Fusion Engineering and Design 124 (2017) 537–541

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Pre-assembly and dimensional inspection at factory of JT-60SA Cryostat Vessel Body Cylindrical Section

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HIGHLIGHTS

- JT-60SA Cryostat Vessel Body Cylindrical Section consists of 12 individual sectors.
- Dimensional inspection of every sector is carried out by laser tracker.
- Sector supporting resulted very critical for the inspections as predicted by FEA.
- Preassembly at factory will check tolerances and prevent problems at final assembly.

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form 19 January 2017
Accepted 13 April 2017
Available online 15 May 2017

Keywords:
JT-60SA
Cryostat
Assembly
Dimensional inspection

ABSTRACT

The superconducting tokamak JT-60SA is currently being assembled at the QST laboratories in Naka (Japan). Within the European contribution in the framework of the Broder Approach, Spain is responsible for providing JT-60SA cryostat. It is a stainless steel vacuum vessel which encloses the tokamak providing the vacuum environment. Due to functional purposes, the cryostat was divided into three large assemblies: the Cryostat Base, the Cryostat Vessel Body Cylindrical Section and the Top Lid. The second is an envelope made from SS304 that will be assembled by mechanical connection between the individual sectors. As part of the manufacturing process, dimensional inspections are carried out by laser tracker to check the tolerances of the pieces. Due to the high mechanical flexibility of the sectors, the way to support the pieces resulted very critical for the inspections as it was predicted by FEA carried out. The paper summarizes the measurement procedure for the dimensional inspections as well as the pre-assembly procedure of the whole component.

1. Introduction

The JT-60SA cryostat is the stainless steel vessel which encloses the tokamak and provides a vacuum environment necessary to limit the transmission of thermal loads to the components at cryogenic temperature. The cryostat assemblies as well as the main parameters are shown in Fig. 1 and Table 1 respectively. The cryostat (excluding the Top Lid) was divided into two large assemblies: the Cryostat Base (CB) [1] that was the first JT-60SA component assembled in 2013 and the Cryostat Vessel Body Cylindrical Section (CVBCS), the aim of this paper. The CVBCS consists of a large structure that due to the transportation limits in Japan will be fabricated in twelve sectors. Each individual sector is a welded structure with different openings and ports. The openings are precisely machined away from the CVBCS shell. The ports are welded to their related sector openings. Each sector is finally machined to get the required tolerances. The CVBCS will be assembled by the mechanical connection between sectors, fastened by bolts.

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http://dx.doi.org/10.1016/j.fusengdes.2017.04.055

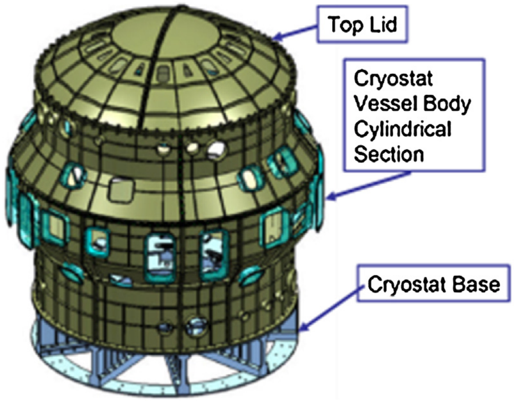

Fig. 1. JT-60SA Cryostat.

Table 1
Main Parameters of JT-60SA Cryostat.

JT-60SA Cryostat	
Operational pressure	Vacuum, 10^{-3} Pa
Cryostat dimensions	φ 13.47 m × 15.85 m
Cryostat weight	~480 t
Volume	1410 m^3
Surface exposed to vacuum	1368 m^2
Design temperature of cryostat wall	293 K
CVBCS dimensions	φ 13.47 m × 11 m height
CVBCS weight	~170 t

The CVBCS has to withstand the weight of the ports and the top lid, as well as the loads originated from the machine (in normal/accidental conditions) such as pressure, electromagnetic forces at the port flanges or seismic loads. The CVBCS design was validated by Finite Element Calculations [2] (elastic and limit load analyses) according to ASME Section VIII, Div.2, 2007, and it is currently under manufacturing by a Spanish company (Asturfeito S.A.).

