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Achievement of precise assembly of the JT-60SA superconducting tokamak

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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.
The JT-60SA project has been designed and constructed under the frameworks of the Satellite Tokamak Programme of the Broader Approach Agreement between EU and Japan, and the Japanese national programme in order to contribute directly to the ITER project and to DEMO by addressing key engineering and physics issues. The JT-60SA is under construction in the Naka Fusion Institute of QST. The tokamak assembly has started in Jan. 2013 and the toroidal magnetic field coils (TFCs), the equilibrium magnetic field coils and 340 degree of the vacuum vessel were assembled and positioned into the Torus Hall in 2018 [A], aiming to complete the construction by the end of Mar. 2020.

1. Vacuum vessel final sector assembly
   After the last FEC [A], the final sector of the vacuum vessel (VV) was welded on-site. The VV is a double shell stainless steel structure with 18mm thickness for each shell, designed to provide a high toroidal one-turn resistance with large torus vessel volume. The VV shells and cooling water provide neutron shielding. The VV is baked at 200℃ by nitrogen gas. In 2019, the VV final 20 degree sector was completely weld-assembled, and its gravity supports were installed into the tokamak. The 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 $\pm$10mm and $\pm$20mm at the inboard and outboard walls respectively). Absence of defects in the welds was confirmed by the non-destructive examinations. The VV is designed to be supported by 9 gravity supports to resist the seismic and operational loads, and to absorb the thermal expansion by radial flexible plates. The required tight tolerance on the positioning of the plates of the VV gravity supports with respect to the tokamak centre axis of $\pm$1 mm was successfully achieved.
2. Central solenoid assembly
   One of the challenging assemblies was the insertion of the central solenoid (CS), because it is a huge component with 11m height, 2.1m diameter and about 100 tons weight [B] with a minimum clearance between TFC in-bore and CS outer surfaces of 10mm (see Fig. 1). Assembly tolerance of the CS magnetic axis is $\pm$2mm to minimize magnetic error field. In order to achieve this tight requirement, about 200 points on the CS outer surface were measured by the laser tracker with a small measurement error of less than 0.1mm beforehand. The vertical alignment between the top and bottom of magnetic axis was achieved within 4mm. During the insertion, the laser tracker measurement was used in real time, tracking one point on CS inside. The CS insertion was carefully controlled by continuous adjustment and visual inspections, tracking data during the vertical insertion to precisely achieve the CS horizontal and circumferential positions. About 80 pressure sensors on the points which were more exposed to the risk of contact were monitored to identify collision between CS and TFC. Finally, a precise centering of the magnetic axis within $\pm$1.4mm with a vertical tilt of 1.6mm was achieved.

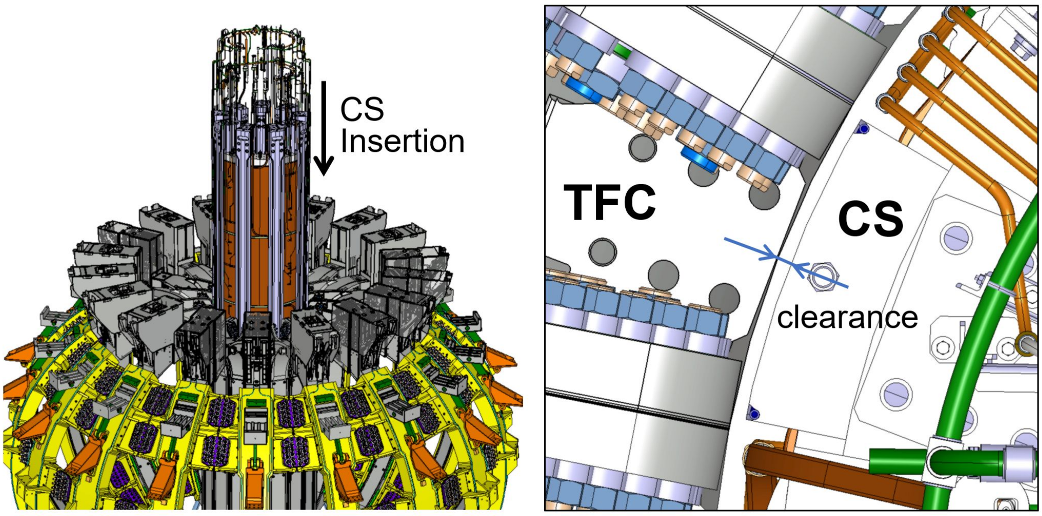

Figure 1: CS insertion and clearance between TFC and CS.

3. In-vessel components assembly
   For the first plasma operation, in-vessel components such as various sensors, first walls and the upper divertor [C] have been installed. Precise assembly for these plasma facing components is required to avoid unacceptable local heat load on the inboard first wall for the limiter configuration at the plasma initiation and on the upper divertor for the divertor configuration. A final alignment of $\pm$1mm of the graphite tiles is required. The waving of the VV surface generates a strong challenge to this accuracy. The C-type steels (see fig.2) representing the interface between the VV surface and the graphite tiles have been precisely machined based on the VV surface measurements obtained by the laser tracker with T-probe. There were 15 points for this measurement along the interface of the C-type steels to the VV surface, and the interfaces were machined along optimum curve by these measured points. By the precise measurement and machining an accuracy of the graphite tile surface alignment within $\pm$1mm has been achieved.

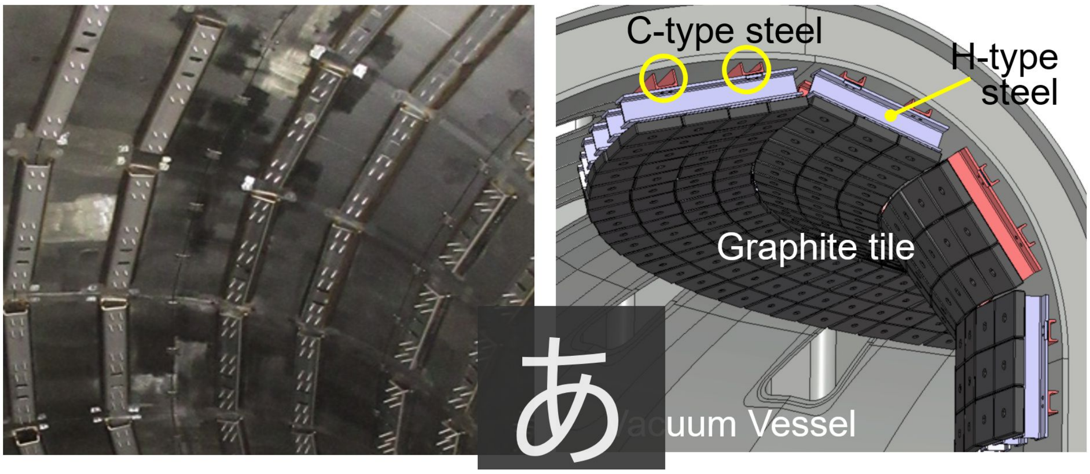

Figure 2: C-type steels of upper divertor.

[A] Y. Shibama, et al., in Proceedings of the 27th IAEA Fusion Energy Conference, 22-27 October 2018, Gandhinagar, India, IAEA-CN-258 FIP/P7-37 (2018).
[B] H. Murakami, et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 28, NO. 3, APRIL 2018.
[C] D. Tsuru, et al. Phys. Scr. T171 (2020) 014023.

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