ACHIEVEMENT OF PRECISE ASSEMBLY OF THE JT-60SA SUPERCONDUCTING TOKAMAK

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Abstract

The JT-60 Super Advanced (JT-60SA) tokamak construction have been achieved respecting the requirements of very tight tolerance for the assembly and by handling very heavy components in a very close space environment. The construction of this large superconducting tokamak represents a big step forward in the world nuclear fusion history, opening the road for ITER and DEMO. Precise assembly is required, not only to avoid mechanical interference, but also to obtain good plasma performance by less magnetic error field. To complete this work, unique and well-considered procedures were introduced. In this paper, the developed technologies and their results are reported, focusing on the assembly of the final sector of vacuum vessel, central solenoid and in-vessel components.

1. JT-60SA TOKAMAK ASSEMBLY AFTER THE LAST FEC

After the last IAEA FEC in 2018 [1], we have been progressed the assembly of tokamak main components, thus, central solenoid, cryostat vessel body, its thermal shield and cryostat top lid as shown in FIG.1. As a consequence, at the end of March in 2020, we have achieved important milestone for this project taking about seven years since 2013. Namely, the tokamak main assembly has been successfully completed, keeping original plan on schedule. In this assembly, high accuracy of millimetre order was realized with respect to huge and heavy components. In this paper, the assemblies of the major components such as the vacuum vessel final sector, the central solenoid and in-vessel components are focused. These components have been precisely assembled meeting these requirements.

FIG. 1. History of JT-60SA assembly after the last IAEA FEC [1].
2. VACUUM VESSEL FINAL SECTOR ASSEMBLY [2]

The final sector of vacuum vessel (VV) was assembled as the final 20-degree sector together with the final sector of the VV thermal shield (VVTS) and the 18th toroidal field coil (TFC). FIGURE 2 indicates the photograph of the final sector pre-assembled in the assembly hall and schematic procedure to complete full torus configuration. The precise positioning of the 18th TFC was reported at the last FEC 2018[1]. The final VV sector was weld-jointed to neighbour sectors in parallel with other assembly works such as port-TSs, EF coils and so on.

FIG. 2. Assembly of final sector consisting of VV, VVTS and 18th TFC.

One of the major concerns for the final sector assembly is welding shrinkage of the final VV sector. It was predicted to happen 8 mm shrinkage in the toroidal direction. To compensate the shrinkage, the shape of the 340-degree sector was designed to be enlarged at the final sector space in the toroidal direction and premised to position the final sector with 6 mm outward offset in the radial direction as shown in FIG. 3.

FIG. 3. Welding of final VV sector via splice plates. (left) Offsets considering shrinkage of welding. (right) Final VV sector with splice plates and welding constraints.

In this welding work, it had difficulties that the welding access and its constraints were limited only on the plasma side. Therefore, the welding procedure was modified to joint the outer wall at the first and then the inner wall at the second. To assemble with the specified dimension by welding, the splice plates were introduced for the position adjustment between the sectors resulted in the dimensional error of the over 6 mm radially at the final sector. The result of the dimensional error of the 360-degree torus shape is shown in the FIG. 4. The dimensional error is larger as the measured data closer to the final sector from the P-03 and P-15, and the error around the final sector is over 10 mm in the radially inward (machine centre) direction. However, the outer clearance between the VV and VVTS was confirmed so that it would not cause any interference with VVTS.
during the operation such as cooling and baking. Moreover, the error on the inner surface was compensated by adjusting the interface parts between the VV inner wall and the in-vessel components as discussed in the later section.

**FIG. 4. Dimensional error at VV sector generatrix.** (a) Inner wall of the in-board (specified in +/-10 mm). (b) Inner wall of the out-board (specified in +/-20 mm).

After the weld-joint of VV final sector, a measurement of VV by the laser tracker was done to fix VV gravity supports (VVGSs) positions. Based on this measurement, the female threads for M200 were opened. Finally, the required tight tolerance on the positioning of the plates of the VVGSs with respect to the tokamak centre axis of +/-1 mm was successfully achieved.