2. Cryostat Vessel Body Cylindrical Section

The CVBCS is made of a single 34 mm thick 304 stainless steel shell, externally reinforced with 20 mm thick ribs. Each sector is also surrounded by 80 mm thick flanges. These are used to connect by bolting all the interfacing sectors or the bottom sectors to the CB. The main requirements in tolerances are ±4 mm in height, ±4 mm inner radius and ±0.25 mm flatness on machined surfaces. The complete manufacturing process of the CVBCS is detailed in [3]. The CVBCS assembly consists of 12 sectors: eight make up the bottom part and four make up the top part. The arrangement of one CVBCS typical quadrant, comprising one upper and two lower sectors can be seen in Fig. 2.

Each sector is a fully welded piece in which the tolerances must be kept during manufacturing. Extra material is provided in the connection flanges in order to ensure the design dimensions during the final machining, anticipating the expected deformations produced by the welding process. The absolute positions of the centre of the ports have to be kept within a tolerance of ±8 mm. Vacuum tightness of the CVBCS will be done by means of thin seal-welding between the different sectors as well as between the lower CVBCS flange to the CB and the upper CVBCS flange to the Top Lid. These welds will be made after the final assembly in Japan.

3. Dimensional inspection of CVBCS individual sectors

As part of the fabrication process the dimensional inspection (DI) of every individual sector after final machining is carried out by laser tracker (LT) aimed at checking the fabrication tolerances. The individual sectors have turned out to be very flexible components due to their open geometry: the shell, even reinforced with external ribs, is a relative thin plate compared with the large dimension of the sectors (e.g. the largest upper sector is 10.5 m long and 4 m height). Moreover, the relatively large number of openings/ports of different dimensions (e.g. ports up to 2.3 × 1.2 m^2) also contributes to the mechanical flexibility of the sector.

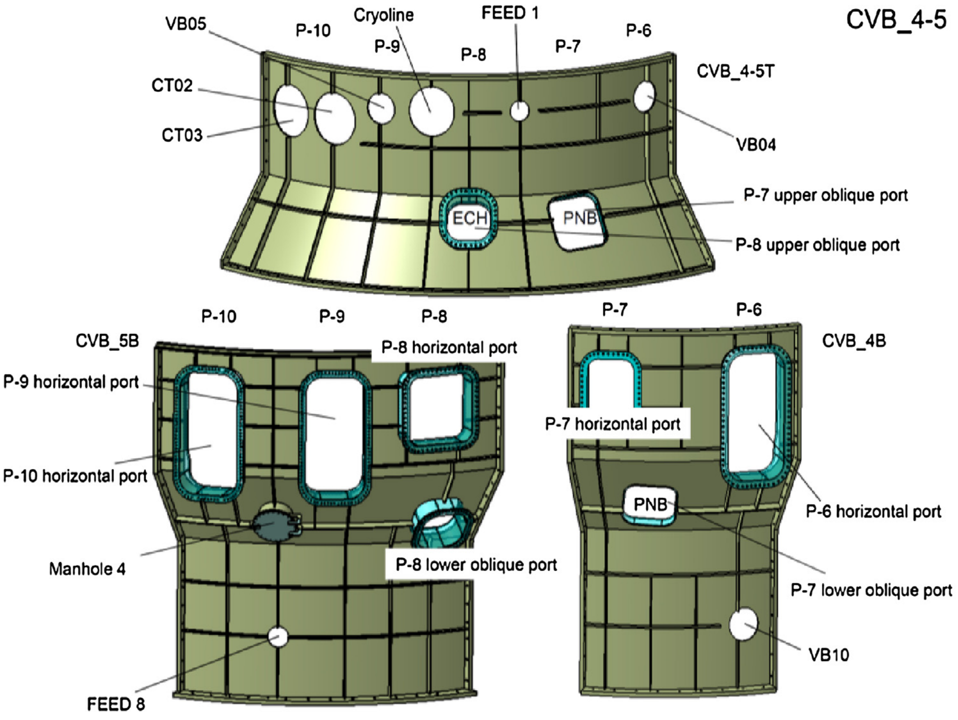

Fig. 2. Configuration of a quadrant of the CVBCS.

