concern for the local direction of the magnetic field because of the low electric conductivity ($\sim 10^2$ S/m) of the breeder material: molten salt FLiBe or FLiNaBe. Consequently, we proposed a simple segmentation of the breeder blanket in a plane with a constant toroidal angle. A breeder blanket allowing such segmentation [hereafter, we refer to this as a Toroidally-Sliced and HELically-Linked (T-SHELL) breeder blanket] can basically be replaced with a movement in a constant toroidal angle only: uniaxial movement or poloidal rotation. We also determined the range of the toroidal angle for one module as 3° (ϕ = 0°, 3°, 6°, . . . , ±1.5°) for the following reason. The total weight of the breeder blanket without the liquid breeder material is estimated to be 1,700 tons (liquid breeder material can be drained during the replacement work). As described in the preceding section, a breeder blanket is classified into two main parts and each part is also divided into two sections: inside/upper and outside/lower parts of the torus. Therefore, the weight of each four-part assembly is estimated to be approximately 400 tons. In the research and development of ITER maintenance technology, remote handling equipment that can handle a payload of approximately 4 tons with a positioning accuracy within 0.5 mm has been demonstrated [5]. Thus, we can use the same level of technology if the breeder blanket of the FFHR-d1 is separated into more than 100 modules. Conversely, the range of angle of a divisor of 72 is favorable because the FFHR-d1 has a 5-fold symmetry. Consequently, we chose the segmentation by every 3° (120 modules) for the T-SHELL breeder blanket.

One of the most time-consuming processes in the replacement work is the cutting and rewelding of the coolant pipes. These processes and the inspection of the soundness of the rewelding points under the high-radiation environment inside the vacuum vessel are quite difficult. Thus, we examined the possibility of replacing the T-SHELL breeder blanket with the cutting/rewelding of the coolant pipes at

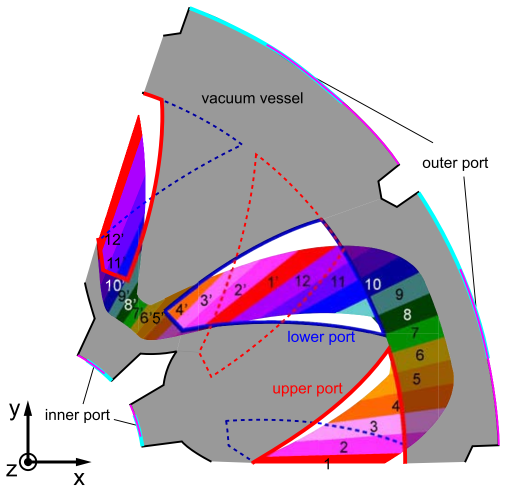

Fig. 4 Top view of one of the series of the breeder blanket modules which face the separatrix (corresponding to the series which locates the upper side at $\phi = 0°$) for $0° \leq \phi \leq 72°$. The shape of the other series for $0° \leq \phi \leq 36°$ and $36° \leq \phi \leq 72°$ are the same as this series for $36° \leq \phi \leq 72°$ and $0° \leq \phi \leq 36°$, respectively. The cyan and magenta curves on the inner/outer ports correspond to the upper and lower sides of the parallelogram-shaped port aperture.

only the edge of the overhanging port structure. Because the lifetime of divertor modules is considered to be shorter than that of the breeder blanket modules, it is assumed that all divertor modules are removed before beginning the replacement of the breeder blanket modules.

For the breeder blanket modules that face the separatrix, most of them face the port aperture directly and can be extracted by only radial or vertical movement (corresponding to the parts facing the apertures of the ports in Fig. 4). Nearly all of the remaining modules can be extracted via the nearest port by movement at the same toroidal angle. The remaining parts (corresponding to the modules numbered 5, 9, 5′, 6′, 9′, and 10′ in Fig. 4) require movement in a toroidal direction; however, the required toroidal movement is only 3° (corresponding to the thickness of only one module). Thus, this toroidal movement can be replaced by a uniaxial movement. Because there is no intersection of the path of the coolant pipes for all of these breeder blanket modules and divertor magnetic field lines, the coolant pipes pass the shortest path and do not interfere with the extraction of each breeder blanket module from the port aperture. Conversely, the coolant pipes for the breeder blanket modules located at the bottom of the helical coils need to be separated from the divertor magnetic field lines and pass behind the di-