3. CENTRAL SOLENOID ASSEMBLY [3]

JT-60SA has three types of superconducting magnet as 18 TFCs, 4 modules of the central solenoid (CS) and 6 equilibrium field (EF) coils. The TFCs and EF coils were successfully assembled by the last IAEA FEC in 2018. On the other hand, the CS insertion became challenging assembly because the CS should have been inserted into TFC bore through a quite narrow clearance less than 14 mm as shown in FIG. 5.

The CS has 4 modules, and each module consists in 7 pancakes as 6 eight-layer octa-pancake and a four-layer quad-pancake. Four CS modules have been manufactured individually and were stacked. The stacked modules were fixed by 9 tie plates with large compress load not to be slid between modules during operation. Finally, the CS is the heaviest component with 11 m height, 2.1 m diameter and about 100 tons weight. This means that any contact was not allowed during its insertion to tokamak.

**FIG. 5. Photograph of CS insertion in the torus hall and minimum gap between CS outer and TF inner radii.**
To make sure an exact insertion avoiding any contacts, we carefully prepared
— three dimensional (3D) scanning and point measurement of CS outer and TFC inner surfaces,
— alignment of vertical axis,
— real time measurement of the position during the insertion,
— contact sensors.

Before the CS insertion, the 3D scanning of the CS outer and the TFC inner surfaces was done by the F4E metrology team and QST. For precise measurement, the network of the laser tracker measurement was carefully built in the assembly hall. The obtained data sets were estimated in 3D CAD (CATIA), and checked the clearances between both surfaces. This measurement provided us not only useful information but also a strong confidence to realize the CS insertion with the clearances.

The CS has about 11m height. It made a difficulty to lift it to tokamak with less margin of lift height. Namely, this limitation did not allow to use chain blocks in the lifting wires for control tilting of the CS. For this difficulty, a vertical alignment between the top and bottom of magnetic axis was carefully done by putting many thin shims between the lifting wires and the lugs, and finally achieved within 4mm before assembly.

During the CS insertion, we have tried a real time measurement of the CS position by using the laser tracker system during the CS insertion. FIGURE 6 shows the CS horizontal position during CS insertion measured by the laser tracker in real time. Based on the tracking data, the CS horizontal and circumferential positions were adjusted several times during the CS insertion.

Moreover, about 80 pressure sensors on the points which were more exposed to the risk of contact were monitored to identify collision between the CS and TFCs. Finally, a precise positioning of the magnetic axis within +/-1.4 mm with a vertical tilt of 1.6 mm was achieved with respect to assembly tolerance of the CS magnetic axis is +/-2.0 mm.

4. IN-VESSEL COMPONENTS ASSEMBLY [4]

After the completion of the tokamak assembly, the integrated commissioning is planned including the plasma operation. Main purposes of this plasma operation are to test the soundness of the in-vessel components and to establish the plasma basic control with only low power EC heating for plasma initiation and wall cleaning. Plasma current of 2.5 MA, which is less than half of nominal maximum plasma current of 5.5MA, is planned. FIGURE 1 shows the initial sets of in-vessel components for initial operation including inboard first wall, upper divertor, protection limiter, glow electrodes and magnetic sensors.
FIG. 7. In-vessel components for initial operation.

It is requested that almost all in-vessel components are installed at the absolute coordinate with a high accuracy within 1 mm to avoid local heat load and to accurately detect magnetic fields for the plasma control. To achieve the accurate installation, the network of the laser tracker measurement was built inside the VV. As shown in FIG. 8, the network outside the VV used for the assembly of the main tokamak components was extended to the VV inside putting the laser tracker at the position close to the port opening where both reference points inside and outside are seen, simultaneously. Finally, the 20 reference points inside the VV were prepared. The accurate measurement with an error much less than 1 mm was available by this network.

FIG. 8. Network of the laser tracker measurement. (left) Schematic procedure to transfer the network referring the quite precise reference points on the wall of the torus hall. (right) Reference points in VV.