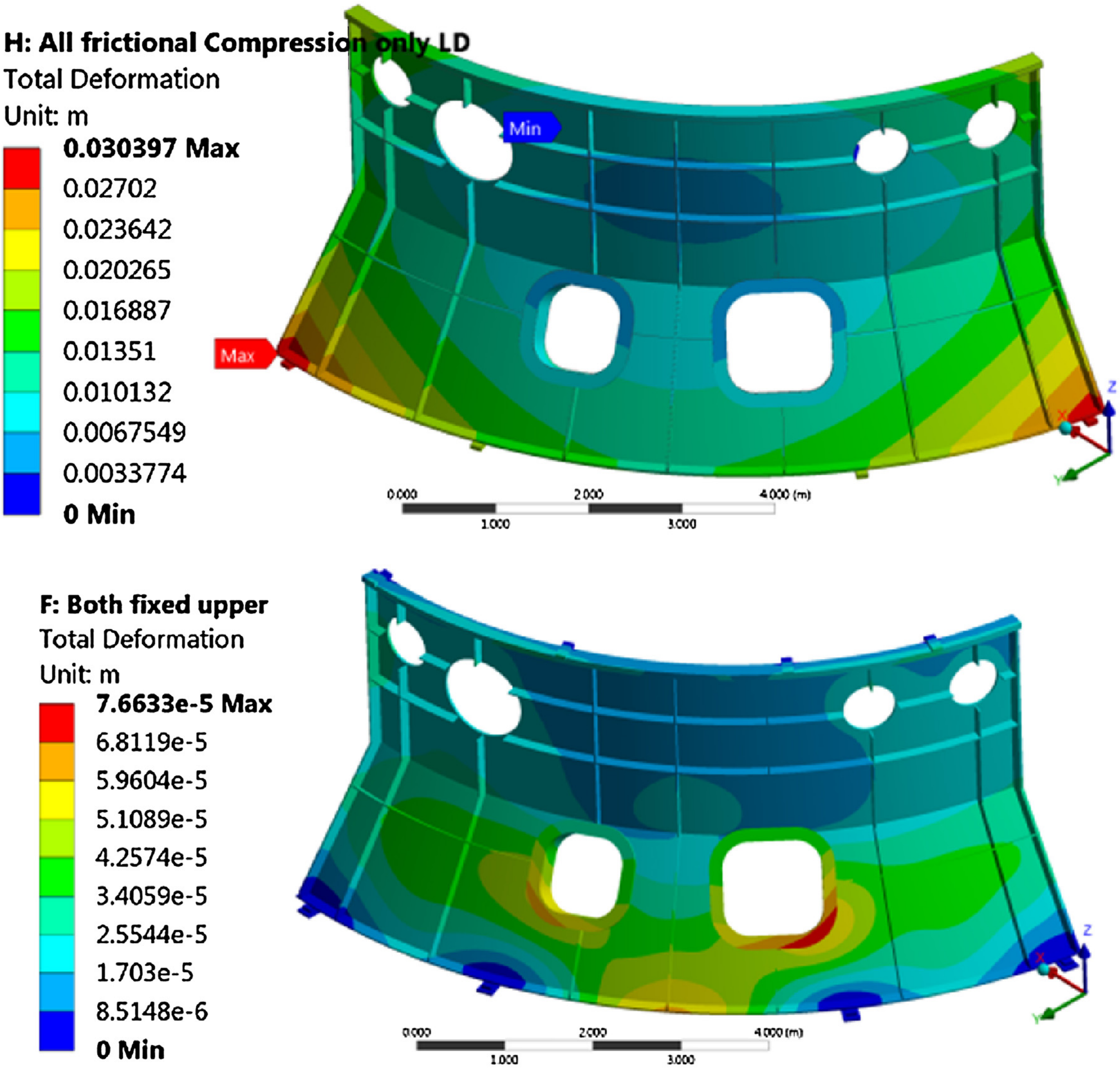

Fig. 3. Total deformation of an upper sector as initially supported at factory (up) and fixing both upper and lower flanges (down).

The first sector dimensionally inspected (an upper one) showed important deviations from the nominal dimensions (up to 40 mm). The sector rested originally with the lower flange on 4 supporting points with an average length between supports above 3 m; some flexible supports consisting of slings and hooks were used to maintain it vertical. A Finite Element Analysis (FEA) was carried out modelling this sector, to check that the observed deformations were due to the slenderness of the sector and not to manufacturing errors. The results showed that the way the sector had been supported induced large deformations under its self-weight. Fig. 3 (up) shows the total maximum deformations up to 30 mm located on the two lower corners, with a tendency of the upper flange radius to be shortened and the lower flange radius to become larger.

Further FEA carried out fixing the sector only at the lower flange – in order to keep the flange into nominal position- showed unacceptable deformations at the upper flange (above 2 mm). Thus, supporting in both flanges was needed to keep the flanges into their nominal radii. The maximum total deformation resulted to be negligible as it is shown in Fig. 3 (down).

