Completion of all Winding Packs for ITER Toroidal Field Coils in Japan*)

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In Japan, National Institutes for Quantum Science and Technology (QST) has the responsibility to develop nine toroidal field (TF) coils, each of which consists of a winding pack (WP) and coil case for the ITER project. The WP consists of seven double-pancakes (DPs), which consist of conductors inserted into D-shaped radial plates (RPs). Although a WP is significantly large (14 m high and 9 m wide), the position of the current center line of the WP must be controlled within a few millimeters. Therefore, numerous technical challenges arose in DP and WP manufacturing. Herein, in the RP manufacturing, the optimization of welding and machining procedures, and accurate manufacturing techniques were established. Subsequently, all RPs were fabricated around the flatness errors of 1 mm from the nominal. In cover plate (CP) welding, the welding procedure was optimized so that a good DP flatness after CP welding was achieved. In the WP insulation, by developing a method to insulate a WP while applying compression, the dimensions within errors of a few milli-meters is achieved in all of WPs. Consequently, all nine WPs were successfully completed for TF coils in Japan in March 2022.

Keywords: ITER, TF coil, winding pack, radial plate, insulation, current center line

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1. Introduction

For the ITER project, the National Institutes for Quantum Science and Technology (QST) procures nine toroidal filed (TF) coils in Japan. Each TF coil has a height, width, and weight of 16.5 m, 9 m, and approximately 300 t, respectively [1]. The TF coil consists of a winding pack (WP) and coil case. A WP consists of seven double-pancakes (DPs). Schematic view of a TF coil is shown in Fig. 1. As nine WPs are needed for nine Japanese TF coils, a total of 63 DPs shall be manufactured.

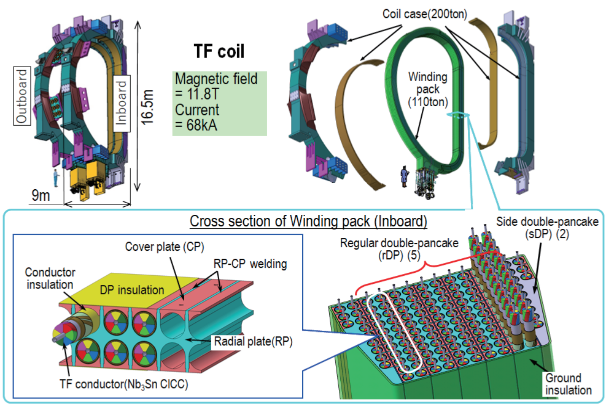

Fig. 1 Overview of an ITER TF coil.

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Although a WP is a huge superconducting magnet, it should be manufactured within error of several millimeter in terms of plasma confinement. To achieve this, high accuracy manufacturing procedure must be established. In the manufacturing, many technical issues arose. They were resolved with considerable effort by QST, TF coil manufacturers, and ITER organization through trials and consideration [2–5]. Consequently, all nine WPs were successfully completed. In this study, technical issues are summarized. Further, the experience and knowledge gained through the WP manufacturing are described in hope that they would be utilized in the development of next fusion magnet.

2. DP and WP Manufacturing Procedures

A series of a WP manufacturing process is shown in Fig. 2. Since a WP consists of seven DPs, the process starts from DP manufacturing. In DP manufacturing, a Nb_3Sn cable-in-conduit (CIC) conductor is wound to D-shape; subsequently, Helium inlet and terminal joint box are installed to particular part of the conductor [6, 7]. The wound conductor with helium inlet and terminal joints is heat treated to generate an Nb_3Sn layer at 650°C for a few weeks [8]. Radial plates (RPs) are manufactured in parallel to the conductor winding and heat treatment. Subsequently, the heat-treated conductor is transferred into an RP groove. Next, cover plates (CPs) are installed to RP

