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Maintainability of the Helical Reactor FFHR-c1 Equipped with the Liquid Metal Divertor and Cartridge-type Blankets

Junichi Miyazawa[a,b], Takuya Goto[a,b], Hitoshi Tamura[a], Teruya Tanaka[a,b], Nagato Yanagi[a,b], Tananori Murase[a], Ryuichi Sakamoto[a,b], Suguru Masuzaki[a], Takeru Ohgo[b], Akio Sagara[a,b], and the FFHR Design Group

[a]*National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan*
[b]*SOKENDAI (The Graduate University for Advanced Studies), 322-6 Oroshi, Toki, Gifu 509-5292, Japan*

The maintenance scheme in the compact helical fusion reactor, FFHR-c1, equipped with the liquid metal divertor, REVOLVER-D (Reactor-oriented Effectively VOLumetric VERtical Divertor) and the cartridge-type molten salt blankets, CARDISTRY-B (CARtridges Divided and InSerTed RadiallY - Blanket), is investigated. The magnetic configuration of the compact variant FFHR-c1 is similar to that of the Large Helical Device (LHD), while the device size is 2.8 times enlarged from LHD and a strong magnetic field strength of ~8 T at the plasma center is adopted. The maintenance of the REVOLVER-D is simpler than that of the helical divertor with a complicated structure as seen in the LHD. In the REVOLVER-D, showers of molten tin are injected into the ergodic layer at 10 inner ports. To circulate the molten tin, 10 sets of the shower system including a liquid metal pump, ducts, a showerhead, a pool, and a heat exchanger, are installed. These can be replaced with simple up/down motions. The CARDISTRY-B consists of 320 tritium breeding blanket cartridges, which are toroidally segmented every two degrees. These cartridges are maintained by using heavy manipulators with a simple 4DOF motion at a constant toroidal angle.

Keywords: *fusion reactor, heliotron, remote maintenance, divertor, liquid metal, blanket*

1. Introduction

Conceptual design of the helical fusion reactor FFHR-d1 has been conducted in NIFS [1-3]. The FFHR-d1 is designed based upon the knowledge obtained in the Large Helical Device (LHD) [4]. The magnetic configuration of FFHR-d1 is similar to that of the LHD, while the device size is four times larger. The major radius of the helical coil center, R_c, is 15.6 m in the FFHR-d1 and 3.9 m in the LHD. Basically, the FFHR-d1 will be operated in the self-ignition mode, where no auxiliary heating is applied for plasma sustainment. The fusion output, P_{fusion}, is ~3 GW and the lifetime of the device is assumed to be more than 30 years. Multiple options have been defined. For example, the FFHR-d1A is the standard option with the magnetic field strength at the helical coil center, B_c, of 4.7 T (the maximum field on the conductor, B_{peak}, is 11.7 T) and the FFHR-d1B is the option with high B_c of 5.6 T (B_{peak} is 14.0 T) [2]. Each of these has two further options called the basic and challenging options [3]. The basic option is based on the conservative technologies, including those being developed for the ITER. On the other hand, the challenging option boldly includes new ideas that are not necessarily well matured but may possibly be beneficial for making the reactor design more attractive. For example, the High-Temperature Superconducting (HTS) magnets, the Liquid Metal (LM) divertor, and the toroidally segmented Molten Salt (MS) blanket are adopted in the challenging option. Typical candidates for the LM divertor and the cartridge-type MS blanket are the REVOLVER-D (Reactor-oriented Effectively VOLumetric VERtical Divertor) [5,6] and the CARDISTRY-B (CARtridges Divided and InSerTed RadiallY - Blanket) [7], respectively.

Discussions led by the Joint-Core Team (JCT), which consists of experts from the Japanese fusion community including industry, on the strategic establishment of technology bases for the Japanese fusion DEMO reactor have progressed [8]. In Japan, the first DEMO reactor is tentatively assumed to be the tokamak, whereas the helical and/or inertial fusion reactors are taken as the alternative. Three missions are proposed for the Japanese DEMO by the JCT: (1) steady power generation beyond several hundred thousand kilowatts, (2) availability which must be extensible to commercialization, and (3) overall tritium breeding sufficient to achieve fuel-cycle self-sufficiency. As an alternative, it is necessary to prepare the conceptual design of a helical fusion reactor that can achieve these three missions. Of course, the FFHR-d1 can be a candidate for the DEMO, since the three missions are inherently included in its design. However, the specification of the FFHR-d1 is too high. A cost-efficient model will be more suitable for the DEMO. A compact version of the FFHR-d1, called the FFHR-c1, has been also investigated in our design activity [2,9]. The FFHR-c1 can be a strong candidate for DEMO. Since the design parameters of FFHR-c1 have not been fixed yet before now, these are determined in this paper to satisfy the requirement for the DEMO.

The missions of DEMO include demonstration of practical availability. This at the same time means that the DEMO should demonstrate sufficient RAMI, that is, Reliability, Availability, Maintainability, and Inspectability. Without establishing a concrete and fast maintenance scheme, it is impossible to achieve the

author's email: miyazawa@LHD.nifs.ac.jp

Table 1. Design parameters of the helical coil major radius, R_c, the ratio of R_c to that of FFHR-d1, R_c / R_{d1}, the ratio of R_c to that of LHD (R_c = 3.9 m), R_c / R_{LHD}, the magnetic field strength at the helical coil center, B_c, the magnetic stored energy, W_{mag}, the auxiliary heating power for steady-state sustainment, P_{aux}, the fusion output, P_{fusion}, and the fusion gain, $Q = P_{fusion} / P_{aux}$, in FFHR-d1 and c1.

