Cartridge-Type Helical Blankets Aiming at Easy Construction and Maintenance for the FFHR-d1

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A new cartridge-type blanket named the CARDISTRY-B is proposed for the helical fusion reactor FFHR-d1. This blanket is composed of the neutron shield and the tritium breeder using molten salt. Both of these 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 superconducting magnet coils. The neutron shield is basically assembled by using mortise and tenon prepared on each of the cartridges and the lower port, instead of the wide area welding. After assembly, the plasma side of the neutron shield is welded to form a vacuum vessel. Another side of the neutron shield facing on the superconducting magnet coils is covered with the thermal shield, which was already attached before assembly. The tritium breeder cartridges can be replaced without cutting or welding of cooling pipes inside the vacuum vessel, where severe radiation dose is expected. Details of the CARDISTRY-B, including the results of motion analysis for all cartridges and estimation of the cartridge weight, are discussed.

Keywords: heliotron, fusion reactor, tritium-breeding blanket, neutron shield, thermal shield, toroidal segmentation, LHD, FFHR, REVOLVER-D, CARDISTRY-B

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1. Introduction

The conceptual design activity on a helical fusion reactor FFHR-d1 is ongoing [1, 2]. The FFHR-d1 is basically a heliotron device similar to the LHD [3] and consists of two main helical coils and 4 planar poloidal field coils [4] of high-temperature superconducting (SC) magnet [5]. The device size is four times larger than the LHD. The magnetic field strength at the plasma center is ~5 T and the fusion output is ~3 GW. The FFHR-d1 is inherently equipped with the helical divertor as in the LHD. There are two serious issues for the helical divertor of the FFHR-d1. The first issue is the extremely high divertor heat load exceeding a few tens of MW/m^2. The second is the difficult maintenance of the helical divertor with three-dimensionally complicated structure. Recently, a liquid metal limiter/divertor system named the REVOLVER-D has been proposed to solve these issues, where showers of molten tin are inserted at 10 inner ports to intersect the ergodic layer [6]. The showers play the role of a limiter and the helical divertor becomes less necessary in this case. At the same time, the neutral gas generated from the plasma hitting the shower can be easily evacuated through the shower and therefore the REVOLVER-D can also work as the divertor. The flowing molten tin tolerates the high heat loads if the flow velocity is fast enough. Since the components of the REVOLVER-D are discretely distributed, the maintenance is easier than in the case of the helical divertor, in which the target plates continuously spread across both toroidal and poloidal directions.

The blanket is one of the essential constituents in a fusion reactor. In the FFHR-d1, the blanket is divided into two components of tritium Breeding Blanket (BB) and neutron Shielding Blanket (SB). The molten salt FLiBe or FLiNaBe is chosen as the first option of the breeder material [1, 2, 7, 8], mainly from the reason of safety. Self-cooling by the molten salt itself is considered as the first option and therefore no other coolant of water or helium gas is assumed for the BB in FFHR-d1. The inlet and outlet temperatures in the case of FLiNaBe BB made of Reduced Activation Ferritic Martensitic steels (RAFM) is supposed to be 350 and 500 °C, respectively, with a temperature margin of 50 °C for both of the lower and the upper limits. The upper limit can be increased to 650 °C by using the vanadium alloys applicable to > 700 °C [1]. The BB suffers from the direct irradiation of 14 MeV neutrons and therefore needs periodical replacement. The replacement cycle and maintenance time of the BB are supposed to be 3 - 5 years and 3 - 6 months, respectively, although these are not yet fixed. The SB is placed behind the BB to protect the SC magnet coils from strong neutron irradiation. Basically, the SB is considered as the permanent component without

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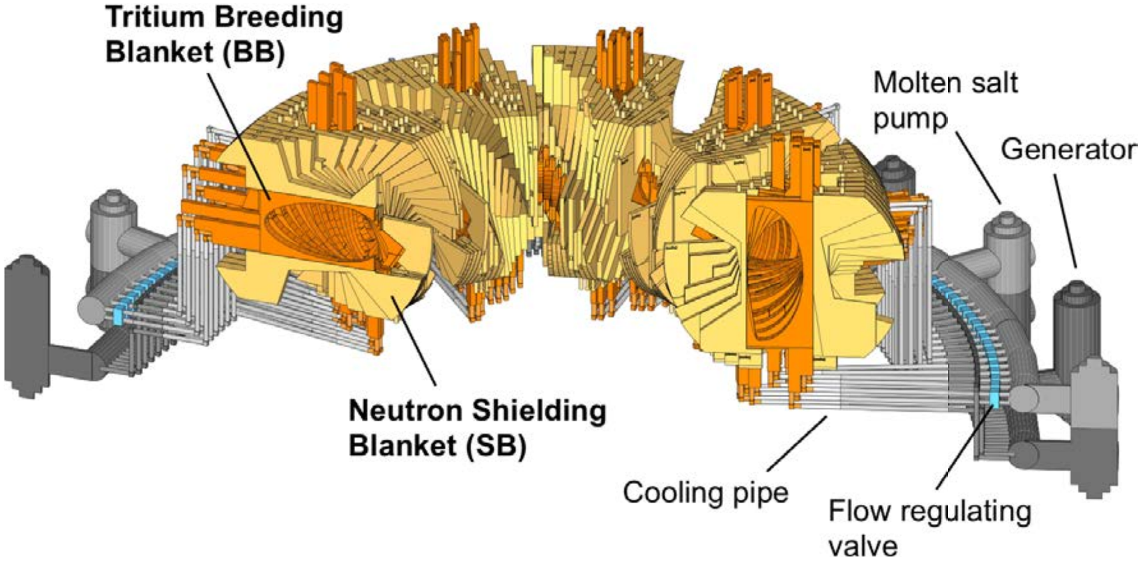

Fig. 1 Schematic view of the CARDISTRY-B for the FFHR-d1. The BB and SB cartridges are drawn by different colors. Each cooling pipe connected to the BB cartridge will be equipped with the flow regulating valve. Arrangement of molten salt pumps and generators is tentative.

periodical replacement. The surface of SB being faced by the SC magnet coils and the SC coil support structure [9], should be covered with the thermal shield, which is cooled by helium gas to 40 - 80 K and insulates the heat intrusion from the SB to the SC magnet coils and the SC coil support structure. At this moment, the construction of SB is scheduled after completion of the SC magnet coils and the SC coil support structure. Both construction and maintenance schemes for the SB and BB should be as easy as possible. For this, it is essential to consider how to divide the SB and BB. It should be noted that the total weight of the SB and BB in the FFHR-d1 is expected to be ~30,000 tons. Therefore, it is inevitable to divide the SB and BB into small parts to enable easy handling.

In the former study [10], we proposed the "T-SHELL" BB. This BB is toroidally segmented every 3 degrees. The motion analysis at replacement was mainly discussed in [10], and it was shown to be possible to replace the segmented parts by a combination of uniaxial movements and poloidal rotation in the plane with a constant toroidal angle without cutting/rewelding of cooling pipes inside the vacuum vessel. The T-SHELL BB was designed to be consistent with the helical divertor. However, the cooling pipe arrangement including consideration of the drainage capability remained for the future work. Open issues related to how to handle the segmented BB, how to segment and construct the SB, and how to install the thermal shield on the SB also remained.

In this paper, we propose a new cartridge-type helical blanket named the CARDISTRY-B, where CARDISTRY and B stand for "CARtridges Divided and InSerTed RadiallY" and "Blanket," respectively. A schematic view of the CARDISTRY-B is shown in Fig. 1. This consists of SB and BB toroidally segmented every 2 degrees. The CARDISTRY-B is designed to be consistent with the REVOLVER-D. Nevertheless, the basic concept of the cartridge-type blanket will be also applicable to the helical divertor configuration. It is possible to construct the SB by inserting the cartridges equipped with thermal shields after completion of the SC magnet coils and the SC coil support structure. The replacement of BB can be easily carried out by pulling the cartridges out in radial and/or vertical directions. Each of the SB and BB cartridges is moved within the corresponding toroidal angle, *i.e.*, toroidal movement or rotation on the halfway is not necessary. Further details of the SB and BB of CARDISTRY-B are described in Secs. 2 and 3, respectively. Summary and issues remaining for future studies are given in Sec. 4. Tables listing the volume and weight of SB and BB cartridges, figures of all SB and BB cartridges (Fig. A1), side views of the assembled SB and BB with Poincaré plots of the ergodic layer and closed magnetic surfaces inside the LCFS (Last-Closed-Flux-Surface) (Figs. A2 and A3), and results of motion analysis on SB and BB cartridges at every 2 degrees from 0 to 34 degrees of toroidal sections (Figs. A4 - A21) are given in the Appendix.

2. The Neutron Shielding Blanket (SB)

The SB of CARDISTRY-B is toroidally segmented every 2 degrees as shown in Fig. 2. Note that the FFHR-d1 has a symmetric structure for every 36 degrees in the toroidal direction, as in the case of LHD. Therefore, ten sets of the cartridges shown in Fig. 2 constitute a complete structure of the SB. Toroidal segmentation is employed as the T-SHELL BB, since it becomes possible to insert or remove the cartridges within a fixed toroidal angle in this case. Horizontal and helical segmentations were also considered. Unfortunately, these were not successful as toroidal segmentation, since three-dimensional movements are necessary in these cases. In this study, 2 (= 36/18) degrees is chosen for toroidal segmentation. In the case of segmentation by every 2.4 (= 36/15) or 3 (= 36/12) degrees, for example, the number of cartridges can be much reduced. However, at the same time, it becomes difficult to design the cartridges of SB and BB that can be inserted or pulled out through the SC coil support structure at a fixed toroidal angle. Furthermore, the weight of each cartridge increases. At least in the case of segmentation by 2 degrees, it is possible to design cartridges that can be moved without collision with the SC coil support structure, as shown in Figs. A4 - A21 in the Appendix.

Each SB cartridge is fixed by using the mortises prepared on the lower port and the tenons prepared on the side of neighbor cartridge that was already installed. An example of the SB assemble procedure is shown in Fig. 3. The thermal shields are set on the SB cartridge surface facing the SC coil support structure before assembly. The thermal shield plate denoted in Fig. 3 is equipped to set the thermal shield for the neighboring SB cartridge in advance. Basically, an SB cartridge is installed by sliding it along the cartridge installed just before. Then, in some cases, it becomes difficult to set the thermal shield before assembly. The thermal shield plates are prepared for such cases. It is supposed that all cartridges equipped with the thermal shield will be manufactured and tested in the factory. Then, it becomes possible to maintain a high precision. It is also possible to carry out the post weld heat treatment to assure the strength of the welded materials [11, 12], if necessary. Since the piping for coolant circulation inside the SB cartridges and thermal shields will be complicated, it is desirable to carry out the leak test in the factory.

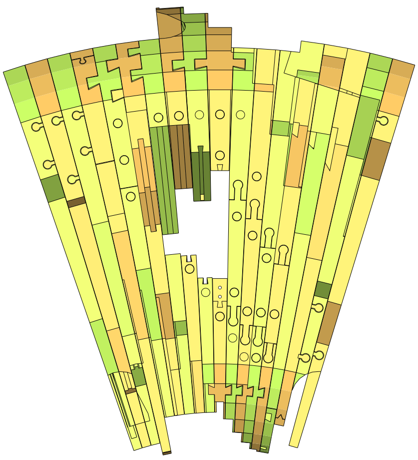

Fig. 2 Top view of the neutron shielding blanket (SB). The SB cartridges are painted in alternating colors to clearly distinguish the cartridges at different toroidal angles.