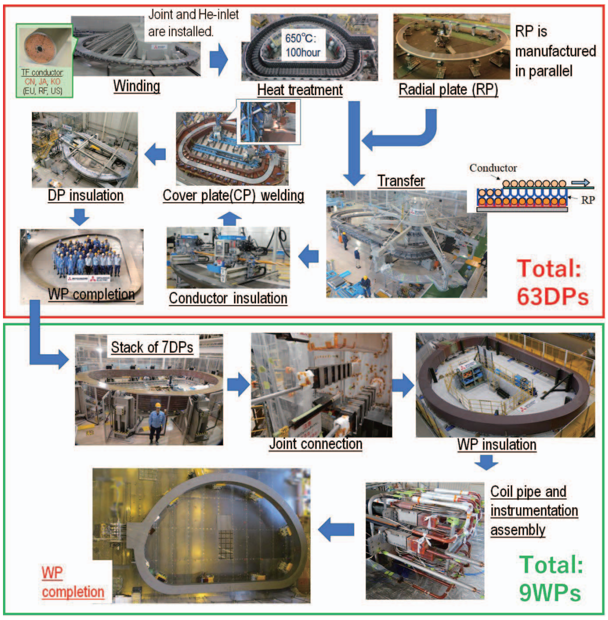


Fig. 2 WP manufacturing process.

and welded. Finally, DP is insulated. In the WP manufacturing, the seven manufactured DPs are stacked. These adjacent joints are connected by soldering. Then, the WP is insulated, and coil pipe and instrumentation wires are assembled.

Herein, nine Japanese WPs were manufactured by two TF coil manufacturers to comply with the ITER project schedule. Hereafter, TF coil manufacturers are called manufacturers A and B. They have own WP manufacturing process line shown in Fig. 2. In the next sections, key results in WP manufacturing are described.

3. Radial Plate Fabrication and Cover Plate Welding

RP is a D-shaped groove structure made by full-austenite stainless steel. It is approximately 14 m high, 9 m wide, and 110 mm thick. A regular RP (rRP), which is stacked at the center of WP, has 11 grooves on both sides of the RP. By contrast, a side RP (sRP), which is stacked at side of WP, has three and nine grooves on the outside and inside of the RP, respectively. The RP consisted of 10 segments initially. Subsequently, they were integrated to 4 sectors with extra material for adjustment. Finally, all sectors is assembled into the RP as shown in Fig. 3. After a conductor is inserted into the RP groove, CPs are installed on the RP. Then, the CP is welded to RP.

RP should be manufactured with 1 mm of flatness, 2 mm of profile, and 100 ppm of groove-length scatter. These targets are severe compared with the RP size. To achieve these targets, a welding procedure that combines a laser and arc welding was established via trials in RP segment and sector assembly. A machining process was also established as well [9]. Consequently, all 63 RPs

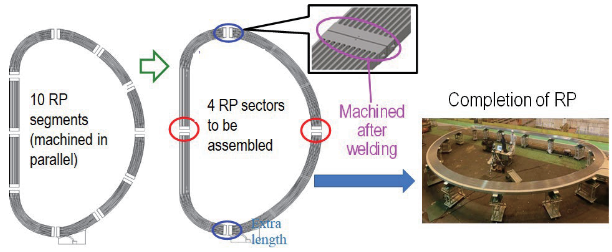


Fig. 3 RP assembly process.

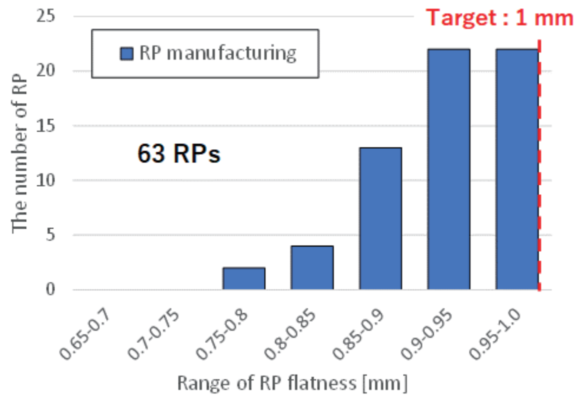


Fig. 4 Results of the RP flatness for all 63 RPs manufactured. Vertical and horizontal axes display the number of RPs and the range of RP flatness, respectively.