	d1	d1A	d1B	←	c1.0	c1.1	c1.2	c1	←
R_c (m)	15.6	←	←	←	13.0	←	10.4	10.92	←
R_c / R_{d1}	1	←	←	←	0.833···	←	0.66···	0.7	←
R_c / R_{LHD}	4	←	←	←	3.33···	←	2.7	2.8	←
$V_{p,vac}$ (m^3)	1,880	1,420	←	←	820	←	420	490	←
B_c (T)	4.7	←	5.6	←	4.0	5.6	←	7.3	←
W_{mag} (GJ)	163	←	224	←	68	125	61	155	←
P_{aux} (MW)	0	←	←	27	53	40	49	45	0
P_{fusion} (GW)	2.7	3.0	1.5	0.43	0.0065	0.25	0.13	0.45	3.0
Q	∞	←	←	16	1.2	6.2	2.6	10	∞

practical availability with high reliability. From this point of view, the FFHR-c1 adopts the challenging option, which consists of the HTS magnets, the REVOLVER-D, and the CARDISTRY-B, as the primary candidate. The basic strategies in maintaining the REVOLVER-D and the CARDISTRY-B are given in this paper.

In the next section, the design parameters of FFHR-c1 are determined first. Discussions on the maintenance schemes for the REVOLVER-D and the CARDISTRY-B are given in sections 3 and 4, respectively. The maintenance schedule is discussed in section 5. Finally, these are summarized in section 6.

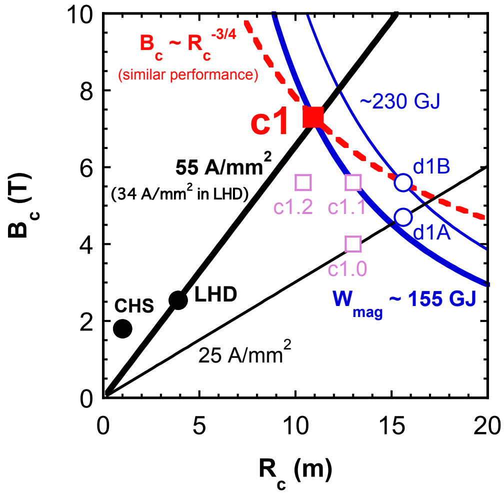

Fig. 1. The design points of the FFHR series in the $R_c - B_c$ plane, where a closed square, open squares, and open circles denote the FFHR-c1, the former versions of FFHR-c1 (c1.0, c1.1, and c1.2), and two versions of FFHR-d1 (d1A and d1B). Two closed circles denote CHS and LHD. Thick and thin solid curves denote the constant W_{mag} of ~155 GJ and ~230 GJ, respectively. The broken curve denotes the constant $B_c \sim R_c^{-3/4}$. Thick and thin solid lines denote constant helical coil current densities of 55 A/mm² and 25 A/mm², respectively, in the devices with similar helical coil cross sections.

2. The FFHR-c1

To design a fusion reactor, what should be defined first is its mission. A simple mission has been defined for the FFHR-c1: "One-year steady-state operation with self-produced fuel and electricity." This automatically includes the three missions for the Japanese DEMO, discussed in the introduction. The sub-ignition operation, where the auxiliary heating of P_{aux} is additionally applied to sustain the fusion plasma, is the main operation scenario. To sustain the plasma with the self-generated electricity, the fusion gain, Q ($\equiv P_{fusion} / P_{aux}$), should be larger than 10. Since the plasma is confined in the nested magnetic surfaces generated by external magnet coils in helical devices, no plasma current is necessary. Since no power for plasma current drive is necessary, the reactor itself only requires electrical power to heat the plasma, to cool the HTS magnet coils, and to circulate LM in the REVOLVER-D, or MS in the CARDISTRY-B. At $Q \sim 10$, however, the "net" electricity generation will be nearly zero. Therefore, the operation at $Q \sim 10$ is the minimum target for the FFHR-c1. The self-ignition operation at $Q = \infty$, as in the FFHR-d1, is also to be considered. Then, how small can the device size be in order to achieve the mission for the FFHR-c1? The answer is given in below.

In a quite rough estimation, the construction cost of a fusion reactor is mainly determined by the material costs of the magnetic coil support structure and the blankets. The material cost of a component is roughly proportional to its weight. According to the Virial's theorem, the weight of the magnetic coil support structure is approximately proportional to the magnetic stored energy, $W_{mag} \propto B_c^2 R_c^3$ [10]. On the other hand, the weight of the blanket is proportional to R_c^3. Here, we are basically considering similar devices with different sizes, instead of assuming an identical blanket thickness required from the points of view of tritium breeding and neutron shielding. The performance of the blanket depends on the device size, in this case. Therefore, it is necessary to evaluate the blanket performance for each case, as in [11]. Under this assumption, size reduction is effective for cost reduction. However, size reduction also results in degradation of the plasma confinement characteristics.

The characteristics of the energy confinement time, τ_E, in stellarators and heliotrons including the LHD have been intensively studied and summarized in the forms of ISS95 and/or ISS04 scalings [12,13]. Both scalings show the so-called gyro-Bohm property, as is also recognized in the scalings for tokamaks [14]. The plasma parameters in FFHR-d1 have been estimated by using the Direct Profile Extrapolation (DPE) method, which is based on the gyro-Bohm model [9,15-18]. According to the DPE method, two devices having an identical value of $R_c B_c^{3/4}$ can