Mortises and tenons with various shapes are used in the design of CARDISTRY-B as shown in Fig. 4. These shapes can be varied if necessary, according to the result of stress analysis that will be carried out in future. The direction of motion to fix a set of mortise and tenon is restricted to the vertical and horizontal directions, to simplify the assemble procedure. Since a SB cartridge is fixed to its proper position by using mortises and tenons, it is basically not necessary to weld it with neighbor cartridges. Nevertheless, these cartridges will be welded on the plasma side to form a vacuum vessel, as shown in Fig. 5. The welding lines are basically straight. The welding depth is supposed to be 10 mm more or less. This welding process should be done after all of the SB cartridges are assembled in order to minimize welding deformation. Complicated three-dimensional welding lines as was the case in the vac-

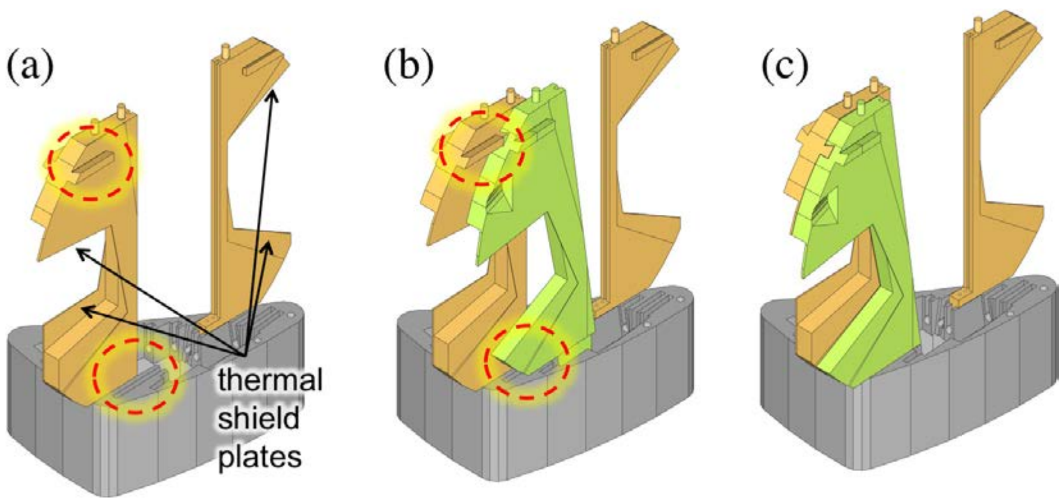

Fig. 3 Schematic of an example of SB assembly procedure, which proceeds from (a) to (c). Broken circles denote the mortise in the L-port and the tenon in the cartridges installed before the cartridge being assembled. The thermal shield plates are denoted by arrows. The SB cartridges already installed and that being installed are painted by different colors to distinguish these clearly.

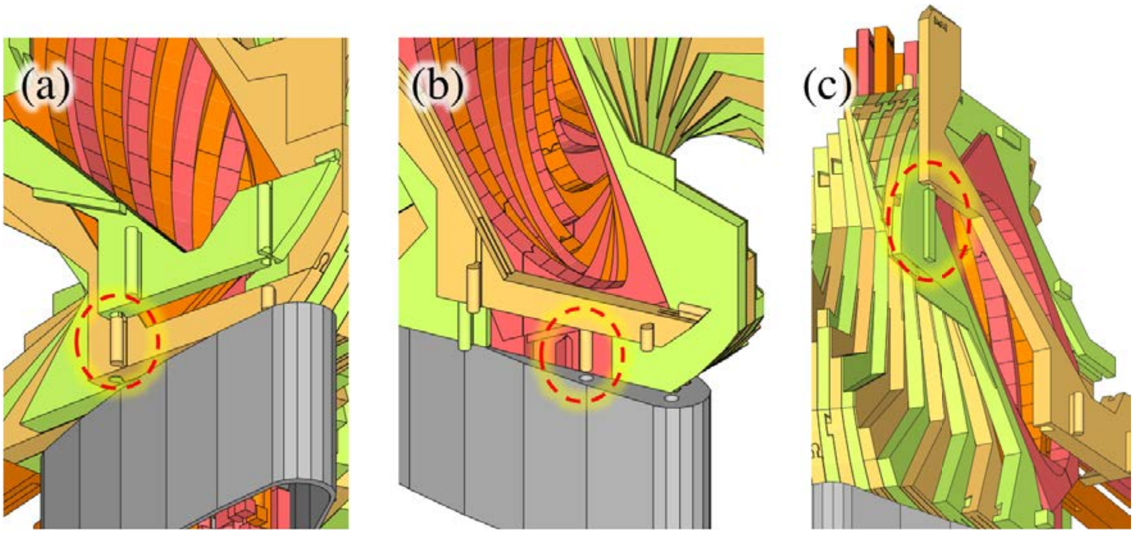

Fig. 4 Examples of the mortise and tenon with various shapes. The SB and BB are painted in alternating colors to clearly distinguish the cartridges at different toroidal angles.

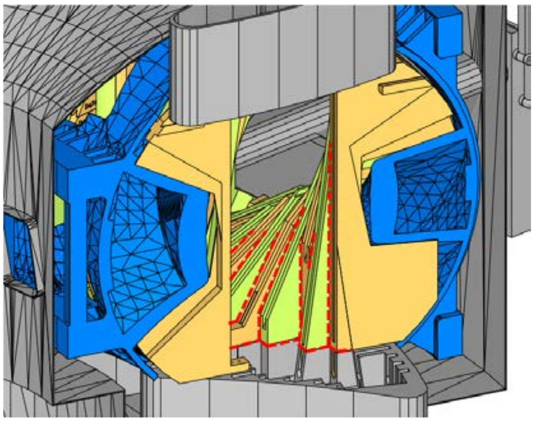

Fig. 5 Welding lines (broken lines) connecting the neighboring SB blankets to form a vacuum vessel.

uum vessel of LHD are not necessary in the CARDISTRY-B. It should be noted that the welding lines play a role of the tritium boundary. Estimation of the mechanical stress, the tritium leak rate, and the soundness of welding lines that will suffer from irradiation by the streaming neutrons through the clearance between the BB cartridges, should be carefully done in the future study.

Weights of SB cartridges are summarized in Table A1 in the Appendix. To obtain these estimations, it is assumed that the SB cartridges are basically hollow boxes equipped with stiffening ribs inside. The material of the box and ribs is assumed to have a density of 8 ton/m^3 and occupancy of 20% in the entire cartridge volume. It is also assumed that pebbles of tungsten carbide (WC) of 16 ton/m^3 of density will be filled into each of the SB cartridges with 40% of the filling rate in 80% of the cartridge volume, after the SB blankets are assembled. Here, we used a moderate filling rate of 40% to enable flexible design of cooling channels. At this moment, we are considering gas cooling of SB using He flowing through the space between WC pebbles. The operation temperature of the SB is supposed to be around the room temperature on the thermal shield side and 350 - 500 °C on the BB side, in the case of the FLiNaBe BB made of RAFM. The simulation studies on the flow and heat transport inside the SB to determine the design of flow channel are left for the future study. The position of the coolant inlet and outlet ports on SB cartridges will be determined after the simulation study. Basically, these should be placed inside the upper, outer, and lower ports to minimize the heat intrusion to the SC magnet coils and the SC coil support structure. The weight of the empty cartridge ranges from 2 to 35 tons. The total weight of the SB, which consists of 10 sets of cartridges listed in Table A1, is estimated to be ~5,600 tons or ~28,000 tons before or after filling the WC pebbles.

All of the SB blanket assemble procedures at each 2 degrees from 0 to 34 degrees of the toroidal angle are shown in Figs. A4 - A21 in the Appendix. The motion of each SB cartridge during installation can be also seen in these figures, which at the same time show that assembly of the SB blankets can be performed after installation of the SC coil support structure and completion of the SC magnet coils and SC helical coil winding.

3. The Tritium Breeding Blanket (BB)

Similar to the SB, the BB is toroidally segmented every 2 degrees as shown in Fig. 6. The BB was designed by the following procedure.

1) Place a rectangular box of 1.04 m × 4.90 m × 1.80 m at the toroidal angle of ϕ deg., according to the definition given in Table 1. The center of the largest side

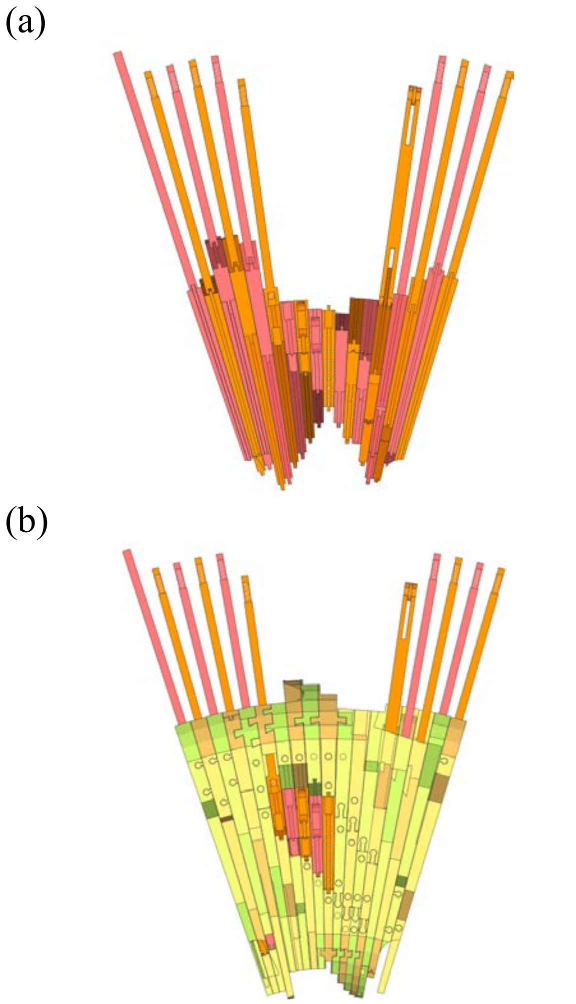

Fig. 6 Top view of the tritium breeding blanket (BB) (a) w/o SB and (b) with SB. The SB and BB are painted in alternating colors to clearly distinguish the cartridges at different toroidal angles.

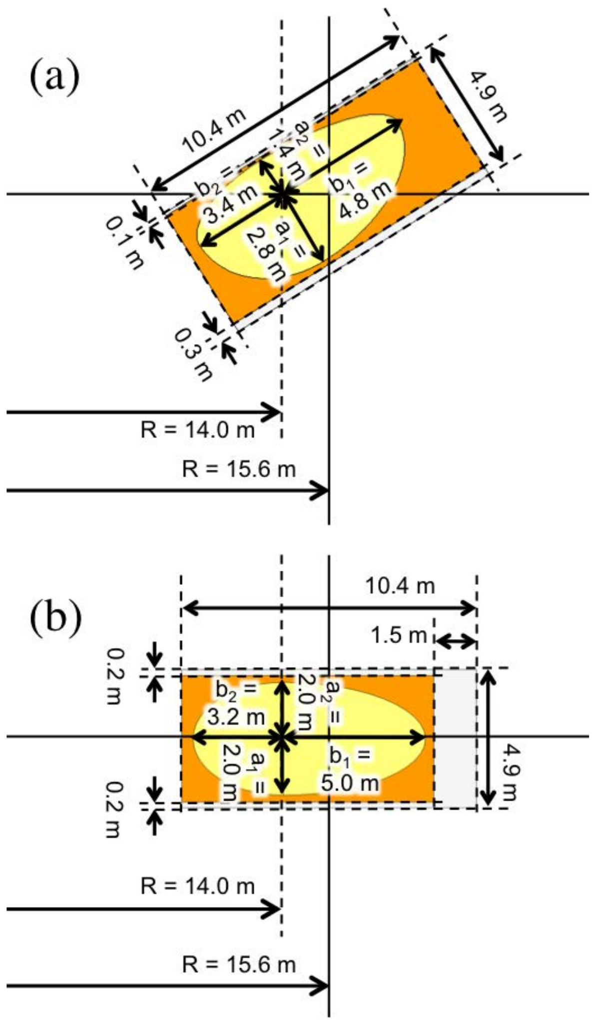

Fig. 7 Basic BB cartridge boxes at (a) $\phi = 12$ deg. and (b) $\phi = 18$ deg.

is set to $R = R_c = 15.6$ m (see Fig. 7), where R_c is the helical coil major radius of the FFHR-d1.

2) Rotate the box poloidally for θ deg. around $R = 15.6$ m, according to the definition given in Table 1.
3) Open an ellipse on the box. The major and minor radii of a_1, a_2, b_1, and b_2 are defined in Table 1. The ellipse is rotated poloidally for θ deg., around the center of the ellipse positioned at $R = 14.0$ m (see Fig. 7, again). In some cases, the side length of the rectangular box is shortened to reduce the cartridge volume, according to the length denoted in the square brackets in the right four columns of Table 1 (see also Fig. 7).
4) Cut the box by two planes supposed to be at constant toroidal angles of $\phi - 1$ deg. and $\phi + 1$ deg.
5) Divide the box into two parts and/or cut a part of the box off, if necessary, in order to extract the divided parts through the SC coil support structure, or to avoid interfering with the inner ports and components of the REVOLVER-D.
6) Add a handle to the (divided) box as seen in Fig. A1 in the Appendix. The handle can be equipped with connecting nozzles to introduce or drain the molten salt to or from the box.