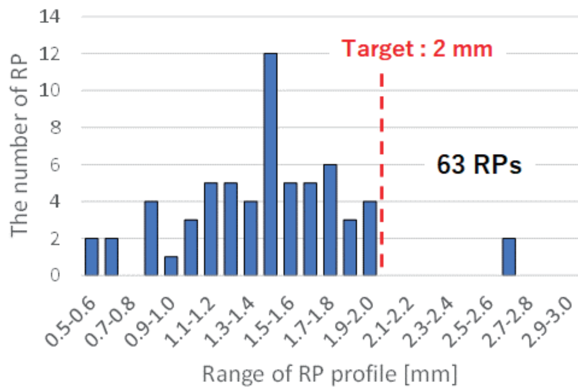


Fig. 5 Results of the RP profile for all 63 RPs manufactured. Vertical and horizontal axes display the number of RPs and range of RP profile, respectively.

were manufactured as per the flatness, profile, and groove-length scatter requirements shown in Figs. 4 - 6, respectively. These figures are histograms; the vertical and horizontal axes show the number of RP and range of measured results, respectively. According to these results, the maximum value was below but close to the target value in RP flatness (Fig. 4) but not in RP profile (Fig. 5) nor groove length variation (Fig. 6). Thus, many RPs were manufactured with a small margin for the target of flatness. This implies that the target RP flatness should be relaxed if a larger RP is required in a future magnet. Note that

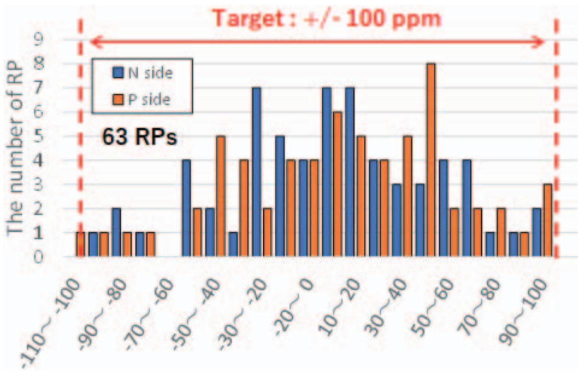


Fig. 6 Results of the RP groove-length variation for all 63 RPs manufactured. Vertical and horizontal axes display the number of RPs and range of groove-length variation, respectively.

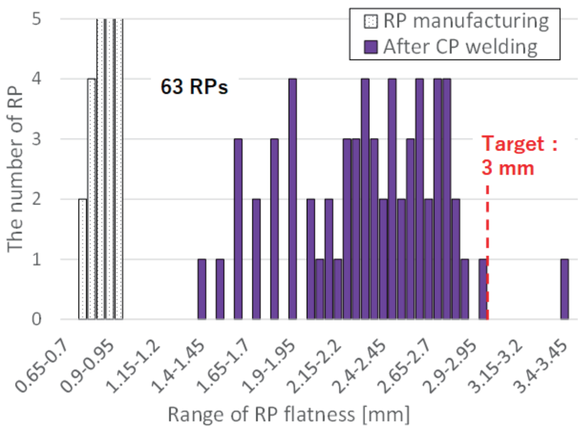
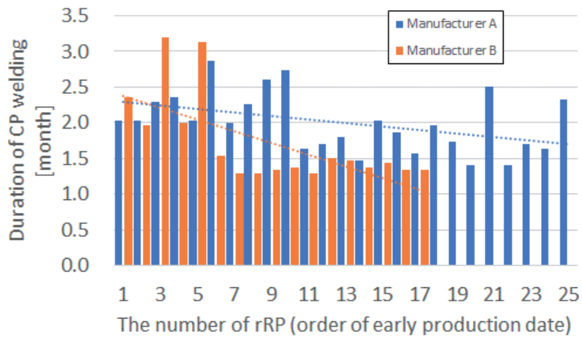


Fig. 7 Results of the RP flatness after CP welding for all 63 RPs manufactured. Vertical and horizontal axes display the number of RPs and range of RP flatness, respectively.