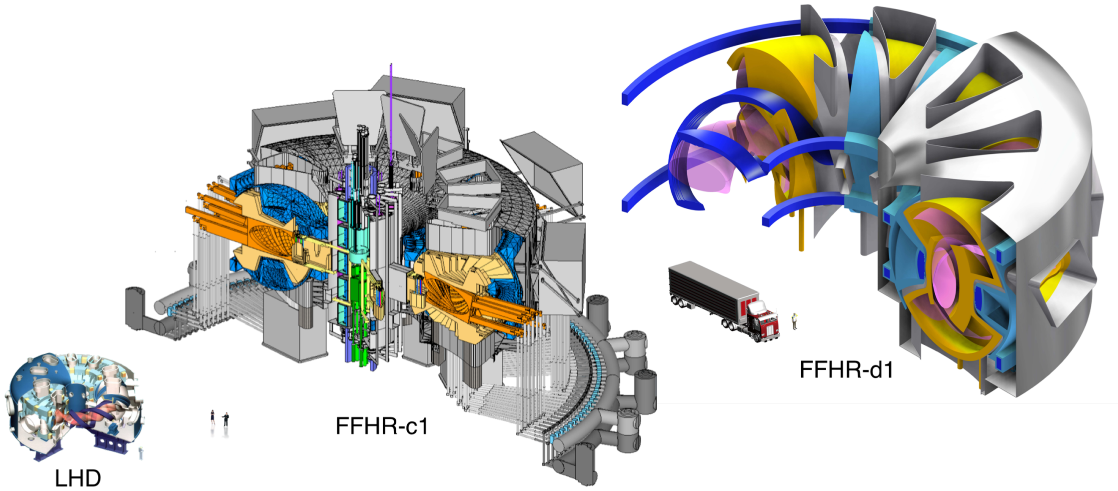

Fig. 2. Comparison of the device size between LHD (left), FFHR-c1 (center), and FFHR-d1 (right).

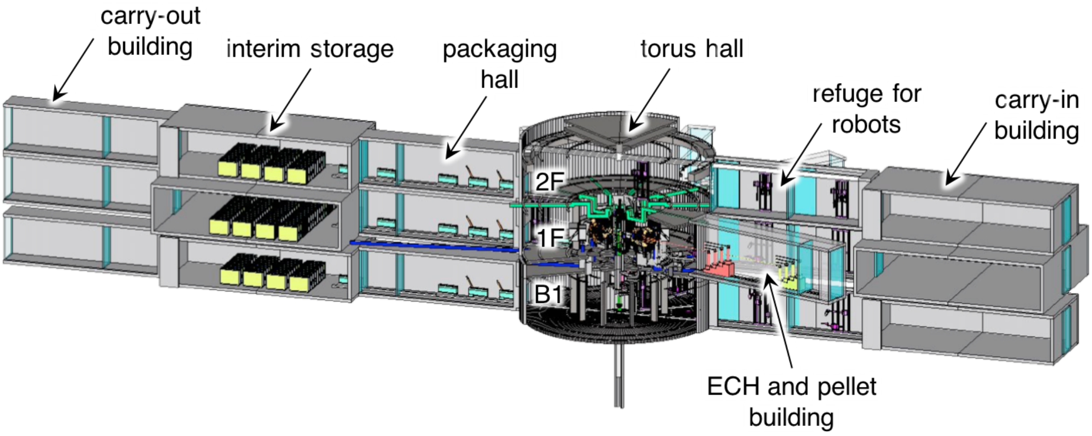

Fig. 3. The building layout for the FFHR-c1.

achieve the same Q, as long as the plasma beta and the confinement improvement factor are fixed [9]. In other words, it is possible to achieve a similar Q in two devices with different R_c, if only $R_c B_c^{3/4}$ is kept constant.

Table 1 summarizes the design points of the FFHR series defined as d1, d1A, d1B, c1.0, c1.1, and c1.2 in the former studies [2,9]. These design points together with those of CHS and LHD are plotted on the $R_c - B_c$ plane in Fig. 1. As discussed above, size reduction is effective for cost reduction. On the other hand, $R_c B_c^{3/4}$ should be kept constant to maintain the plasma performance. In determining the design point of c1 in this study, the design point of d1B is taken as the reference point, since the detailed physics analyses of the plasma characteristics have been most intensively conducted on d1B [17,18]. The self-consistent solution of $Q \sim 10$ has been established using the parameters of d1B, where both requirements from the MHD stability and the neoclassical transport theory are simultaneously satisfied within the range observed so far in the experiment on the LHD [18].

As listed in Table 1 and plotted in Fig. 1, the design point of the FFHR-d1 is finally set at R_c = 10.92 m and B_c = 7.3 T [19]. The B_{peak} and the helical coil current density, J_{HC}, are tentatively considered to be ~19 T and ~48 A/mm^2, respectively. Note that these depend on the detailed coil design and not yet fixed at this moment. The device size is 0.7 times reduced from the FFHR-d1, or, 2.8 times enlarged from the LHD. Device sizes of LHD, FFHR-c1, and FFHR-d1 are compared in Fig. 2. The self-consistent solution of $Q \sim 10$ as in d1B can be achieved in c1, since high B_c of 7.3 T is adopted to keep $R_c B_c^{3/4}$ the same as that of d1B. Although the detailed physics analysis is beyond the scope of this paper and will be published elsewhere, P_{fusion} at $Q \sim 10$ is estimated to be ~450 MW with $P_{aux} \sim$ 45 MW [~~18~~ 19]. If one can ignore the requirements from the MHD stability and the neoclassical transport theory, or unknown confinement improvement takes place, it becomes possible to achieve self-ignition of $Q = \infty$ in the FFHR-c1. In that case, P_{fusion} will be increased to ~3 GW. It should be noted that since the thickness of the neutron shielding blanket in the FFHR-c1 is reduced by 0.7 times compared with that in the FFHR-d1, the nuclear heating on the superconducting magnet will become extremely high. The system code HELIOSCOPE predicts ~770 kW of nuclear heating on the superconducting magnet coils, which requires ~250 MW to remove it, in the FFHR-c1 operated at $P_{fusion} \sim$ 3 GW [19]. Furthermore, the neutron damage reduces the lifetime of the superconducting magnets. If the FFHR-c1 is operated at $P_{fusion} \sim$ 3 GW, the lifetime of the device will be within a few months [19].