The major and minor radii of the ellipse opened on a cartridge box and constituting the first wall of vacuum vessel are determined so as to avoid direct contact between the first wall and the LCFS, as shown in Figs. A2 and A3 in the Appendix. A so-called ergodic layer surrounds the LCFS in FFHR-d1, as is also the case in LHD. The magnetic field lines travel for more than a few km in the ergodic layer and finally reach the divertor targets, in the case of ordinary helical divertor. In the CARDISTRY-B, it is assumed that the REVOLVER-D, which plays the role of a limiter inserted to the ergodic layer, is applied at the same time. Then, the plasma in the ergodic layer hits the liquid metal shower of REVOLVER-D and becomes neutralized before reaching the helical divertor targets. This is the reason why no armor tile is placed on the cartridges, even at the positions where the magnetic field lines of the ergodic layer are in-

Table 1 A list of the poloidal rotation angle, θ, and major or minor radii of the elliptic hole on the BB cartridges, a_1, a_2, b_1, and b_2, at each toroidal angle of ϕ. The number in the square bracket in the columns of a_1, a_2, b_1, and b_2, denotes the shortened length of the rectangular side parallel to the corresponding radius.

No.	Toroidal angle ϕ (deg.)	Poloidal rotation angle θ (deg.)	a_1 (m)	a_2 (m)	b_1 (m)	b_2 (m)
1	0	90	2.8 [0.60 m]	0.80	4.8	4.8
2	2	82	2.8 [0.80 m]	0.80	4.8	4.5
3	4	74	2.8 [0.70 m]	0.80	4.8	4.2
4	6	65	2.8 [0.60 m]	0.90	4.8	4.0
5	8	59	2.8 [0.60 m]	1.17	4.8	3.8
6	10	44	2.8 [0.40 m]	1.20	4.8	3.6
7	12	32	2.8 [0.30 m]	1.40 [0.10 m]	4.8	3.4
8	14	20	2.6 [0.25 m]	1.60 [0.15 m]	4.8	3.3
9	16	10	2.3 [0.20 m]	1.80 [0.20 m]	5.0 [1.50 m]	3.2
10	18	0	2.0 [0.20 m]	2.00 [0.20 m]	5.0 [1.50 m]	3.2
11	20	170	2.3 [0.20 m]	1.80 [0.20 m]	5.0 [1.50 m]	3.2
12	22	160	2.6 [0.25 m]	1.60 [0.15 m]	4.8 [1.50 m]	3.3
13	24	148	2.8 [0.30 m]	1.40 [0.10 m]	4.8 [1.50 m]	3.4 [0.25 m]
14	26	136	2.8 [0.40 m]	1.20	4.8 [1.05 m]	3.6
15	28	121	2.8 [0.60 m]	1.17	4.8 [1.00 m]	3.8 [0.25 m]
16	30	115	2.8 [0.60 m]	0.90	4.8	4.0
17	32	106	2.8 [0.70 m]	0.80	4.8	4.2
18	34	98	2.8 [0.80 m]	0.80	4.8	4.5

tersecting (see Figs. A2 and A3 in the Appendix). If the REVOLVER-D is not adopted, then it becomes necessary to place armor tiles at proper positions on each cartridge. In this case, however, the armor tiles should be carefully designed by taking into account the direct 14 MeV neutron irradiation and severe heat loads on them.

To protect the SB cartridges from direct irradiation by 14 MeV neutrons, guarding fins are equipped on the plasma side of BB cartridges, as shown in Fig. 8. The thickness of the guarding fin should be as thick as possible while keeping enough clearance to the plasma. At this moment, the thickness of the guarding fin is supposed to be 100 mm. If the BB is made of 5 - 10 mm thick plates, then there remains a space of 80 - 90 mm thick inside the guarding fin. The molten salt also flows through this space to cool the guarding fin. A simulation study to investigate the complicated flow pattern together with the heat transport inside the BB is now underway. The thickness of the material plates and guarding fins, which also compose the first wall, will be finally determined after this simulation.

A BB cartridge is inserted or withdrawn along the mortises prepared on the SB cartridge. The shapes of the mortise on the SB and the corresponding tenon on the BB are rectangular or trapezoidal, as shown in Fig. 9. The clearance between the mortise and tenon should be carefully determined in order to insert or withdraw the BB cartridges smoothly at maintenance. Ceramic coating on the surfaces of the mortise and tenon will be beneficial for smooth movement.

Weights of BB cartridges are summarized in Table A2 in the Appendix. It is assumed that a BB cartridge is basically a hollow box with flow channels inside. The material of the box and channels is assumed to have a density of 8 ton/m^3 and occupancy of 20% in the entire cartridge volume. As listed in Table A2, 32 BB cartridges are used at one section of 36 degrees, and the weight of the empty BB cartridge ranges from 6 to 22 tons. The total weight 320 empty BB cartridges at 10 sections is ∼3,700 tons. It is also assumed that the molten salt of 2 ton/m^3 will be filled into the cartridge during the operation. Then, the total weight increases to ∼7,200 tons. At maintenance, α% of the molten salt in each cartridge is drained, where α is roughly determined by taking the vertical position of the drainpipe with respect to the cartridge into account (see the rightmost column of Table A2). The weight of a cartridge at maintenance is expected to be $\leq$ 24 tons and the total weight of 10 sets is ∼4,700 tons.

Two pipes are connected to a BB cartridge to supply or drain the molten salt, *i.e.*, 640 pipes are connected to 320 BB cartridges. Each cooling pipe will be equipped with the flow regulating valve to control the outlet temperature of the molten salt, as was shown in Fig. 1. At maintenance, these pipes are separated from the BB cartridge as shown in Fig. 10. Since the radiation dose in the plasma confinement region surrounded by ellipses of the BB inevitably becomes quite high due to direct irradiation by 14 MeV neutrons, it is desirable to complete the maintenance without any work inside the BB. In the case of CARDISTRY-B, the separation and connection of pipes can be performed in the outer or lower ports, *i.e.*, outside of the BB, where the radiation dose is expected to be lower than that inside the BB. Quantitative estimation of the radiation dose inside and outside of the BB depends on the operation scenario and remains for future study. To reduce the maintenance time, use of a coupler to connect the cooling pipes to the BB cartridges, instead

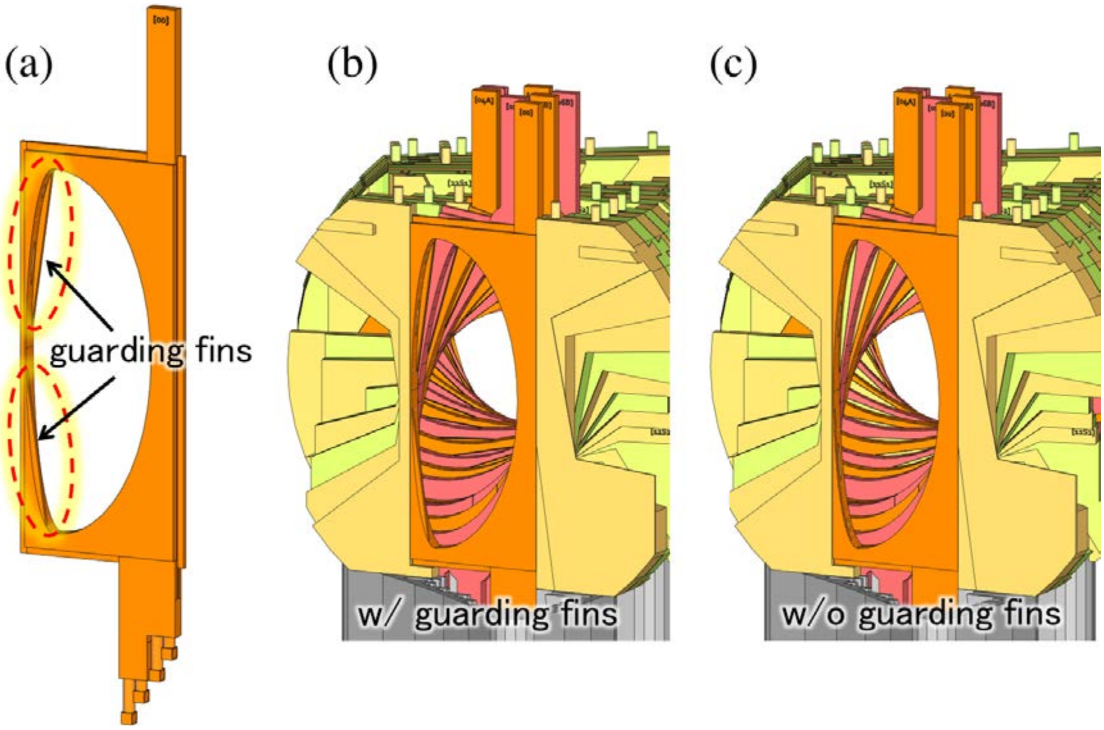

Fig. 8 (a) An example of the guarding fins at $\phi = 0$ deg. SB and BB (b) with or (c) without the guarding fins. The guarding fins protect the SB from direct irradiation by 14 MeV neutrons.

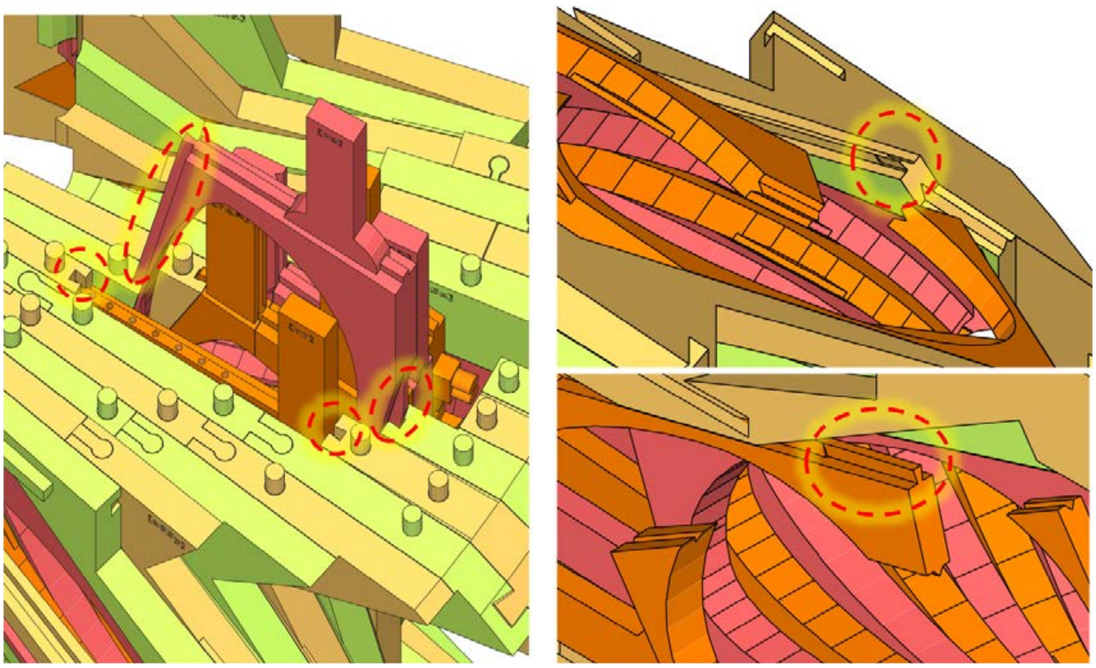

Fig. 9 Examples of mortises on the SB that work as a track to guide tenons on the BB at installation or replacement.

of cutting and welding, is desirable. As mentioned in Introduction, the operation temperature of the FLiNaBe BB made of RAFM is 350 - 500 °C. Although the operation pressure, which depends on the design of the flow channel inside the BB, is not determined yet, the target pressure for the design is supposed to be ~1 MPa. Development of a coupler applicable for fluoride molten salt at these temperature and pressure is highly required. Detailed estimation of the maintenance time is not carried out yet, although it is supposed to be done within roughly two month after one month of the cooling phase. For example, if six BB cartridges are replaced in one day using two upper ports, two