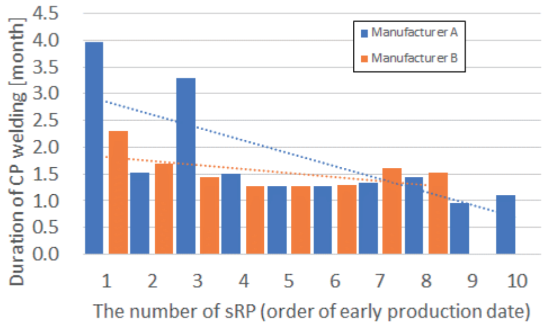
some RPs were out of tolerance, particularly in the profile (Fig. 5). However, these were used by adjusting the RP position when DPs were stacked in WP manufacturing.

In CP welding, the RP shape is deformed by welding deformation, whereas the flatness is controlled within 3 mm. Consequently, a proper welding method was established. The details are described in [2, 10]. The results of RP flatness after CP welding are shown in Fig. 7. It is same style with Fig. 4; the flatness after the RP manufacturing is shown as a reference. According to Fig. 7, the most of RPs were manufactured within the target. Only some RPs deviated from the target. However, these RPs were corrected in the DP insulation process. These results are shown in next section.

Although CP welding was completed for all 63 RPs, the work schedule was also important considering the project schedule. In the DP manufacturing process shown in Fig. 2, CP welding was a bottle neck while RPs were manufactured in parallel with other processes. Therefore, reducing the duration of CP welding was effective in terms of the project schedule. Figure 8 shows the CP welding duration of each manufacturer in each rRP and sRP. In Fig. 8, the horizontal axis presents the number of RPs. The vertical axis is the CP welding duration. According to Fig. 8, approximately 3 - 4 months were required for initial production process of rRP and sRP. However, the duration (straight-dotted line) reduced as the production advanced owing to optimization of the welding procedure and learning effect. Thus, DP manufacturing could accelerate about 1 month. Note that the duration in Fig. 8 was evaluated by the days from the work start date to the work completion date.



(a) rRP



(b) sRP

Fig. 8 CP welding duration of TF coil manufacturers: (a) rRP and (b) sRP.

The usage of RP for future superconducting magnet is discussed here through the RP manufacture and CP welding. Although RP manufacturing is off-critical in the schedule, more than 1 year is required to manufacture RP. In addition, if RP is not used, CP welding is not needed. In that case, a few months of acceleration is expected in a DP manufacturing. It may be attractive in terms of the schedule. The technical point shall be considered as the first priority; however, the schedule and the cost aspects must be considered in discussion of RP usage.

4. Electric Insulation

The TF coil should survive in neutron condition of approximately 10^{22} n/m^2 during ITER operation. Therefore, dedicated insulation materials were developed and selected experimentally [11–14]. The insulation requirement

Table 1 Requirements for the electric insulation of WP.

Electrical strength (atmosphere)	
RP (conductor)	DC 2.2 kV / AC 0.4 kV
RP (RP)	DC 3.4 kV / AC 0.8 kV
WP (ground)	DC 19 kV / AC 2.5 kV
Electrical strength (1, 10, 100, 1000, 10000 Pa)	
WP (ground)	DC 8 kV

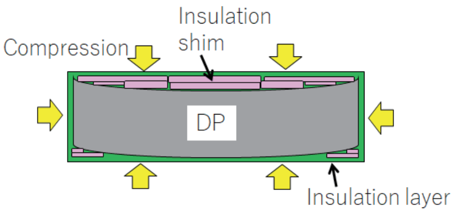


Fig. 9 Sketch of the DP insulation.

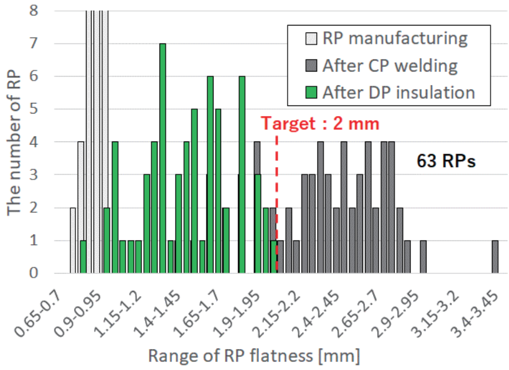


Fig. 10 Results of the DP flatness after DP insulation for all 63 DPs manufactured. Vertical and horizontal axes are the number of DPs and range of DP flatness, respectively.

is listed in Table 1. In addition, WP flatness must be maintained below 4.5 mm in the insulation process considering the current center line (CCL) and assembly with coil case.