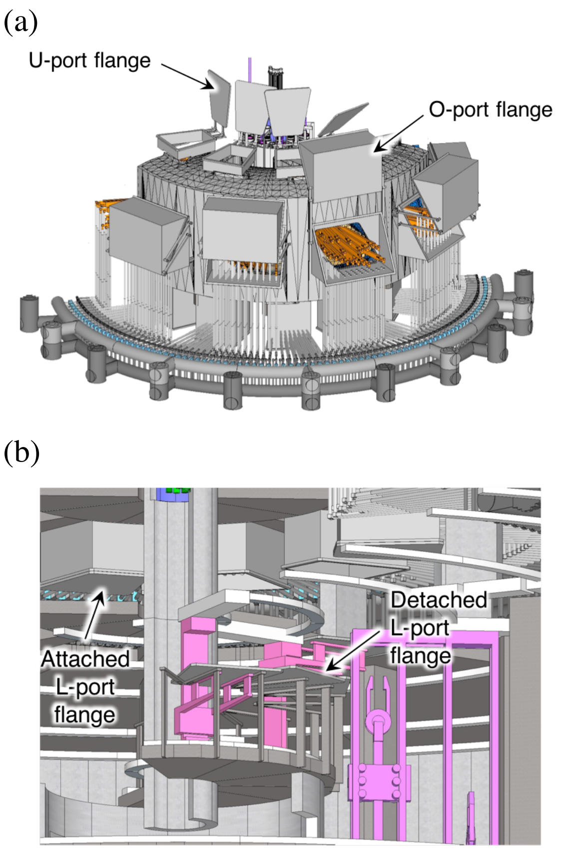

Fig. 4. (a) The U-ports and O-ports and (b) the L-ports of the FFHR-c1.

Because of these, it will be necessary to limit the duration time of the high P_{fusion}, even though the self-ignition operation becomes possible. Since W_{mag} is reduced for 0.58 times and the blanket volume is reduced for 0.34 times compared with the d1B, the construction cost of the c1 can be roughly halved from the d1B. Detailed cost analysis will be performed in the near future.

Solid lines in Fig. 1 denote the J_{HC}. In similar devices such as the FFHR-d1 and c1 series, J_{HC} is identical if the ratio of B_c / R_c is the same. For example, if the FFHR-c1 is designed by simply reducing the scale length of the FFHR-d1A with J_{HC} ~ 25 A/mm^2 for 0.7 times, the helical coil current in FFHR-c1 should be increased to ~55 A/mm^2. This is a large value even compared with the J_{HC} in LHD of ~34 A/mm^2 at B_c ~ 3 T. Note that the relative cross-section of the helical coil in LHD is ~1.6 times larger than that in d1. A high J_{HC} is not preferable since it can easily cause an unacceptable local temperature increase exceeding 200 K when an unexpected quench takes place. Such a high "hot spot" temperature produces a large mechanical stress on the coil that can seriously damage the coil. To reduce the J_{HC}, the helical coil cross-section should be enlarged. Since we are planning to enlarge the helical coil cross-section in the FFHR-c1, the J_{HC} will be reduced to ~48 A/mm^2, as was already mentioned. Detailed design of the helical coil remains for the future study. There is a possibility to reduce the B_c from 7.3 T, depending on the detailed coil design and the results of stress analysis on the magnetic coil support structures.

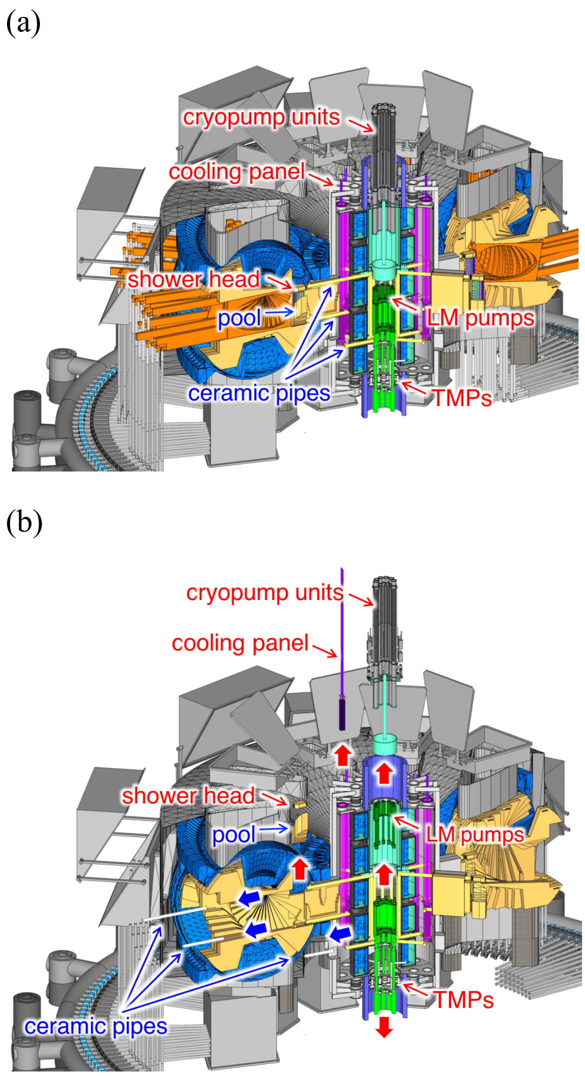

Fig. 5. Schematic views of the REVOLVER-D (a) before and (b) during/after maintenance.