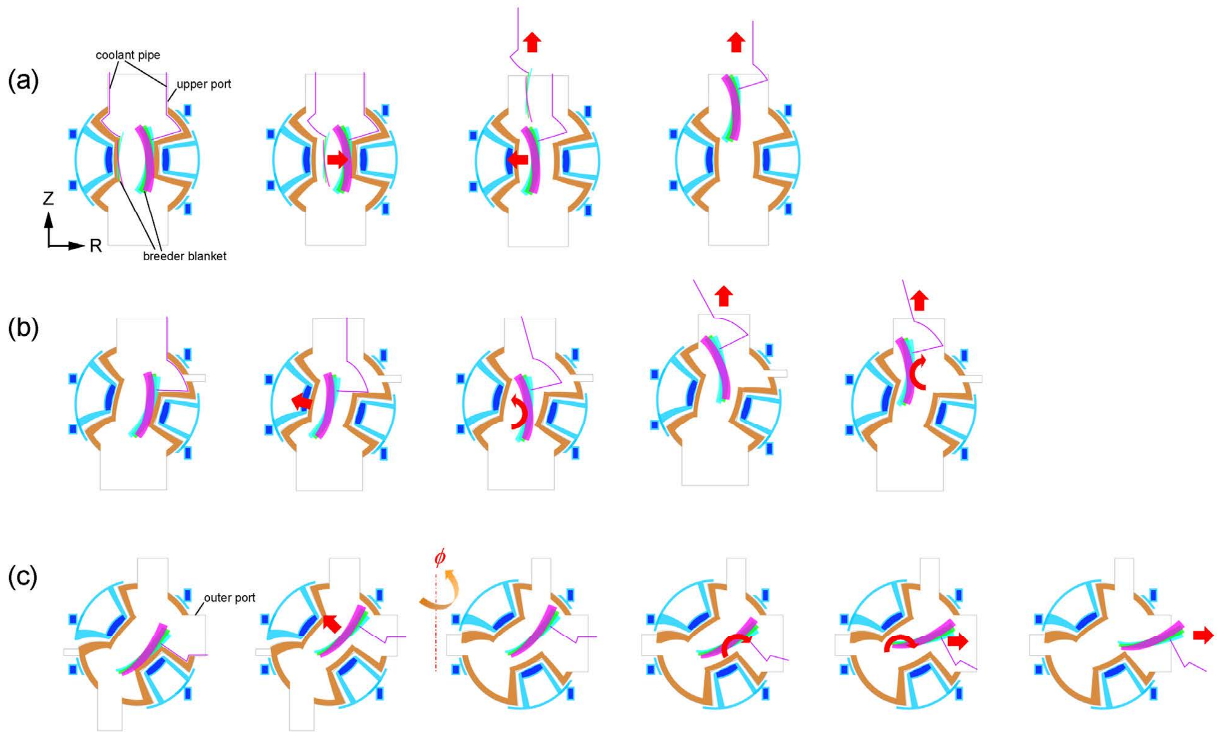

Fig. 5 Example of the required movements of breeder blanket modules: (a) combination of radial and vertical movement only (for the module located at $\phi = 0°$, corresponding to the modules numbered 1 and 1′ in Fig. 6) , (b) movement of (a) plus poloidal rotation in a plane with a constant toroidal angle (for $\phi = 3°$, module 2 in Fig. 6), and (c) movement of (b) plus toroidal transport (for $\phi = 9°$, module 4 in Fig. 6). The shapes of the breeder blanket modules shown in red and blue correspond to the projections of its shape at both ends in the toroidal direction (+1.5° and −1.5° from the cross-section shown in the figure). Green corresponds to the cross-sectional shape of the blanket module in the cross-section shown in the figure.