Insulation is performed in timing of DP manufacturing for interlayer insulation and WP manufacturing for ground insulation. In DP insulation, DP flatness may be deviated by 3 mm owing to CP welding. Thus, achieving WP flatness when seven DPs are stacked is challenging. Hence, DP flatness should be reformed by 2 mm during DP insulation. In addition, resin rich should be avoided in the insulation. Therefore, a method was developed to insulate a DP while compressing it with insulation shims to adjust flatness. Its schematic view is displayed in Fig. 9. A DP is compressed in all directions with shims [5]. Using this method, DP flatness was reformed by 2 mm for all 63 DPs, as shown in Fig. 10. Figure 10 is a same style with Fig. 4. The RP flatness in RP manufacturing and after CP welding were used as references.

Similarly, a method to insulate a WP while applying compression was developed in the WP insulation process.

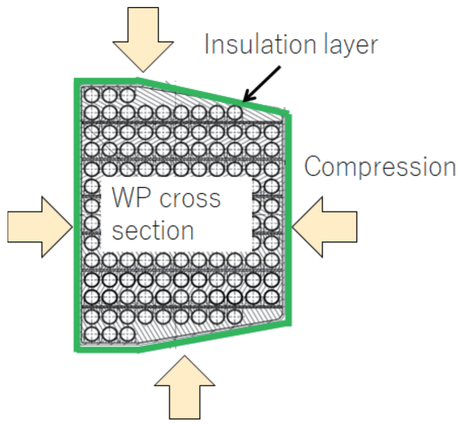


Fig. 11 Sketch of the WP insulation.

Flatness values of seven DPs were further changed by this compression; the schematic view is shown in Fig. 11. In case of WP insulation, wrinkle of insulation tape may occur during the compression because length of insulation tape is long compared with one of DP insulation. Such a wrinkle in insulation tape may develop into an insulation weakness point because a wrinkle may include a void or resin rich. Therefore, a taping machine to apply preliminary tension for insulation tape was developed [15]. Owing to this preliminary tension, the wrinkle of insulation tape was prevented when WP was compressed. The result of WP flatness deviation after insulation is shown in Fig. 12. In Fig. 12, the WP flatness deviations in representative points of CCL (Nos. 1 - 8) are shown; the vertical and horizontal axes are the WP flatness deviation from the nominal and CCL representative points, respectively. Thus, WP flatness deviated less than 4.5 mm in all nine WPs.

The high voltage (HV) wires to measure the voltages of RP or conductors are extracted along the cooling pipes. The insulation weakness point is an area where an HV wire goes through ground insulation as shown in Fig. 13. In the initial design, some discharge happened at this area when electric test listed in Table 1 was performed. This was caused by a resin drop around an HV wire exit owing to the low viscosity of the resin. Therefore, the HV wire exit area was redesigned. Consequently, each manufacturer developed sophisticated designs based on their trials; the schematic view is shown in Fig. 14. In the design of manufacturer A, an HV wire was held by upper and lower insulation layer while the space around the HV wire was filled by glass materials soaked in filler mixed resin with high viscosity [15]. By contrast, in the design of manufacturer B, the HV wire was extruded step by step of insulation layers and the resin is filled by impregnation [16]. In both designs, a heat shrinkable tube was installed at the HV wire exit to mitigate the stress on the HV wire. Subsequently, solid insulation was achieved. It passed the electric test listed in Table 1 for all nine WPs.