Due to the high magnetic field in the FFHR-c1, the Larmor radius of alpha particles normalized by the plasma minor radius in the FFHR-c1 is 1 / (0.7 × (7.3 / 4.7)) ~ 0.9 times smaller than that in the FFHR-d1, where the energy loss of alpha particle is expected to be 10 – 20 % [17]. Although detailed simulation studies should be done in the future, the alpha confinement in the FFHR-c1 can be expected to be similar to, or even better than that in the FFHR-d1, because of the smaller normalized Larmor radius of alpha particles.

The layout of buildings for the FFHR-c1 is tentatively considered to be as that shown in Fig. 3. From right to left in Fig. 3, three-story buildings (including the basement floors) for carry-in, refuge for robots, torus hall, packaging hall, interim storage, and carry-out stand in a line. Ten buildings for Electron Cyclotron Heating (ECH) and pellet injection devices surround the torus hall. During the plasma operation with fusion reaction, robots for maintenance stay in the refuge. At maintenance of the tritium Breeding Blanket (BB) cartridges of CARDISTRY-B, each of the removed BB cartridge is packed in a box in the packaging hall. The boxes are then moved to the interim storage. In Fig. 3, the boxes that

Table 2. Summary of volumes and weights of the BB cartridges.

No.	Toroidal angle ϕ (deg.)	Cartridge name	Volume V (m^3)	Weight w/o molten salt (8×0.2) × V (ton)	Weight w/ molten salt ($8 \times 0.2 + 2 \times 0.8$) × V (ton)	Weight after α % drainage	α (%)
1	0	00	4.4	7.1	14.2	7.1	100
2	2	02	4.2	6.7	13.3	6.7	100
3	4	04A	2.1	3.3	6.7	3.3	100
4	4	04B	2.7	4.3	8.6	4.3	100
5	6	06A	1.7	2.8	5.6	2.8	100
6	6	06B	2.7	4.3	8.6	4.3	100
7	8	08A	1.8	2.9	5.9	4.4	50
8	8	08B	2.1	3.3	6.6	6.2	10
9	10	10A	2.6	4.2	8.4	8	10
10	10	10B	2.5	4	8.1	7.3	20
11	12	12A	2.7	4.3	8.7	8.3	10
12	12	12B	2.6	4.1	8.3	7.9	10
13	14	14A	3.1	4.9	9.8	5.9	80
14	14	14B	2.2	3.6	7.2	6.1	30
15	16	16A	1.9	3	6.1	5.5	20
16	16	16B	2.1	3.3	6.6	5	50
17	18	18	4.7	7.5	15	8.2	90
18	20	20A	2.1	3.4	6.8	4.4	70
19	20	20B	1.7	2.7	5.5	4.1	50
20	22	22A	2.3	3.6	7.2	4.3	80
21	22	22B	1.7	2.7	5.4	3.3	80
22	24	24A	2.1	3.3	6.7	4	80
23	24	24B	1.8	2.9	5.8	3.5	80
24	26	26A	2.5	4	8.1	5.3	70
25	26	26B	1.4	2.2	4.4	2.2	100
26	28	28A	2.8	6.7	9	7.2	40
27	28	28B	1.6	2.5	5	2.5	100
28	30	30A	2	3.2	6.5	3.2	100
29	30	30B	1.5	2.5	4.9	2.5	100
30	32	32A	2.3	3.6	7.2	3.6	100
31	32	32B	1.6	2.6	5.1	2.6	100
32	34	34	3.4	5.4	10.8	5.4	100
		Total	76.9	125.3	246.1	159.3	

correspond to those used for 8 times of BB cartridge removal are drawn inside the interim storage. Both diameter and height from the B1 floor to the rooftop of the torus hall are tentatively assumed to be ~90 m. The total length between the far ends of the carry-in and the carry-out buildings is ~500 m.

The design of remote handling compatible port flanges is quite important for maintenance. The FFHR-c1 is equipped with ten Upper (U-) ports, ten Outer (O-) ports, and ten Lower (L-) ports. The U-port flange is connected to each U-port by a hinge, whereas the O-port flange is connected to each O-port by a link (Fig. 4(a)). The L-port flanges are detached and temporarily placed near the L-port at maintenance (Fig. 4(b)). Vacuum sealing with metal gaskets is considered at all flanges. It should be noted that the metal gaskets can be put on the ports or flanges from the upside at every port. This makes handling of gaskets easy, since it is not necessary to temporarily fix the gaskets. The design of the clamping device to provide uniform line pressure around the gasket during tightening is remained as a challenging issue. In the present design, the BB cartridges are connected to the piping for MS supply inside the O-ports and the L-ports using connectors. It is necessary to develop a nuclear standard connector that is applicable to high-temperature MS of ~800 K.

3. Maintenance of the REVOLVER-D

The REVOLVER-D is an ergodic limiter/divertor consisting of ten showers of molten tin jets stabilized by IFRs (Internal Flow Resistances) [5]. The showers of molten tin jets are inserted to the ergodic layer at 10 inner ports. Tin is selected as the working fluid because of its low melting point (~505 K), low vapor pressure (< 10^{-5} Pa at < 1,000 K), low material cost, and high safety. To circulate molten tin, 10 sets of the shower system including an LM pump, ducts, a showerhead, a pool, and a heat exchanger are installed (see Fig. 5). For the ducts intersecting the strong magnetic field, insulated pipes of, for example, the double pipe, in which a ceramic lined pipe is installed inside the outer stainless pipe, should be