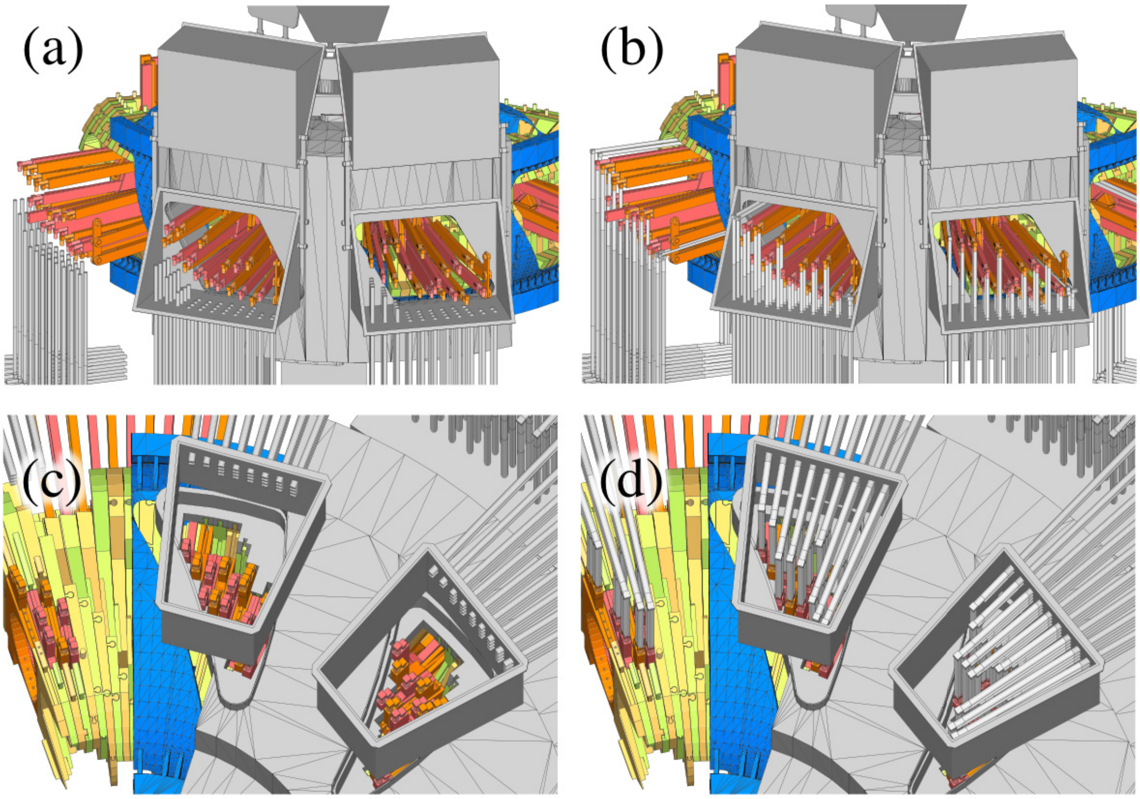

Fig. 10 Example views of the outer ports ((a) and (b)) and the lower ports ((c) and (d)), before ((a) and (c)) and after ((b) and (d)) connecting the pipes to the BB cartridges for molten salt supply.

outer ports, and two lower ports, simultaneously, then ~53 days are needed for full replacement. A concrete maintenance scheme is now under discussion.

Note that a rink mechanism is adopted for the cartridge of 28A at $\phi = 28$ deg. (see Figs. A1 and A18), in order to insert or withdraw the cartridge through the narrow space on the SC coil support structure at this toroidal angle. If the rink mechanism is difficult to use in the reactor condition, then toroidal movement should be allowed as an exception for this cartridge.

The motion analysis using two-dimensional (2D) figures alone is not necessarily perfect. Even though a cartridge seems to be movable without collision, it is sometimes difficult to hold the cartridge tightly, due to the narrow working space around the cartridge. Therefore, three-dimensional (3D) consideration is inevitable. Recently, the technology of 3D printers has been progressing significantly. Using a 3D printer that can reproduce a model with 16 - 100 μm of resolution, we have made a 1/100 scale model of the CARDISTRY-B and the SC coil support structure of FFHR-d1, as shown in Fig. 11. Lessons learned from this work are immediately fed back to the design. For example, the clearance between mortises and tenons, or adjoining cartridges were set to 0.1 mm for the first time. In this case, however, the cartridges often become fixed because of the lack of clearance. Therefore, we have increased all of the clearance to 0.2 mm. Since the model is 1/100 scale of the CARDISTRY-B, this clearance corresponds to 2 cm in the real scale. The clearance in the real scale should be determined in the future study by taking into account the manufacturing accuracy and thermal expansion of the cartridges during operation. If the clearance is determined to be 2 cm, as suggested above, or larger, it will be necessary to use a kind of keystone or spacer to rigidly fix each cartridge at its proper position under strong electromagnetic force. Spacers will be also beneficial to decrease the neutron streaming through the clearance between the SB cartridges.

4. Summary

A new cartridge-type helical blanket CARDISTRY-B has been proposed. This is composed of SB and BB, both of which are toroidally segmented every 2 degrees. The segmented parts are divided further, in order to enable installation and replacement in a plane at fixed toroidal angle. The thermal shields are installed on each of the SB cartridges before assembly. The SB cartridges are assembled using mortises and tenons after installation of the SC magnet coils and the SC coil support structure. Then, the neighboring SB cartridges are welded on the plasma side for ~10 mm in depth, to form a vacuum vessel. After completion of the SB, pebbles of WC are filled into the SB cartridges. Weight of the empty SB cartridges ranges from 2

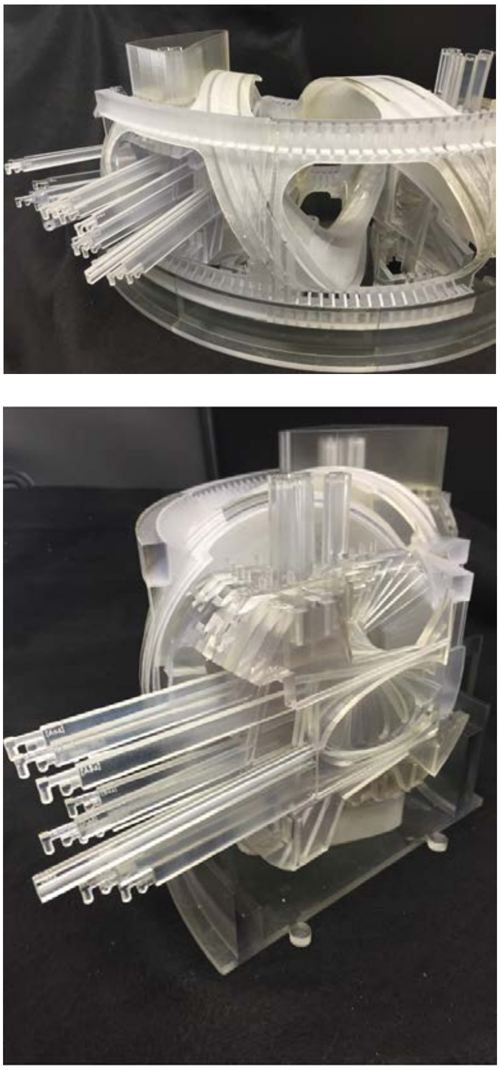

Fig. 11 1/100 scale model of the CARDISTRY-B made by using a 3D printer.

to 35 tons and the total weight of the complete SB with WC pebbles filled inside is ~24,000 tons. The BB cartridges are installed or replaced along the mortise prepared on the SB. Replacement of the BB cartridges can be performed without cutting or rewelding of cooling pipes inside the vacuum vessel. Pipes to supply or drain the molten salt into or from the BB cartridge are connected inside the outer and lower ports. The total weight of the complete BB filled with molten salt is ~7,200 tons. At maintenance, the molten salt is drained as much as possible and the weight of the drained BB cartridges ranges from 6 to 24 tons. Motion analysis to check the collision between SB cartridges and the SC coil support structure, and that between SB and BB cartridges has been carried out using 2D figures and 3D models.

It has been shown that the CARDISTRY-B has a good possibility to realize easy construction and maintenance for the FFHR-d1. Nevertheless, there remain several important issues to increase the possibility of CARDISTRY-B. Listed below are the issues to be solved in future studies.

1) Design of the flow channel of cooling gas in SB and molten salt in BB.
2) The flow and heat transport analysis on the SB and BB cartridges, to determine the thickness of material plates and the design of flow channels.
3) Structural analysis of the cartridges including the welding lines, with considerations on the thermal expansion and neutron irradiation.
4) Three-dimensional neutronics analysis to estimate the Tritium Breeding Ratio (TBR), neutron streaming, activation, and nuclear heating in the SC magnet coils.
5) Establishment of the construction and maintenance scenarios, including design of cranes and/or robots, development of high-temperature and high-pressure coupler for fluoride molten salt, concrete plans of decontamination and storage.

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Appendix

Large tables and figures that are difficult to include in the main body of the text are given in this appendix. Summaries of volumes and weight of the SB and BB cartridges are given in Tables A1 and A2, respectively. Figures and names of all SB and BB cartridges are shown in Fig. A1. Clearance between the BB and magnetic surfaces at $\phi = 0$ - 16 deg. and 18 - 34 deg. are shown in Figs. A2 and A3, respectively. The assemble procedures of SB and BB at every 2 deg. of $\phi = 0$ - 34 deg. are shown in Figs. A4 - A21.

[1] A. Sagara *et al.*, Fusion Eng. Des. **89**, 2114 (2014).
[2] A. Sagara *et al.*, 2016 IAEA Fusion Energy Conf., Kyoto, Japan, FIP/3-4Ra, submitted to Nucl. Fusion. https://conferences.iaea.org/indico/event/98/session/40/contribution/204/material/paper/0.pdf
[3] A. Komori *et al.*, Fusion Sci. Tech. **58**, 1 (2010).
[4] J. Miyazawa *et al.*, Plasma Fusion Res. **7**, 2402072 (2012).
[5] N. Yanagi *et al.*, Cryogenics **80**, 243 (2016).
[6] J. Miyazawa *et al.*, 2016 IAEA Fusion Energy Conf., Kyoto, Japan, FIP/P7-2. https://conferences.iaea.org/indico/event/98/session/31/contribution/16/material/paper/0.pdf
[7] T. Tanaka *et al.*, Plasma Fusion Res. **7**, 2405132 (2012).
[8] T. Tanaka *et al.*, Fusion Eng. Des. **87**, 584 (2012).
[9] H. Tamura *et al.*, Fusion Eng. Des. **88**, 2033 (2013).
[10] T. Goto *et al.*, Plasma Fusion Res. **11**, 2405047 (2016).
[11] J. Moon *et al.*, Metall. Mater. Trans. A **46A**, 156 (2015).
[12] H. Fu *et al.*, Plasma Fusion Res. **10**, 3405015 (2015).

Table A1 Summary of volumes and weights of the SB cartridges. The cartridge names are defined in Fig. A1. See text for assumptions to estimate the weights before and after filling the WC pebbles.

No.	Toroidal angle ϕ (deg.)	Cartridge name	Volume V (m^3)	Weight w/o WC pebbles $(8 \times 0.2) \times V$ (ton)	Weight w/ WC pebbles $(8 \times 0.2 + 16 \times 0.8 \times 0.4) \times V$ (ton)
1	0	00S1	7.6	12	51
2	0	00S2	21.7	35	146
3	2	02S1	6.9	11	46
4	2	02S2	20.7	33	139
5	4	04S1	7.1	11	47
6	4	04S2	16.0	26	107
7	6	06S1	6.2	10	41
8	6	06S2	12.9	21	86
9	8	08S1	4.5	7	31
10	8	08S2	2.0	3	13
11	8	08S3	5.3	9	36
12	10	10S1	5.7	9	38
13	10	10S2	5.8	9	39
14	10	10S3	6.1	10	41
15	12	12S1	5.4	9	36
16	12	12S2	6.8	11	46
17	12	12S3	3.1	5	21
18	12	12S4	1.6	3	11
19	14	14S1	8.2	13	55
20	14	14S2	9.4	15	63
21	16	16S1	8.6	14	58
22	16	16S2	10.1	16	68
23	18	18S1	9.0	14	60
24	18	18S2	10.5	17	70
25	20	20S1	8.2	13	55
26	20	20S2	9.5	15	64
27	22	22S1	8.1	13	54
28	22	22S2	7.6	12	51
29	24	24S1	5.7	9	38
30	24	24S2	10.8	17	73
31	26	26S1	6.2	10	42
32	26	26S2	5.2	8	35
33	28	28S1	7.0	11	47
34	28	28S2	1.7	3	11
35	28	28S3	3.8	6	26
36	30	30S1	6.9	11	47
37	30	30S2	1.2	2	8
38	30	30S3	14.2	23	95
39	32	32S1	6.5	10	44
40	32	32S2	1.4	2	10
41	32	32S3	19.1	31	129
42	34	34S1	6.8	11	46
43	34	34S2	1.5	2	10
44	34	34S3	19.1	31	129
		Total	352.0	563	2,365

Table A2 Summary of volumes and weights of the BB cartridges. The cartridge names are defined in Fig. A1. See text for assumptions to estimate the weights before and after filling the molten salt.