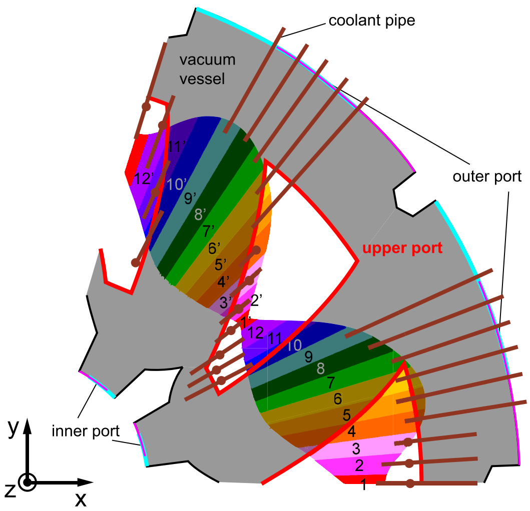

Fig. 6 Top view of one of the series of the breeder blanket modules on the bottom of the helical coils (corresponding to the series which is located on the outboard side at $\phi = 0°$) for $0° \leq \phi \leq 72°$. Brown radial lines are the coolant pipes. The solid circles correspond to the position of the vertical supply/return path that passes through the upper port. The supply/return path of the pipes without solid circles passes through the outer port. The meaning of the cyan and magenta curves is the same as in Fig. 4.

vertor modules. For simplicity, we consider as design in which the coolant pipe for each breeder blanket module passes in the same poloidal cross-section (with no path in the toroidal direction). Because the detailed shape and location of the divertor module have not yet been decided, we consider the path of the supply pipe that enters the vacuum vessel through the nearest port aperture and reaches the module by passing along the inner (vacuum) side of the shielding blanket. The path of the return pipe is assumed to be the same as that of the supply pipe. With this simple arrangement of the coolant pipes, the necessary movement to extract each breeder blanket module was examined. Consequently, the necessary movements are classified in the following three patterns: (a) a combination of radial and vertical movements, (b) movement of (a) plus poloidal rotation, and (c) movement of (b) plus toroidal transport. Figure 5 shows examples of these movements. Figure 6 shows the top view of the breeder blanket modules and pipes. As is apparent, only five modules (corresponding to the modules numbered 3, 4, 10, 4′, and 10′ in Fig. 6) need toroidal transport. As for the case of the breeder blanket modules that face the separatrix, the required toroidal movement for these modules is only 3°. This means that all breeder blanket modules can be extracted by a combina-

Table 1 Required movement for replacing each blanket module.

Toroidal angle [°]	Section No.	For module locates outboard side at $\phi = 0$	For module locates inboard side at $\phi = 0$
−1.5–1.5	1	(a) Radial + upward	(a) Radial + upward
1.5–4.5	2	(b) Poloidal rotation required	(a) Radial + upward
4.5–7.5	3	(c) poloidal rotation + toroidal transfer ($-\phi$ direction)	(b) Poloidal rotation required
7.5–10.5	4	(c) poloidal rotation + toroidal transfer ($+\phi$ direction)	(c) poloidal rotation + toroidal transfer ($-\phi$ direction)
10.5–13.5	5	(b) Poloidal rotation required	(b) Poloidal rotation required
13.5–16.5	6	(a) Radial + upward	(b) Poloidal rotation required
16.5–19.5	7	(a) Radial + upward	(a) Radial + downward
19.5–22.5	8	(b) Poloidal rotation required	(a) Radial + downward
22.5–25.5	9	(b) Poloidal rotation required	(b) Poloidal rotation required
25.5–28.5	10	(c) poloidal rotation + toroidal transfer ($+\phi$ direction)	(c) poloidal rotation + toroidal transfer ($+\phi$ or $-\phi$ direction)
28.5–31.5	11	(b) Poloidal rotation required	(b) Poloidal rotation required
31.5–34.5	12	(a) Radial + upward	(a) Radial + upward

tion of uniaxial movements and poloidal rotation without the cutting/rewelding of the coolant pipes inside the vacuum vessel. Although the detailed design and analysis of the coolant pipes in view of its cooling capacity, pumping power, and drainage capability is required, the utility of the T-SHELL breeder blanket was demonstrated in principle. The required movements for replacing each breeder blanket module are summarized in Table 1.

4. Summary

The segmentation method of replacing the breeder blanket of the LHD-type helical reactor FFHR-d1 was examined and simple toroidal segmentation was proposed. Although further detailed analysis of the pipe arrangement including the consideration of drainage capability and cooling capacity is required, it was found that the breeder blanket modules can be replaced by a combination of uniaxial movements and poloidal rotation in the plane with a constant toroidal angle without cutting/rewelding of coolant pipes inside the vacuum vessel.

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