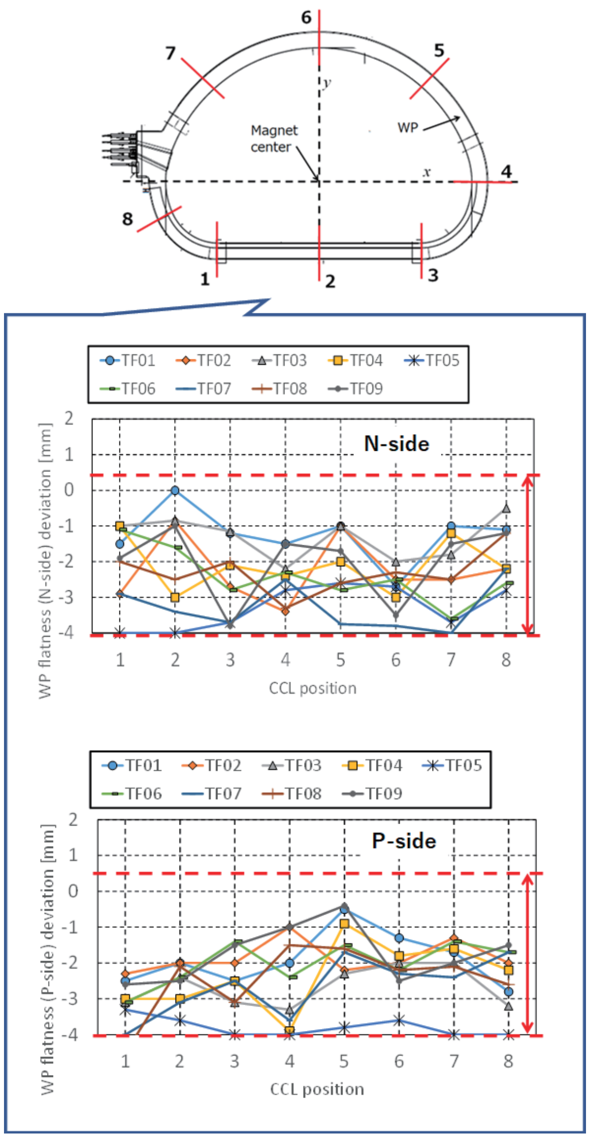


Fig. 12 Result of the WP flatness deviation for all nine WPs.

5. Completion of WP Fabrication

Some of the technical issues mentioned in the earlier sections and described in the references were resolved by joint effort of QST, TF coil manufacturers, and ITER organization. Finally, WP CCL was evaluated. The requirement of WP CCL is +/−1 mm in inboard (Nos. 1 - 3 in Fig. 12) and +/−2 mm in outboard (Nos. 4 - 8 in Fig. 12). The details of evaluation method were described in [15]. Figure 15 shows the results of WP CCL for all nine WPs. Thus, these passed the requirements, and all nine WPs were completed. Figure 16 shows photos of final WP in each manufacturer. The completed WPs are assembled with coil case in further process of TF coil manufacturing. Finally, Fig. 17 shows the WP manufacturing duration of each TF coil manufacturer. Approximately 5 years were required to manufacture the first WP. By contrast, the duration of WP manufacturing could be reduced by both manufacturers, except for the WP of a spare TF coil, which does not require a strict schedule. Note that WP manufacturing duration was evaluated by counting the days from the start date of conductor winding to the completion date of WP final inspection. In addition, cold test [15] was performed for the first two WPs produced by the manufacturer A and the first WP by the manufacturer B. This test duration is also included in Fig. 17. Such a schedule will become a reference point for future development plan of fusion magnets.

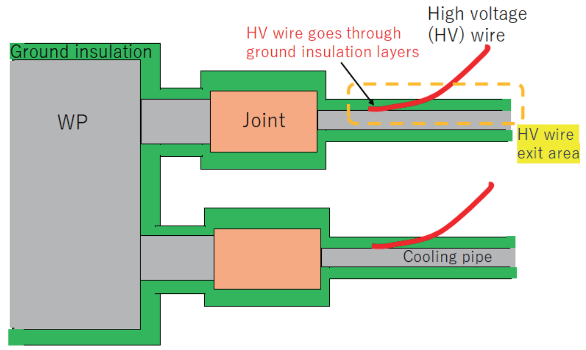


Fig. 13 Sketch of the HV wire installed on a WP.