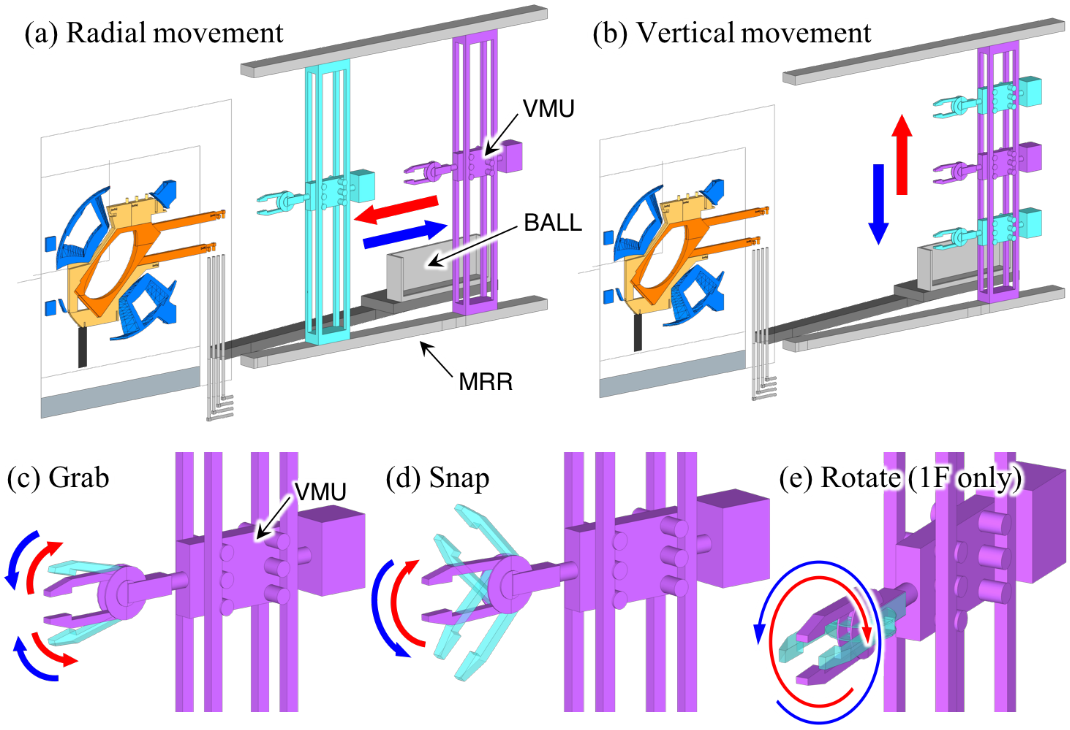

Fig. 6. Basic motions of the GM.

used. Otherwise, an extremely high LM pump power becomes necessary due to the large MHD pressure loss [6]. The LM pump together with the cryopump units and TMPs (Turbo Molecular Pumps) for vacuum pumping are installed inside the HTS-CS (High-Temperature Superconductor Center Solenoid) at the center region of the torus. This HTS-CS is adopted to shield the strong magnetic field in the torus center region of ~5 T (see Fig. 14 in [5]).

The components of REVOLVER-D are divided into two groups from the viewpoint of maintenance. The first group consists of the components that need periodic replacement. The shower heads, cooling panels in the heat exchanger, cryopump units, TMPs, and LM pumps belong to the first group. The second group consists of the components that will be replaced as necessary. The pools and ceramic lined pipes belong to the second group. As shown in Fig. 5, the components of the first group can be replaced with simple up/down motions. The ceramic lined pipes can be replaced from the horizontal direction. Both removal and reinstallation of the components of the first group are assumed to be completed within 10 days, respectively.

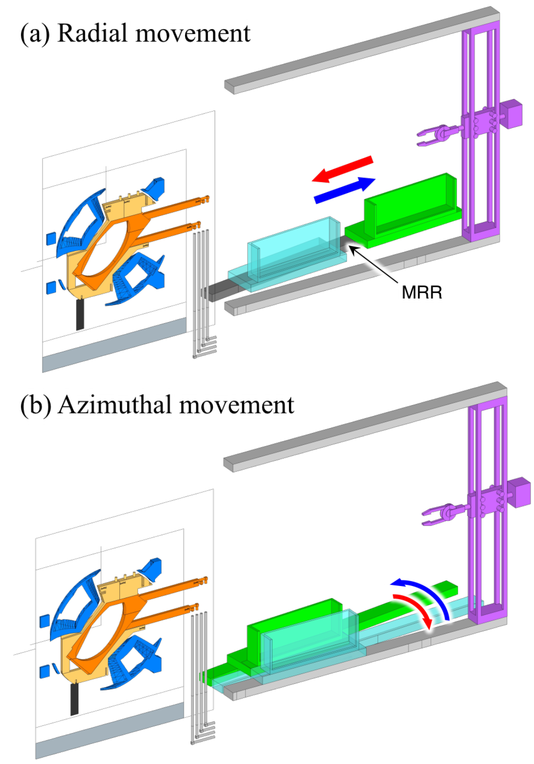

Fig. 7. Basic motions of the BALL.

4. Maintenance of the CARDISTRY-B

In FFHR-c1, the MS blanket is adopted for the reasons of high safety and high tritium breeding ratio, following the former FFHR designs [1-3]. The CARDISTRY-B is also an MS blanket and is composed of ten sets of 44 cartridges for the neutron Shielding Blankets (SB) and ten sets of 32 BB cartridges [7]. Both shielding and breeding blankets are toroidally segmented every two degrees. At each toroidal angle, the segmented parts are divided further into several cartridges, in order to make it possible to assemble these cartridges after completion of the unjointed continuous HTS magnet coils. The SB cartridges are basically assembled by using mortises and tenons prepared on the neighboring cartridges and the L-ports to avoid large area welding. After assembly, the plasma side of the SB is welded along the straight lines of the spaces between the SB cartridges to form the vacuum vessel. U-shaped fillers will be put into the spaces between two SB cartridges and welded at the two edges of “U”. The U-shaped fillers also act as bellows to absorb the thermal deformation of SB cartridges. The gap distance between the SB cartridges is tentatively considered to be 20 – 30 mm. The Tritium Breeding Ratio (TBR) depends on the gap distance. Preliminary results of the neutronics simulation using the MCNP6.1 code shows that the TBR can be larger than 1.1 even with the gap distance of 20 – 50 mm, where the side wall thickness of the SB cartridges and the ^{6}Li enrichment are assumed to be 20 mm and 90 %, respectively [11]. The neutron streaming through the gaps are now under consideration. Depending on the results of the neutronics simulation, proper labyrinth structures and/or fillers will be added to the design. Another side of the SB facing on the magnetic support structures is covered with the thermal shield, which was already attached before assembly. The SB cartridges are used throughout the lifetime of FFHR-c1 without removal and/or reinstallation. On the other hand, 320 BB cartridges in total are replaced and reinstalled periodically. Both replacement and reinstallation of the BB cartridges can be done without cutting or welding of cooling pipes inside the vacuum vessel. Instead, these are connected to the piping with connectors inside the ports, as was already explained in section 2. Further details regarding the CARDISTRY-B are described in [7].