No.	Toroidal angle ϕ (deg.)	Cartridge name	Volume V (m^3)	Weight w/o molten salt $(8 \times 0.2) \times V$ (ton)	Weight w/ molten salt $(8 \times 0.2 + 2 \times 0.8) \times V$ (ton)	Weight after α % drainage	α (%)
1	0	00	12.9	21	41	21	100
2	2	02	12.1	19	39	19	100
3	4	04A	6.1	10	19	10	100
4	4	04B	7.8	12	25	12	100
5	6	06A	5.1	8	16	8	100
6	6	06B	7.9	13	25	13	100
7	8	08A	5.4	9	17	13	50
8	8	08B	6.0	10	19	18	10
9	10	10A	7.7	12	25	23	10
10	10	10B	7.4	12	24	21	20
11	12	12A	7.9	13	25	24	10
12	12	12B	7.6	12	24	23	10
13	14	14A	9.0	14	29	17	80
14	14	14B	6.5	10	21	18	30
15	16	16A	5.5	9	18	16	20
16	16	16B	6.1	10	19	15	50
17	18	18	13.6	22	44	24	90
18	20	20A	6.2	10	20	13	70
19	20	20B	5.0	8	16	12	50
20	22	22A	6.6	11	21	13	80
21	22	22B	4.9	8	16	9	80
22	24	24A	6.1	10	19	12	80
23	24	24B	5.3	9	17	10	80
24	26	26A	7.4	12	24	15	70
25	26	26B	4.0	6	13	6	100
26	28	28A	8.2	20	26	21	40
27	28	28B	4.5	7	15	7	100
28	30	30A	5.9	9	19	9	100
29	30	30B	4.5	7	14	7	100
30	32	32A	6.6	11	21	11	100
31	32	32B	4.7	7	15	7	100
32	34	34	9.9	16	32	16	100
		Total	224.2	365	717	464	

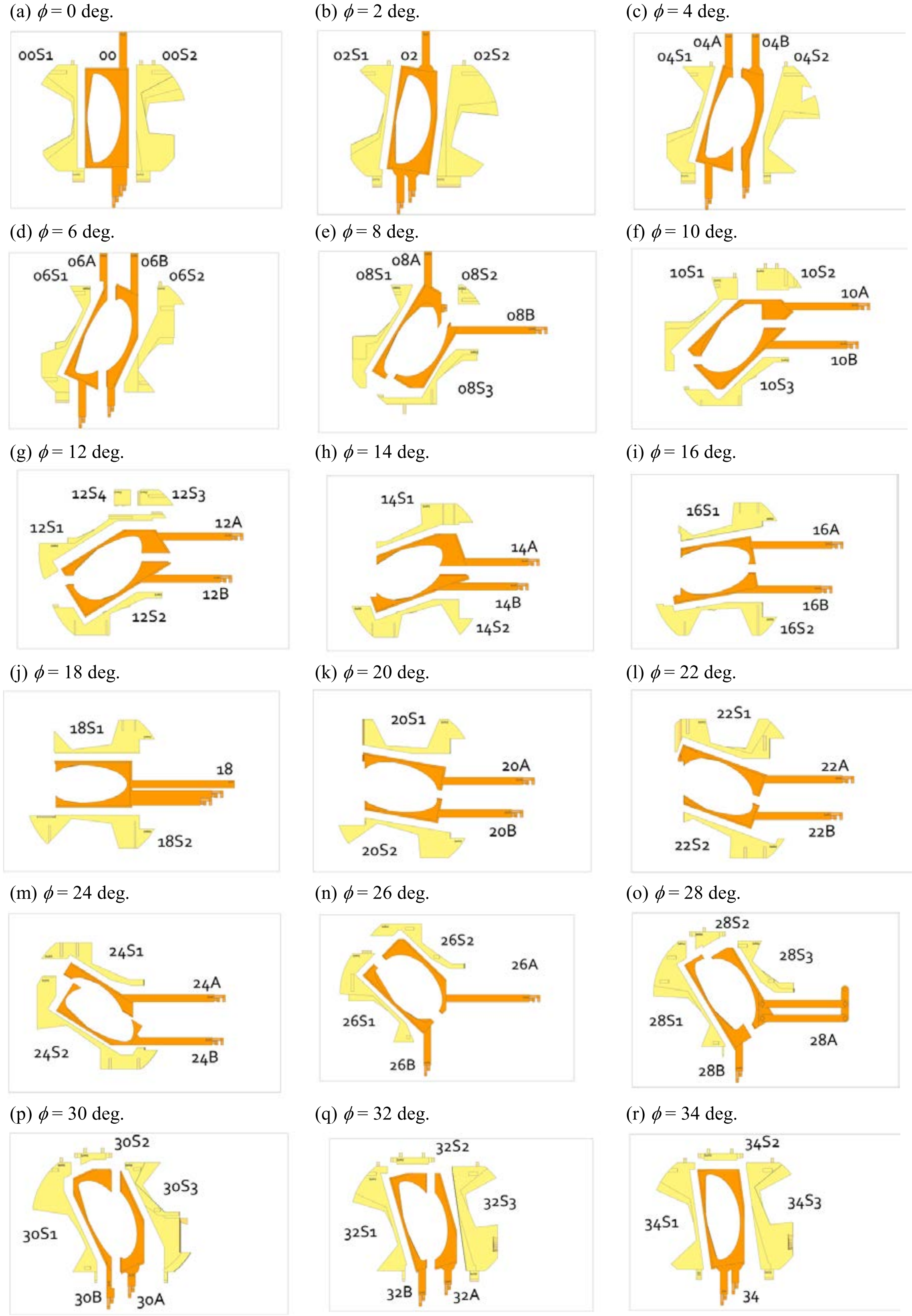

Fig. A1 The SB and BB cartridges of the CARDISTRY-B. The cartridge groups at every 2 deg. from 0 to 34 deg. of toroidal angle are shown from (a) to (r).

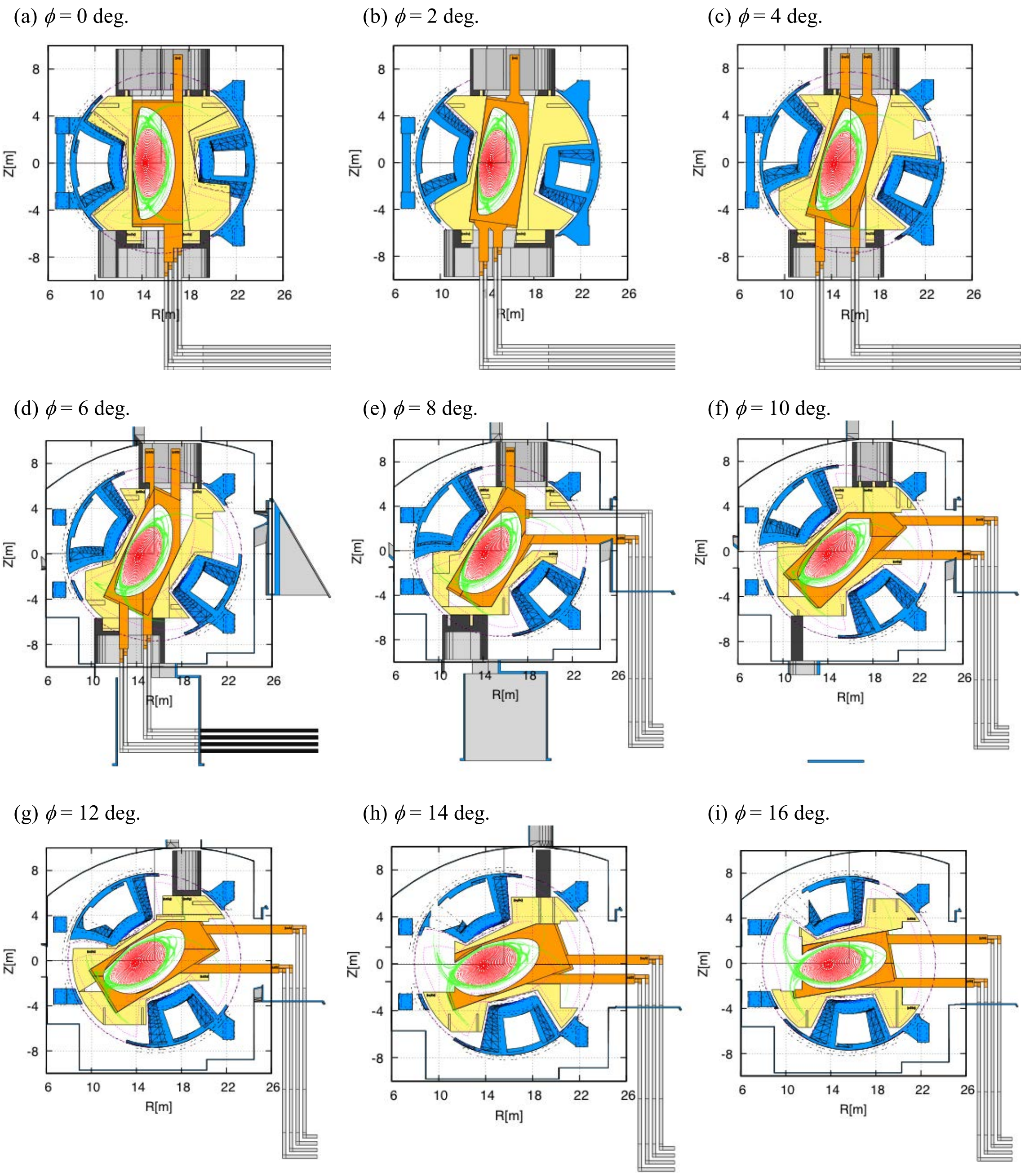

Fig. A2 Clearance between the BB and magnetic surfaces. Side views at every 2 degrees from 0 to 16 degrees of toroidal angle are shown from (a) to (i). The ergodic layer and the closed magnetic surfaces inside the LCFS are drawn by green and red dots, respectively.