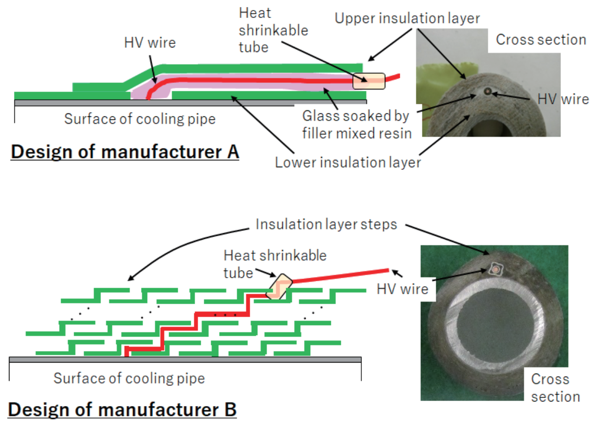


Fig. 14 Sketch of the design of HV wire exit by each manufacturer.

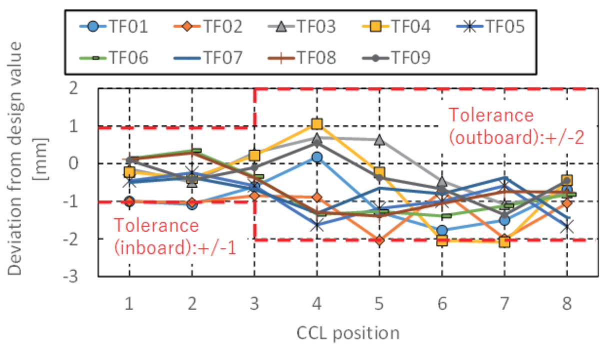
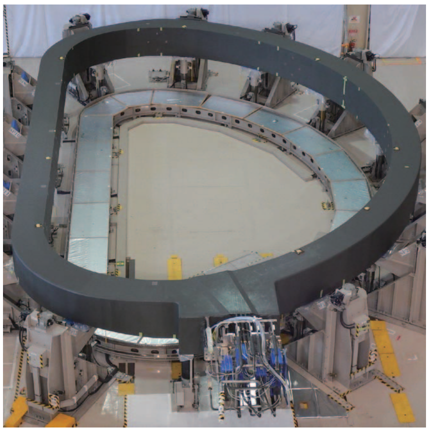
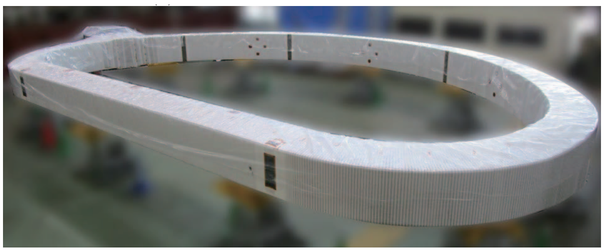


Fig. 15 Results of the WP CCL positions for all nine WPs.



(a) TF coil manufacturer A



(b) TF coil manufacturer B

Fig. 16 Photograph of completed final WP in each TF coil manufacturer. TF coil manufacturers (a) A and (b) B.

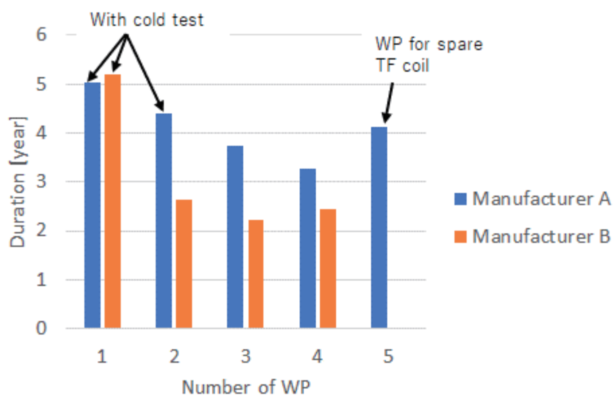


Fig. 17 WP manufacturing duration of each TF coil manufacturer.

6. Conclusion

All nine WPs were successfully manufactured in beginning of 2022. Among them, seven WPs were already assembled with the coil cases. The remaining two WPs are in assembly process with the coil cases as of September 2022. They will be also completed soon.

The experience and knowledge gained through WP manufacturing of ITER TF coil will contribute toward the development of fusion magnets.

Acknowledgment

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