Therefore, a dedicated support structure was designed consisting of two sub-structures in order to be valid for all the 12 sectors:

1) A rigid base ring assembled onto five levelling supports anchored to the floor, than can be set in two different radii (mobile) corresponding with the nominal sectors radius at the lower flange. The horizontal planarity of the ring can be kept within 0.3 mm (measured by LT). The sector lower flange is fixed to this ring by bolts.
2) A vertical frame made up of structural profiles that can be located at two different heights (covering all sectors height); the frame is equipped with several articulated arms to clamp the sector upper flange to its nominal radius. The arrangement for the DI of a lower sector can be seen in Fig. 4.

The verification is performed with a 3D coordinate measuring machine, Leica Laser Trackers LTD 640/AT960 (software METROLOG X4). The measurement is based on a polar method which consists in measuring the direction with two angular optical encoders and the distance with a single beam laser interferometer and a high precision absolute distance-meter, between the tracking head and the reflector (placed in the point to be measured). The theoretical accuracy on a 3D coordinates is 15 μm ± 6 μm/m (AT960). To achieve this accuracy, environmental stability and measurement system stability must be kept under control. Since nominal dimensions are defined at 20 °C, the part temperature is moni-

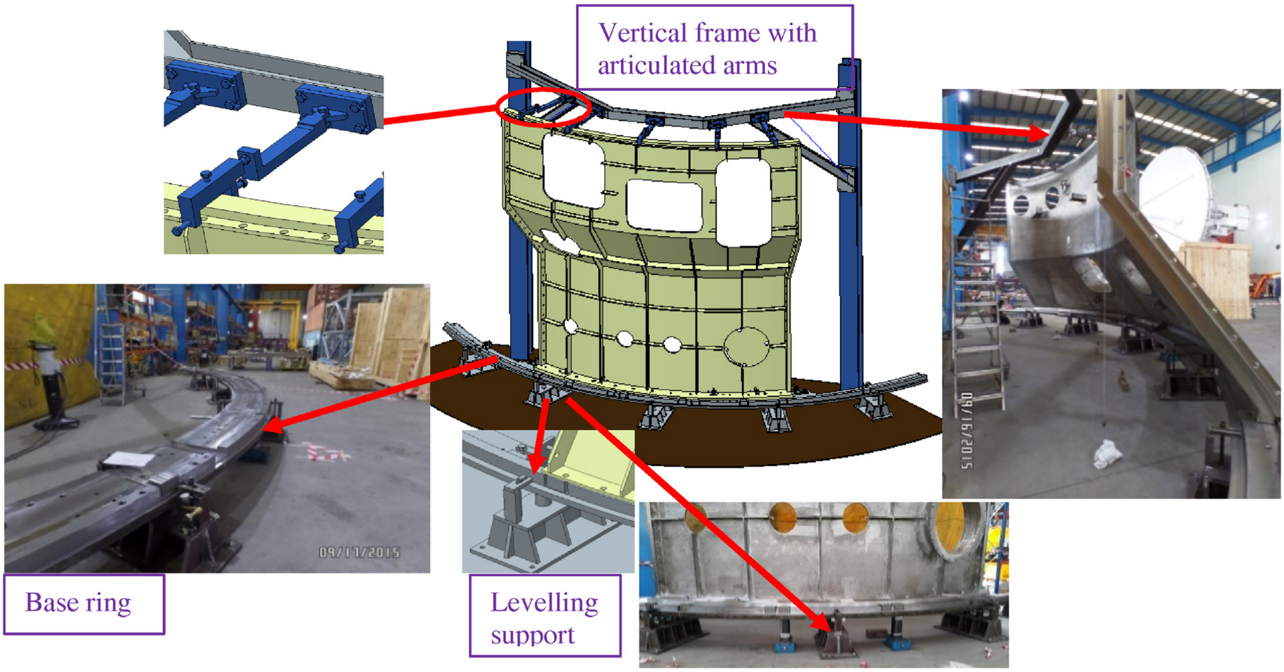

Fig. 4. DI arrangement of a lower sector.