To maintain the CARDISTRY-B, remote handing devices called the GM (Giant Manipulator) and BALL (Box ALL around) will be used. The GM is a simple robot hand fixed to a Vertically Moving Unit (VMU) on a Moving Radial Rail (MRR). The MRR moves in the azimuthal direction and is fixed at the toroidal angle, ϕ, where the BB cartridge to be removed or reinstalled is located. Available motions of the GM, *i.e.*, radial movement along the MRR, vertical movement using the VMU, and three motions of grab, snap, and rotation of the robot hand, are summarized in Fig. 6. Rotation of the robot hand is needed at the first floor alone and it can be omitted if it is difficult to rotate the robot hand holding a heavy cartridge. In other words, at least 4DOF motion is enough to install/remove the BB cartridges at a given toroidal angle. Volumes and weights of the BB cartridges are listed in Table 2. The heaviest cartridges at installation are those of No. 1 and 17 at $\phi = 0$ and 18 deg. of 7.1 and 7.5 tons, respectively. During plasma operation, the MS is filled into each empty BB cartridge and the cartridge weight increases. At maintenance, the MS is drained as much as possible. The percentage of MS drainable from each BB cartridge, α, is also listed in Table 2. After α % drainage of MS, weights of the heaviest cartridges of No. 9, 11, 12, and 17 are 8.0, 8.3, 7.9, and 8.2 tons, respectively. Thus, GMs need to handle ~8 tons of the BB cartridge. This will be possible because the motions of GM are simple. On the other hand, the BALL carries a box to the GM. As depicted in Fig. 7, the BALL moves radially and azimuthally along the MRR. After the removed cartridge is placed in the box by the GM, the BALL carries it to the packaging floor (see Fig. 2).

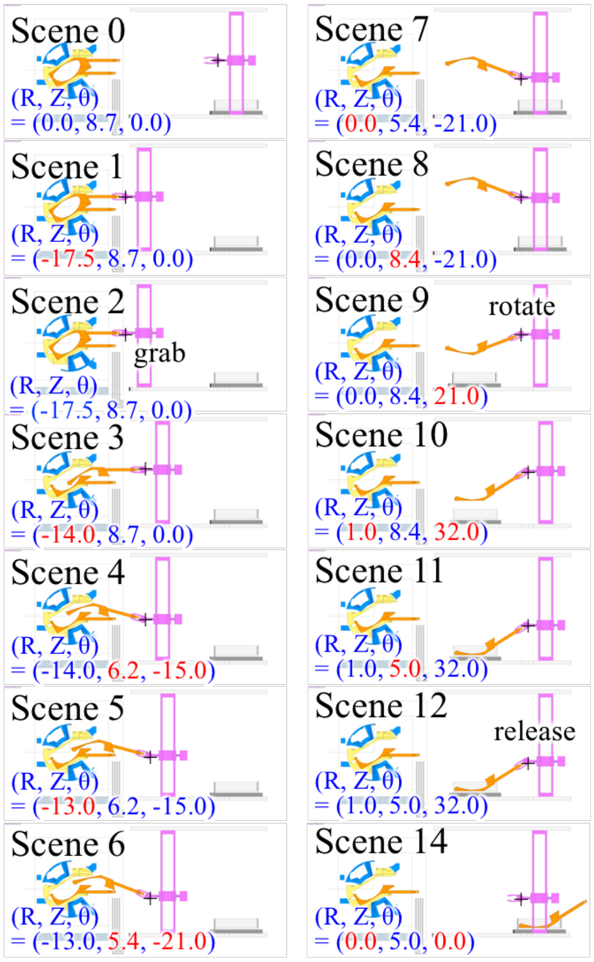

Fig. 8. Schematic views of the removal sequence for the BB cartridge at $\phi = 12$ deg. The scene 13 is omitted.

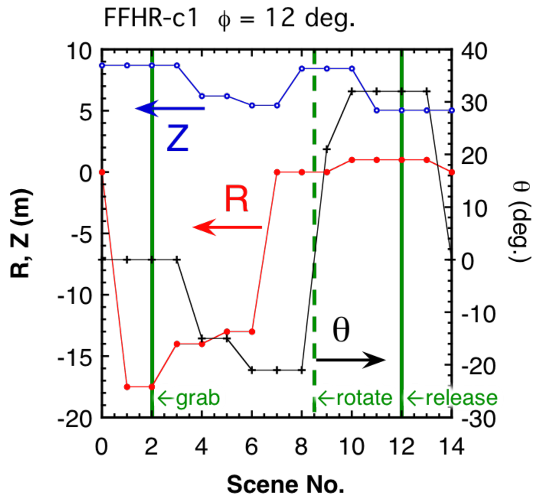

Fig. 9. Preprogrammed positions/motions of the GM at the removal sequence as shown in Fig. 8, for the BB cartridge at $\phi = 12$ deg.