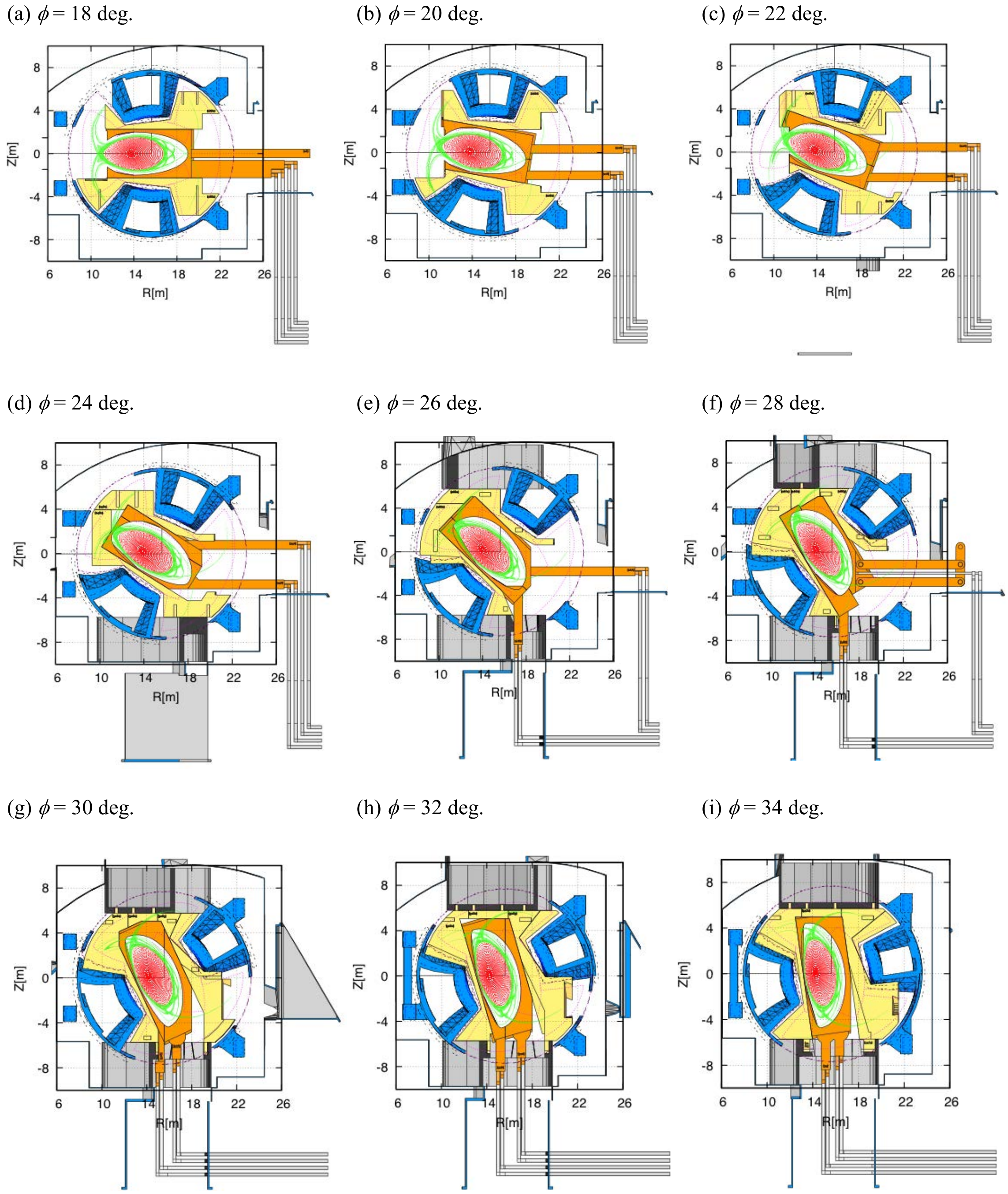

Fig. A3 Clearance between the BB and magnetic surfaces. Side views at every 2 degrees from 18 to 34 degrees of toroidal angle are shown from (a) to (i). The ergodic layer and the closed magnetic surfaces inside the LCFS are drawn by green and red dots, respectively.

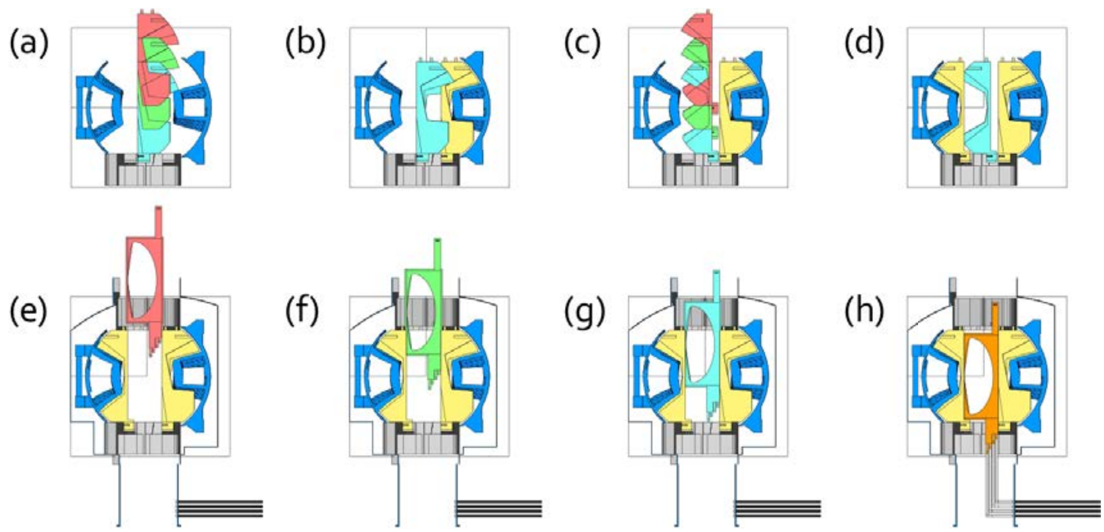

Fig. A4 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 0$ deg.

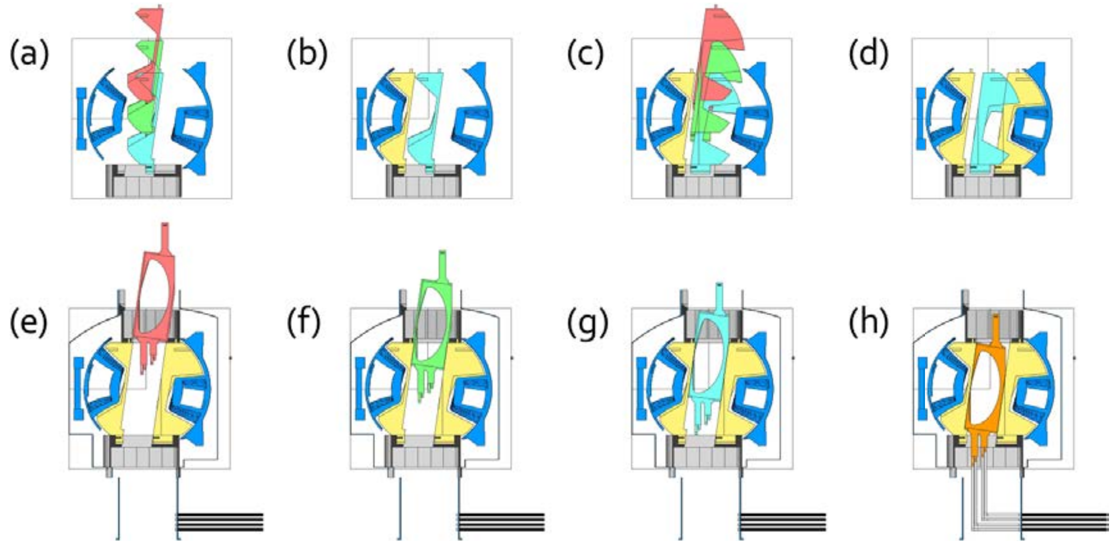

Fig. A5 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 2$ deg.

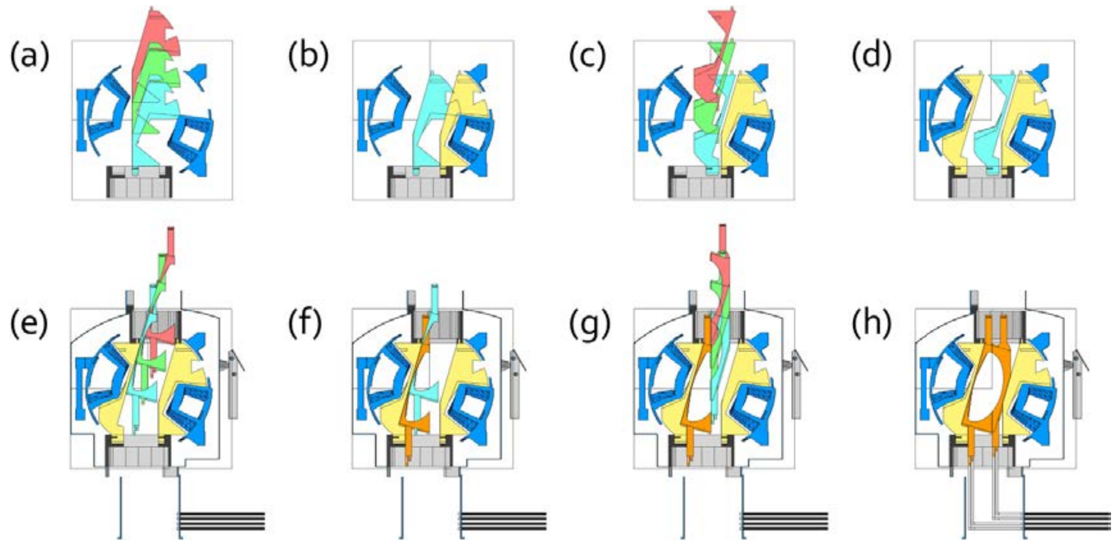

Fig. A6 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 4$ deg.

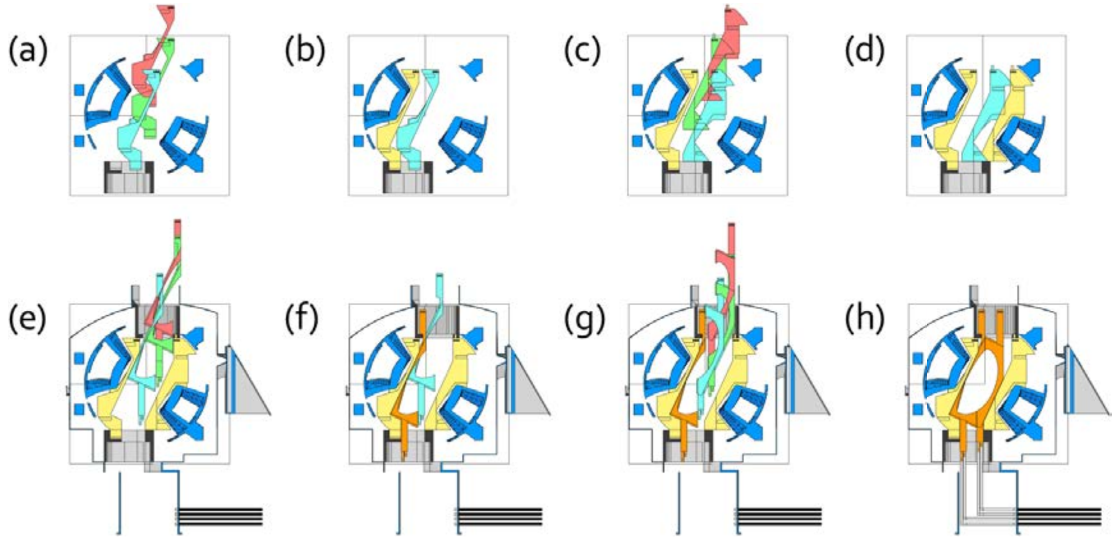

Fig. A7 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 6$ deg.

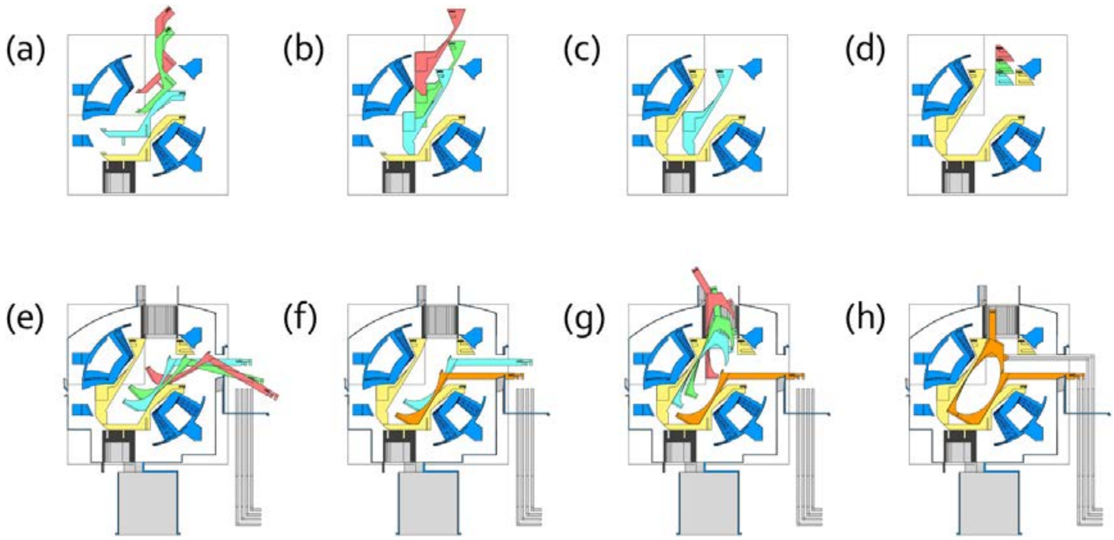

Fig. A8 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 8$ deg.