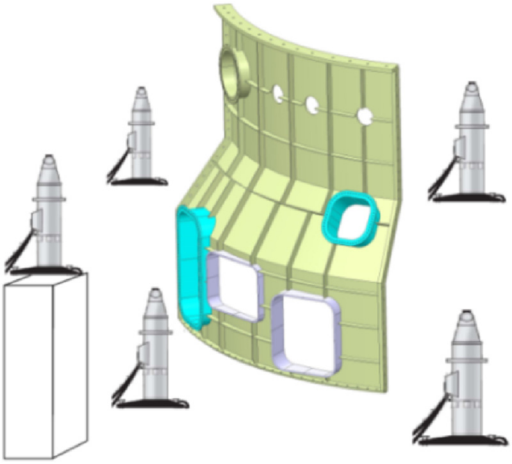

Fig. 5. Location of measurements stations.

tored at different locations and the measurement compensated by software considering the material thermal expansion coefficient (17 µm/m/°C). Due to the dimensions of the pieces, the LT stations are positioned all around the sector in five locations (Fig. 5). Before starting, a network of points will be established and remain fixed during the inspection to join the measurements from each station; some of these points are measured periodically to assess the drift. Once the collection of the data is finished, the coordinate system will be established and the required dimensional, geometrical and positional tolerances evaluated.

The following parameters are measured on the sectors: 1- Upper and lower flange flatness, radius and height between them. 2- Flatness and angle of lateral flanges. 3- Planarity, angle and dimensions of ports, port flanges and openings as well as their distance to the lower flange. 4- Position of particular points on the shell. 5- Position of holes of upper, lower and lateral flanges.

The results are calculated with the software as follows: 1- The sector height as the mean distance between upper and lower flanges; 2- the radii and flanges flatness/parallelism are obtained based on the measured best-fit flange circles and planes respectively; 3- the absolute position of the cryostat ports, port flanges and openings is evaluated with their measured position (cylindrical coordinates) with respect to their theoretical position; 4- the radius of the shell in the measured points is calculated in the cylindrical system respect to their theoretical position.

DI of 5 sectors has been completed showing acceptable results. Tolerances imposed to the individual sectors have been more restrictive than the ones required for final assembly in order to get enough margin for the assembly tolerances. It is also expected that final tolerances of the whole component after final assembly will be slightly different than the ones obtained in the individual sectors DI.

4. Pre-assembly of CVBCS at the factory

The whole CVBCS will be pre-assembled, adjusted and dimensionally inspected at the factory before shipment to Japan, following the assembly procedure established for the tokamak. The latter considers the assembly of the lower sectors in the tokamak, one by one; after checking their final position, the set of the 4 upper sectors previously pre-assembled in the assembly hall is positioned on top of the former. Following this, the design of the support structure for the pre-assembly at the factory comprises a unique rigid support base anchored to the floor and two dummy rings which replicates the seating surfaces for upper and lower sectors sub-assemblies respectively. A levelling system based on screw-type mechanisms will be used to get the planarity required for the rings, measured by LT. Appropriate tools will be used to centre the dummy rings on the support base. Marks corresponding to the axes of the cryostat will be done on the support structure. Fig. 6 shows the design of the support structure.

4.1. Sub-assembly of the upper/lower sectors

The pre-assembly of the CVBCS will start with the sub-assembly of the 4 upper sectors on the ring which replicates the lower sectors upper flange. Firstly the verification of the ring (e.g. flatness, posi-

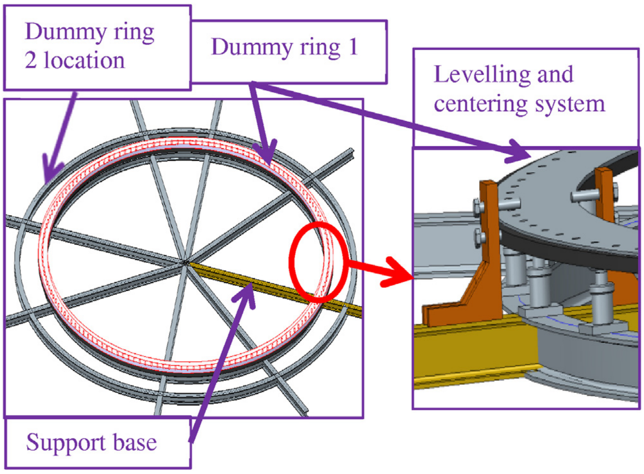

Fig. 6. Design of the support structure for the pre-assembly.