The inboard first wall is installed on the wall around centre post of the VV as a plasma facing wall and limiter. The first wall is not actively cooled by the water due to a small heating power for the initial operation. Finally, it will be upgraded to have heatsinks with active cooling water. The inboard first wall consists of base rails, pedestals and graphite tiles as shown in FIG. 9. The base rails are fillet-welded on the inboard VV. Sets of one pedestal and two graphite tiles are bolted on each set of the base rails. Even with a small heating power for the initial operation, the local heat load is predicted to be unacceptable at the limiter configuration if there is a misalignment of the graphite tiles facing plasma. It requests a precise installation of the graphite tiles within tolerance of +/-1 mm. To satisfy this request, the shims between the base rail and the pedestal are carefully tuned based on the measurement by the laser tracker. Finally, the installation error of radial position of the graphite tile surface within +/-1 mm has been achieved.
FIG. 9. Plasma facing components such as inboard first wall and upper divertor required +/- 1mm accuracy.

For the initial operation, the upper divertor is installed to investigate the controllability of divertor configuration. The upper divertor consists of C-beams, H-beams, pedestals and graphite tiles as shown in FIG. 9. The C-beams are welded on the VV surface. The H-beams are bolted and welded on the C-beams. The graphite tiles and pedestals are bolted on the H-beams. The upper divertor is designed to withstand cyclic heat load of \( \sim 0.3 \text{ MW/m}^2 \) for 10 s and withstand not only 2.5MA plasma disruption but also 5.5MA. This also requests the same precise installation as the first wall within tolerance of +/-1 mm.

Basically, the C-beams are welded in the toroidal direction on the VV. The toroidal cross-section of the VV is a regular polygon with 36 sides, whereas the poloidal cross-section has curved line. This makes complicated interfaces between the C-beam and the VV surface. Moreover, the VV surface are waved with an order of millimetre due to welding beats and undulation originated in the manufacture process.

To realize the precise assembly of the C-beams, all (144) C-beams were machined along the measured VV surface. First, the VV surface at the C-beams welding position with T-probe and laser tracker was measured. After that, the measured surface data was modelled in CATIA with C-beams and H-beams. To keep the graphite tile surface, the position of the H-beam was fixed. Then, the position of the C-beams was shifted so that the C-beam includes the measured surface and have the shim with most thin integer thickness of 1 mm to 9 mm. Based on this design the C-beams were successfully machined as shown in FIG. 10. This machining enabled to realize the gap between machined C-beams and VV surface was within 0.5 mm. Finally, the installation with required accuracy of +/-1 mm at the graphite tile surface on the upper divertor has been achieved.

FIG. 10. Situations before and after machining of interface between C-beams of upper divertor and waved VV surface.

5. SUMMARY

We have achieved important milestone for this project at the end of March in 2020 taking about seven years since 2013. Namely, the tokamak main assembly has been successfully completed, keeping original plan on schedule. In this assembly, high accuracy of mm order was realized with respect to huge and heavy components.
Vacuum vessel final sector assembly: 18 sectors of the 10m-diameter and 7m-high VV were assembled onsite by welding and the welding contraction was predicted and compensated to achieve the required high precision (typically +/-10 mm and +/- 20 mm at the inboard and outboard walls respectively). The required tight tolerance on the positioning of the plates of the VV gravity supports with respect to the tokamak centre axis of +/-1 mm was successfully achieved.

Central solenoid assembly: The insertion of the central solenoid (CS) component was successfully done even with a minimum clearance between TFC in-bore and CS outer surfaces of 14 mm by using the laser tracker measurement in real time. Finally, a precise centring of the magnetic axis within +/-1.4 mm with a vertical tilt of 1.6 mm was achieved.

In-vessel components assembly: For precise assembly of In-vessel components aiming to avoid unacceptable local heat load, its interface facing with the waved VV surface were precisely machined based on the VV surface measurements obtained by the laser tracker with T-probe. An accuracy of the graphite tile surface alignment within +/-1 mm has been achieved.

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