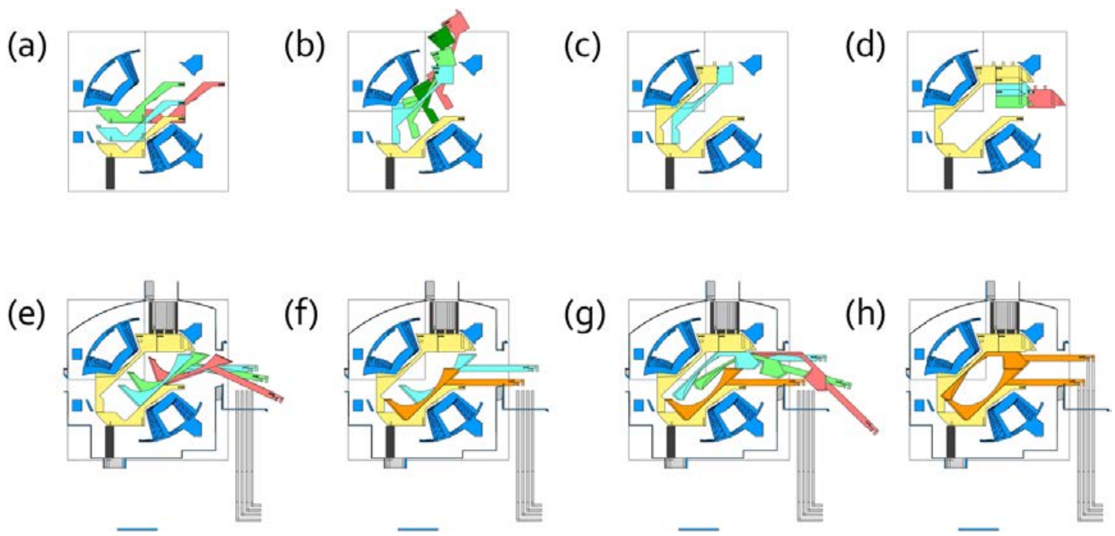

Fig. A9 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 10$ deg.

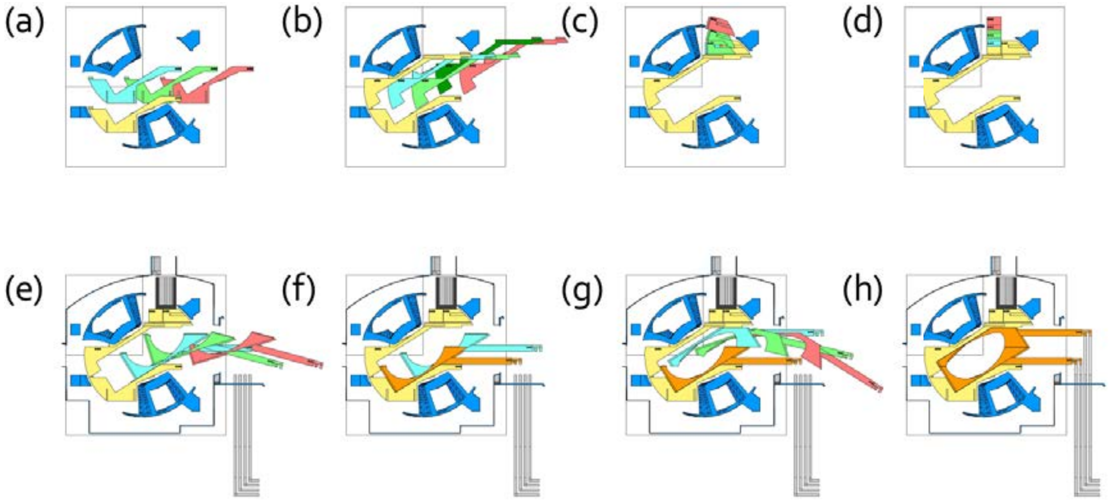

Fig. A10 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 12$ deg.

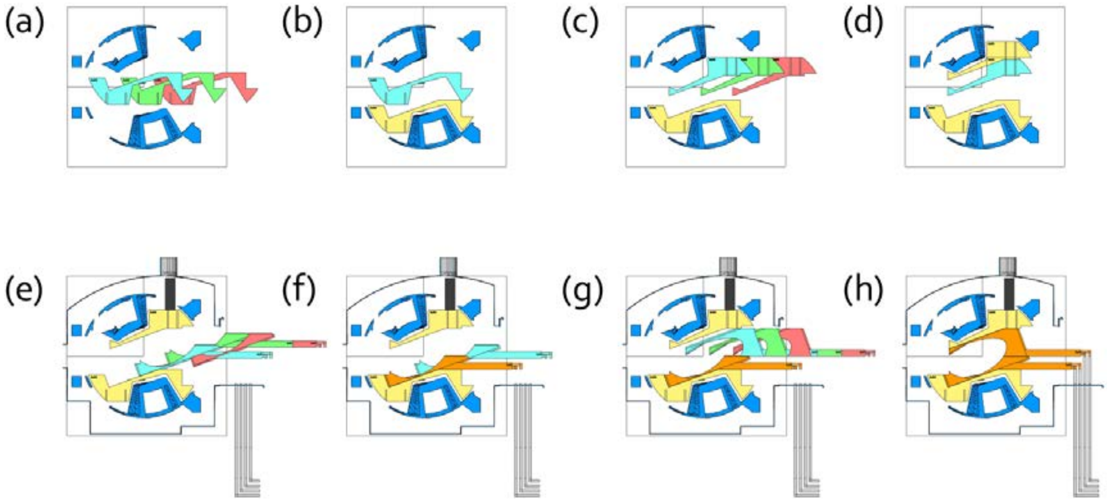

Fig. A11 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 14$ deg.

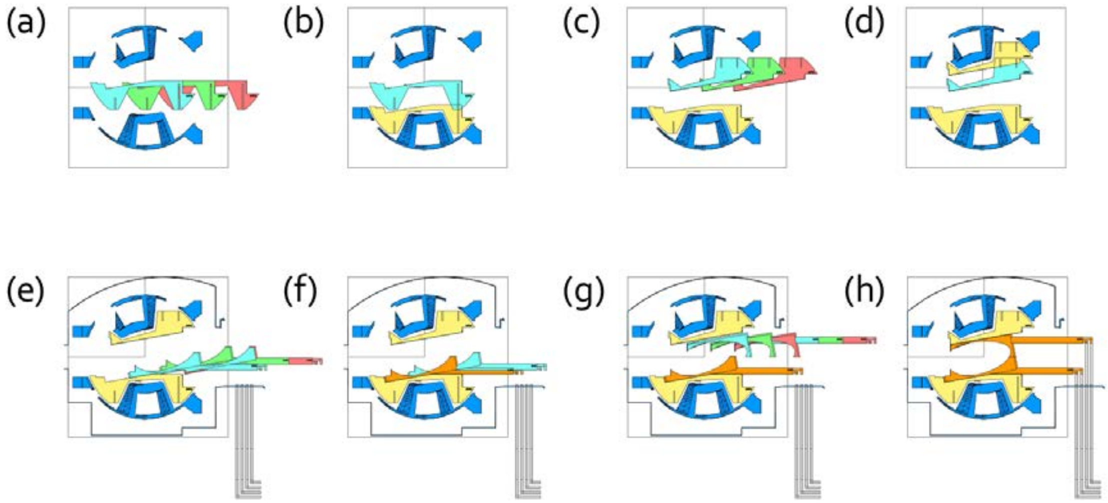

Fig. A12 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 16$ deg.

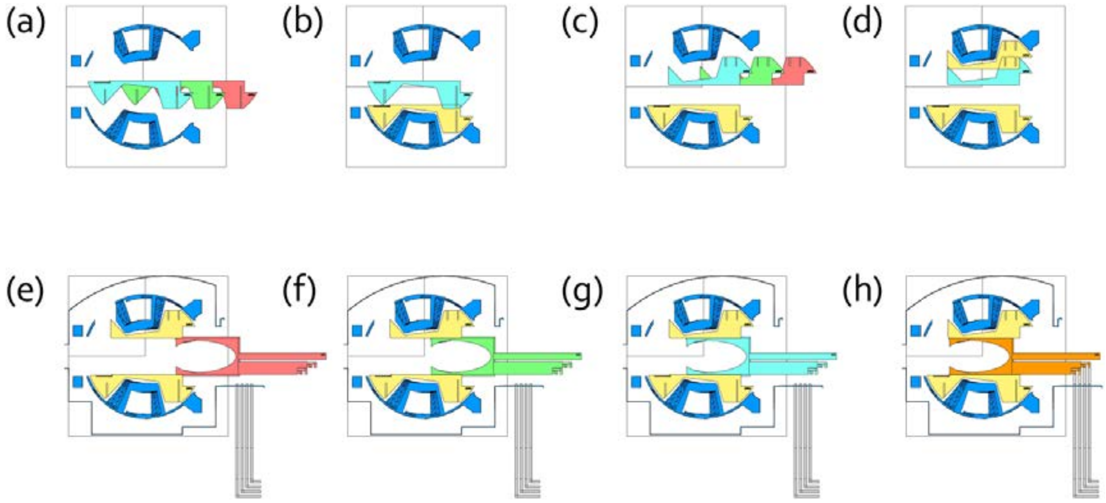

Fig. A13 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 18$ deg.

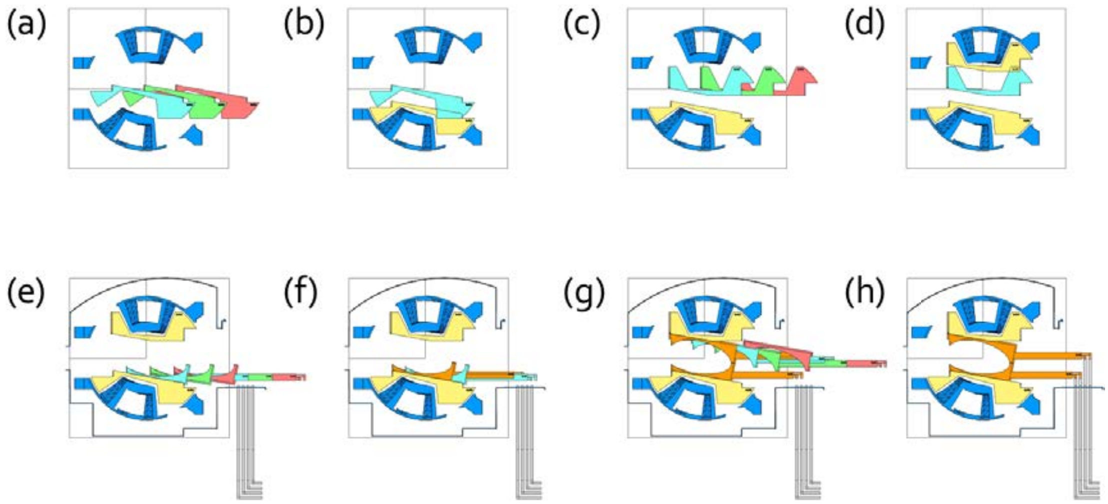

Fig. A14 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 20$ deg.

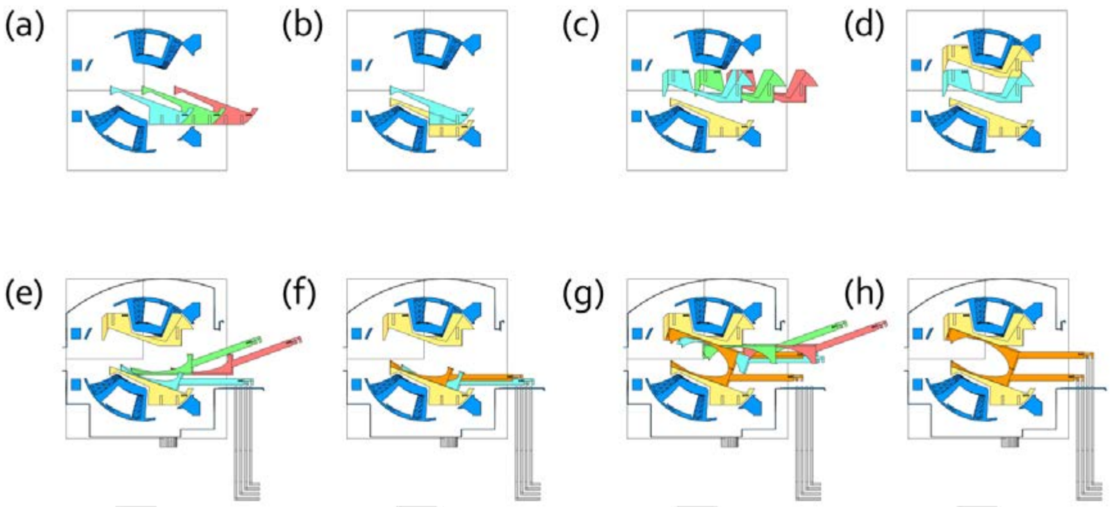

Fig. A15 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at $\phi = 22$ deg.