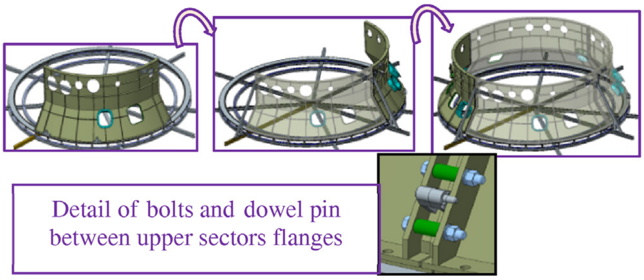

Fig. 7. Pre-assembly sequence of upper sectors.

tion of holes and radius) will be carried out by LT. The first sector will be placed on the dummy ring and adjusted in radial and angular positions by means of specific centering/pushing tools. Once the correct position is achieved it will be bolted to the ring. In addition temporary external supports will be used to fix the sector to the support structure. The verification of the angular position and verticality of the sector with respect to ring horizontal plane will be carried out by DI. The second sector will be placed on the dummy in a similar way. Both sectors will be fastened at the adjoining lateral flanges with a few bolts up to a certain torque. The adjustment of the joint has to be carefully done to match up the holes in radial direction. The position of the joint as well as flatness of the upper flange will be controlled by DI. Once the adjustment is achieved the bolts will be slightly pre-loaded. The same sequence will be applied to the remaining sectors. The conceptual pre-assembly sequence of upper sectors can be seen in Fig. 7. The final verification of the complete set will be done by LT. With the sectors fitted in their correct position, two dowels pin will be inserted between each pair of flanges. These shall ensure to reproduce the same assembly tolerances in Naka. Once finished, the set will be moved away from the support structure to proceed with the lower sectors sub-assembly.

The same procedure as for sub-assembly of the upper set will be followed for the lower sectors. In this case, the base ring replicates the CB ring where the CVBCS is fastened by M48 bolts. Specific tools have been designed for the lifting of the sectors. Lower sectors will be fastened at the adjoining flanges with bolts up to an adequate torque. The pre-assembly sequence for the lower sectors together with the detail of the fastening between sectors is shown in Fig. 8. The final verification of the complete sub-assembly will be done by LT and once the sectors are fitted in their correct position, three dowels pin will be inserted between each pair of lateral flanges.

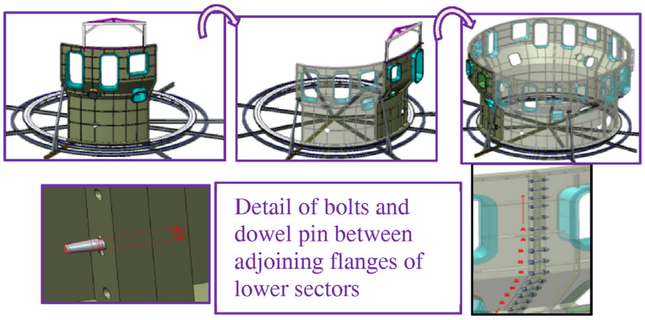

Fig. 8. Pre-assembly sequence of lower sectors.

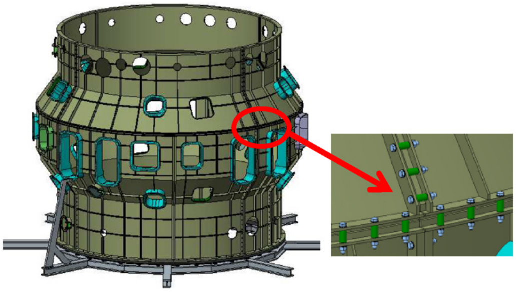

Fig. 9. Pre-assembly of CVBCS.

4.2. Completion of the pre-assembly

With the lower sectors fitted in their correct position, the upper set is placed on top of them. The fastening between upper and lower sectors is done by M36 bolts as it is shown in Fig. 9. The final verification of the CVBCS will be done according to the corresponding procedure.

The measurement will be taken from all around the assembly in four locations. All the information will be bundled in the same coordinate system thanks to the network of fixed reference points. A set of reference marks will be engraved on the CVBCS during the verification of the component to facilitate the assembly in Japan.

References

[1] M. Medrano, et al., Manufacturing of JT-60SA Cryostat Base, Fusion Eng. Des. 88 (2013) 711–715.

[2] J. Botija, et al., Structural analysis of the JT60-SA cryostat vessel body, Fusion Eng. Des. 88 (2013) 670–674.

[3] J. Botija, et al., Manufacturing of the JT-60SA Cryostat Vessel Body Cylindrical Section (this SOFT Conference), 2017.