The motions of GM and BALL are preprogrammed as shown in Figs. 8 and 9, where radial and vertical positions together with the snap angle, (R, Z, θ), of the robot hand of GM are defined at each numbered scene. Here, the

Table 3. Summary of the maintenance processes for the FFHR-c1.

Tasks		Days	Contents
Cooling (30 days)	Decontamination	15	Glow (or other) discharge cleaning for tritium removal.
	Vent	2	Release the air into the vacuum vessel.
	Removal of REVOLVER-D	10	Loosen the clamping devices and open the port flanges. Remove shower heads, heat exchangers, cryopump units, TMPs, and LM pumps.
	MS drainage	3	~900 tons of MS in total is drained from 320 cartridges
Removal of BB cartridges		54	Loosen the clamping devices and open the port flanges. Disconnect the MS supplying pipes from the BB cartridges. 6 BB cartridges are removed in one day using two U-ports, two O-ports, and two L-ports.
Reinstallation of REVOLVER-D		10	Reinstall ten shower heads, ten heat exchangers, the cryopump unit, ten LM pumps, and TMPs. Replace the gaskets, close the ports and fasten the clamping devices.
Reinstallation of BB cartridges		54	6 BB cartridges are reinstalled in one day using two U-ports, two O-ports, and two L-ports. Connect the MS supplying pipes to the BB cartridges. Replace the gaskets, close the ports and fasten the clamping devices.
Evacuation		5	Vacuum pumping and leak test
MS circulation test		2	Heat up the BB cartridges from ~300 K to ~600 K and circulate MS.
Discharge cleaning		5	Glow (or other) discharge for vacuum vessel wall cleaning.

origin of (R, Z) = (0, 0) is set at (R', Z') = (38.787 m, -6.711 m) measured from the torus center. The timing to grab/release/rotate the robot hand is also determined at the corresponding scene. The motion of BALL is also preprogrammed (not shown). All motions of GM and BALL are summarized in an animation video. It should be noted that no contamination containment (or radiation shielding) is depicted in Fig. 8. How to confine the tritium and radioactive dusts emitted from the BB cartridges is an important issue and still under discussion at this moment. For example, a folding radiation resistant tent that can keep a negative pressure inside can be a candidate to confine the tritium and dusts. In this case, the tent should enclose the whole working space including the port flange, GM, and BALL.

Small Versatile Manipulators (VMs) are also necessary to support GM and BALL. The VM is used to loosen/fasten the clamping device on each port flange, to place the sealing gasket, and to connect/disconnect the BB cartridges from the MS supplying pipes. The design of the VM is not fixed yet.

5. Maintenance schedule

The availability of a device, A, is defined by A = MTBF / (MTBF + MTTR), where MTBF is the mean time before failure and MTTR is the mean time to repair, respectively. To give the maximum A in the FFHR-c1, the working time of the device that corresponds to the maximum of MTBF and the time needed for periodic maintenance that corresponds to the minimum of MTTR have been estimated. The working time is, of course, one year, or more, since the mission of the FFHR-c1 is the one-year operation, as was discussed in section 2. As for the periodic maintenance, tasks listed in Table 3 should be completed. In Table 3, the number of days needed at the least to do the task, and the contents of each task are also summarized. After the plasma operation of 365 days, at least 30 days are needed before removing the BB cartridges, to wait for the gamma-ray irradiation from BB cartridges to become low enough to be remote-handled by the GM. During these 30 days, decontamination of the BB cartridges, vacuum vent, removal of the REVOLVER-D components, and MS drainage from the BB cartridges are done. At first, glow (or another kind of) discharge cleaning is done for 15 days to remove tritium from the BB cartridge surface. Then, the air is released into the vacuum vessel within two days. After the pressure inside the vacuum vessel increases to 1 atm, a part of the components of REVOLVER-D that require periodic replacement (see section 3) are removed using the GM on the second floor. This may take ten days. The MS in each BB cartridge is drained as much as possible (see section 4 and Table 2). This MS drainage process can be done simultaneously with the removal process of the RE VOLVER-D components. After 30 days of cooling, 320 BB cartridges in total are removed. It may be possible to remove 6 BB cartridges in one day, using two U-ports, two O-ports, and two L-ports, simultaneously. This process is expected to take at least 54 days. After all BB cartridges are removed and it becomes possible to use the GM on the second floor, the removed components of the REVOLVER-D are reinstalled. This may take 10 days as the removal process. Then, new empty BB cartridges are reinstalled again taking 54 days. After 5 days of vacuum pumping and leak tests, the BB cartridges are heated up to ~600 K and MS circulation is started. If there is no problem due to MS circulation, discharge cleaning of the vacuum vessel wall is performed for 5 days. The total number of days for this periodic maintenance is 160 days. The availability is then estimated to be: A = 365 / (365 + 160) ~ 69.5 %. It is possible to increase this by optimizing each process, and/or increasing the number of remote handling robots operating in parallel, and/or extending the MTBF.

6. Summary

The design point of the compact helical fusion reactor FFHR-c1 aimed at a mission of "one-year steady-state operation with self-produced fuel and electricity" has been set at R_c = 10.92 m and B_c = 7.3 T. To ease maintenance and demonstrate high availability, the LM divertor, REVOLVER-D, and the cartridge-type MS blanket, CARDISTRY-B, have been chosen as the primary option for the FFHR-d1. The components of the REVOLVER-D to be replaced periodically can be removed and reinstalled with simple up/down motions. The BB cartridges of CARDISTRY-B, of which the maximum weight is ~8 tons, are maintained by the remote handling robots of GM and BALL. Motions of GM and BALL are preprogrammed and in particular, the GM can remove BB cartridges within a fixed toroidal angle with a simple motion. The periodical maintenance is expected to take 160 days and the availability can be larger than ~70 %, if the MTBF is longer than 365 days.

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