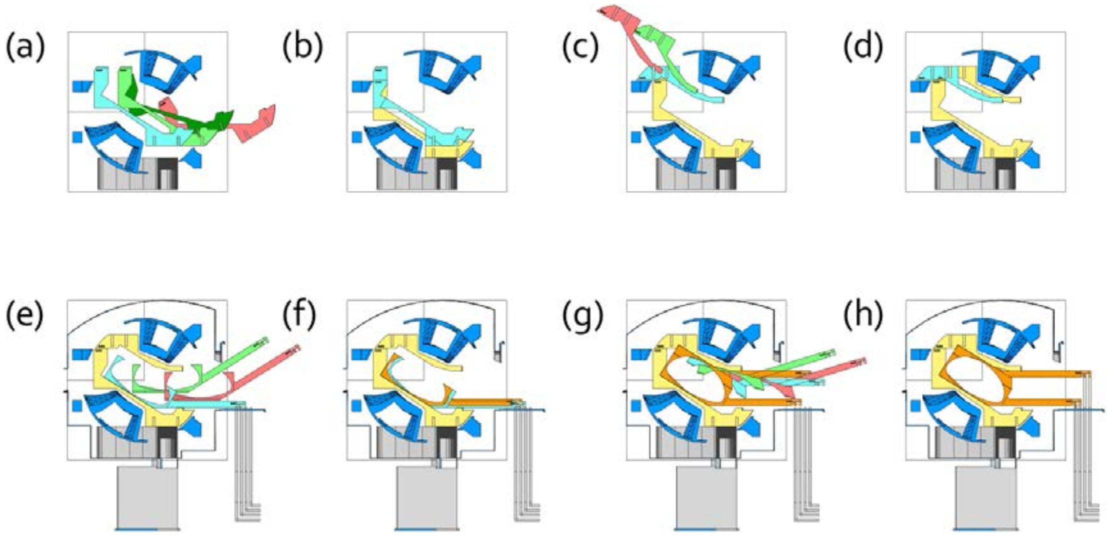

Fig. A16 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at ϕ = 24 deg.

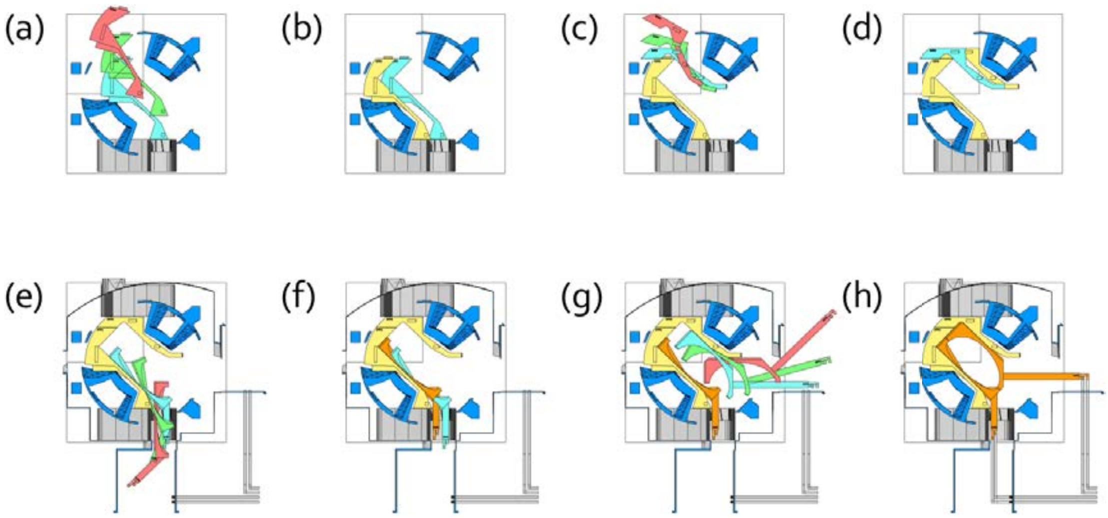

Fig. A17 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at ϕ = 26 deg.

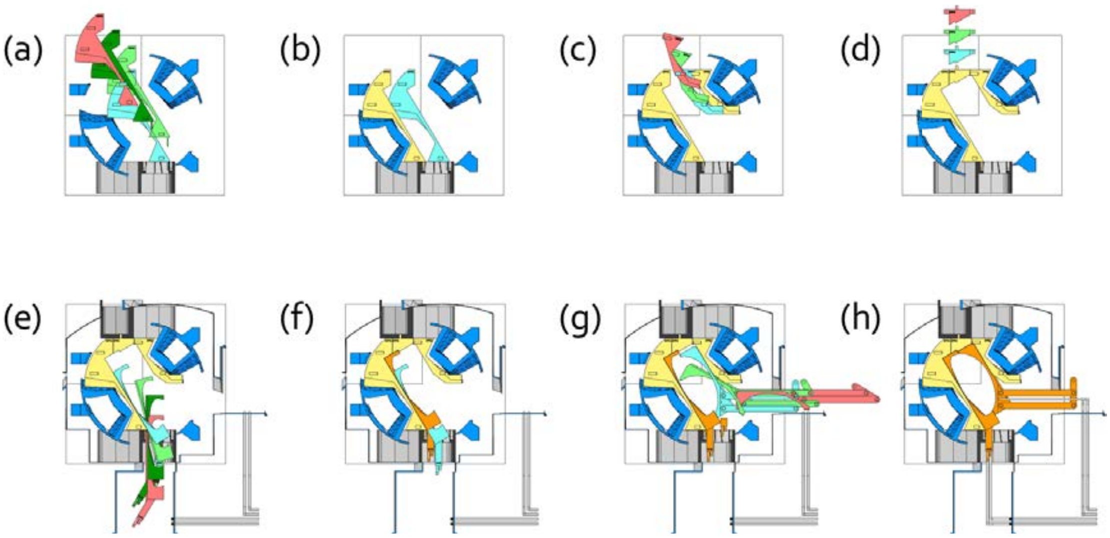

Fig. A18 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at ϕ = 28 deg.

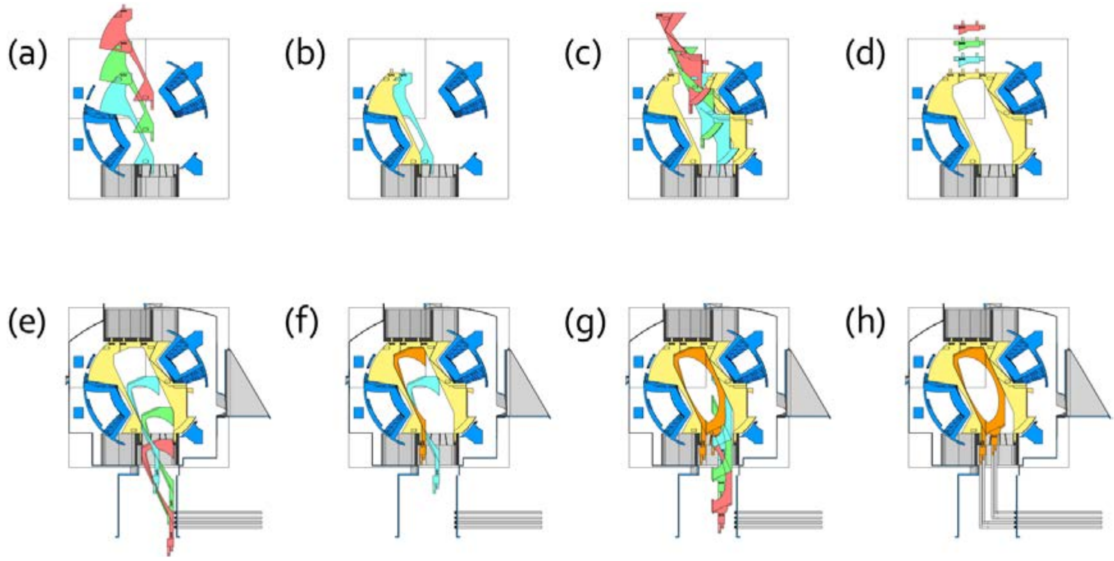

Fig. A19 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at ϕ = 30 deg.

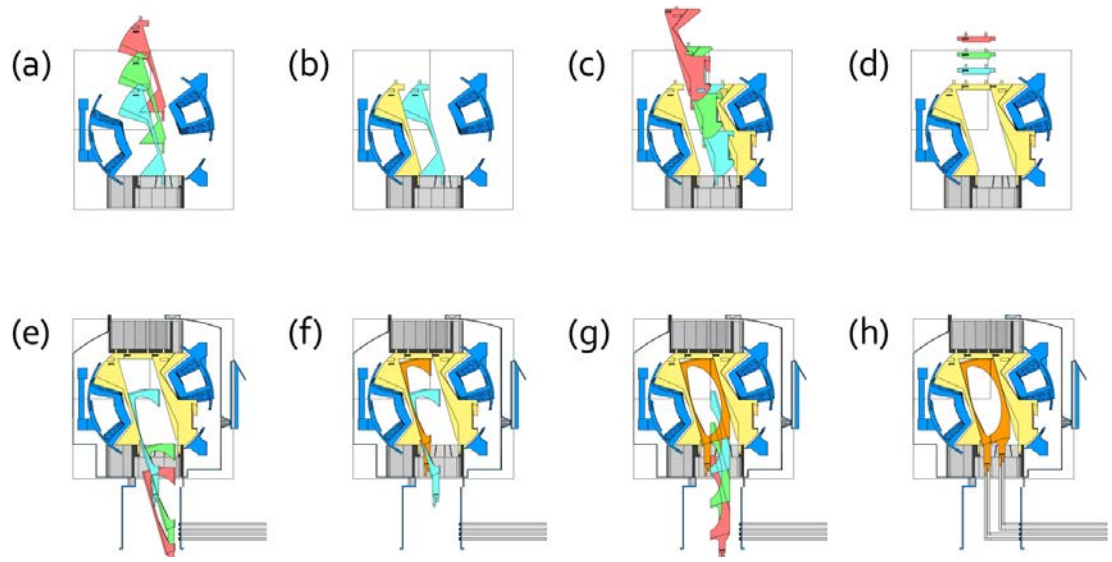

Fig. A20 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at ϕ = 32 deg.

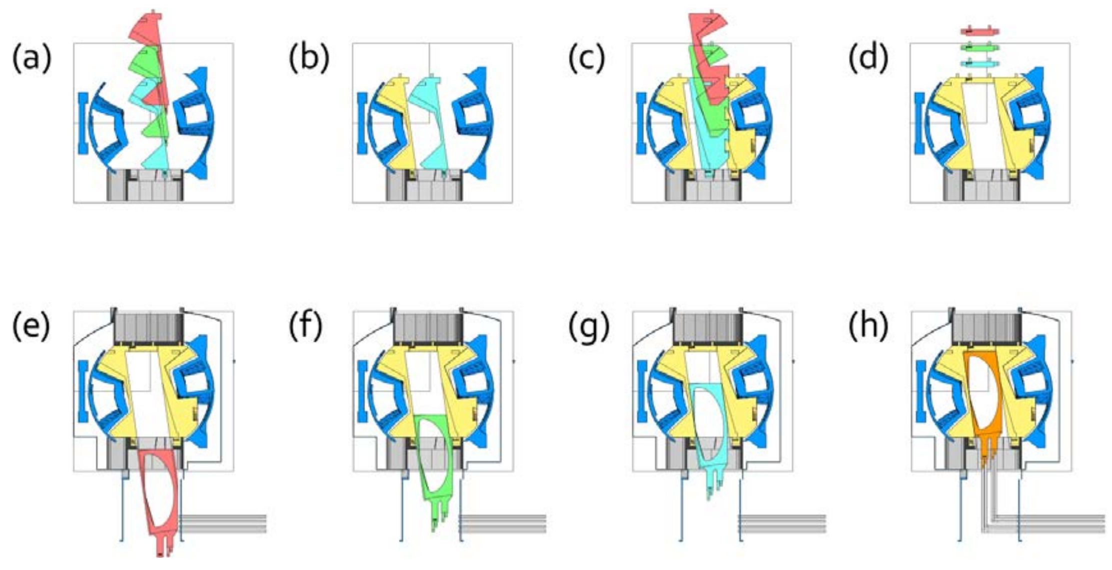

Fig. A21 The assembly procedure of SB ((a) - (d)) and BB ((e) - (h)), at ϕ = 34 deg.