ITER Machine Assembly – Challenges and Progress

K Blackler\textsuperscript{1}, V Bedakihale\textsuperscript{1}, K Im\textsuperscript{2}, B. Macklin\textsuperscript{1}, P. Petit\textsuperscript{1}, R. Shaw\textsuperscript{1}, D. Wilson\textsuperscript{1}

\textsuperscript{1}ITER Organization, Route de Vinon sur Verdon, 13115 St. Paul lez Durance, France
\textsuperscript{2}ITER Korea, National Fusion Research Institute, Daejeon 305-333, Republic of Korea;

E-mail contact of main author: ken.blackler@iter.org

Abstract. The basic ITER machine has around 1 million parts which must be successfully integrated and assembled. This complex and challenging task requires robust planning, processes, heavy lifting, welding and precise alignment and tolerance control. This paper summarises these challenges and presents the progress and present status of preparations for the assembly of the ITER machine.

1. Introduction

The ITER Organization is responsible for the assembly of the ITER Tokamak machine from components delivered in-kind from each of the Domestic Agencies. IO is currently undertaking detailed design, trials and planning for the assembly of the machine, to define the sequence and kinematics of each operation. The design of the necessary assembly tools, many by the Korean Domestic Agency, is progressing in parallel as the component designs are finalized.

The components to be assembled (Figure 1) are large and heavy (Table 1), and controlling the geometry of the machine during the assembly process will be a very demanding activity which can only be achieved by managing variation at each stage. Accurate dimensional control will be applied to ensure that the exacting tolerances required for machine operation are achieved.

The drivers for the assembly are plasma performance (Toroidal error field limit of $B_{3, mode}/B_{\alpha} < 5 \times 10^{-5}$), component stresses (e.g. TF coil nose stress $\sim$800MPa), French nuclear safety code requirements (RCC-MR) and functional limits such as clearances and adjustment capabilities.

There are also practical constraints, such as pit geometry (assembly from the bottom up), handling capacity, maximum lift height and physical interfaces between machine systems. Many of the operations are highly unconventional and require a safe mix of mechanically assisted and hands-on operations.
2. Main Tokamak Components

The following are the sub-systems to be assembled:

- Cryostat and penetrations
  - TCWS pipes and bellows
- Bioshield lid
- Magnet system, comprising:
  - Toroidal field coils and structures
  - Gravity supports
  - Poloidal field coils and supports
  - Central solenoid and supports
  - Correction coils and supports
  - In-cryostat feeders
- Vacuum vessel, comprising:
  - Vacuum vessel
  - Ports
  - VV gravity supports
  - VV instrumentation
  - Ex-vessel magnetics
- Thermal shields, comprising:
  - Vacuum vessel thermal shields
  - Cryostat thermal shields
  - Transition thermal shields
- In-vessel components, comprising:
  - Divertor
  - Blanket modules
  - In-vessel coils
  - In-vessel diagnostic components
  - Fuelling systems (PIS,GIS)
- In-port components, comprising:
  - Cryopumps
  - Diagnostics
  - Test blanket modules
  - Additional heating systems
  - GDC, IVVS

as well as all associated in-cryostat pipework, instrumentation and cabling. Table 1 lists the major components and their physical dimensions.

3. Assembly Sequence

The assembly sequence is divided into 5 major activities (sector sub-assembly, lower cryostat, sector assembly, ex-vessel, and in-vessel) and will proceed in an essentially bottom up manner, defined by component tolerances and practical considerations such as crane limitations.

The Tokamak([6], [7], [8], [9]) is assembled from nine sectors, each with a toroidal angle of 40°, and each comprising a sector of Vacuum Vessel (VV), two Toroidal Field (TF) coils, the associated VV Thermal Shield (VVTS), two TF Gravity Supports (TFGS) and VV Gravity Support (VVGS) which provide both the vertical support and lateral stabilization to the VV in the completed Tokamak. The components are delivered to the site individually, and sub-assembled into sectors using purpose built tools ([11]), and standard heavy handling and support tools. The tools have the capability of supporting and adjusting the largest of the ITER components; with maximum linear dimension 19m and mass 1200 tonne, with a precision in the low millimetre range.

3.1. Pre-assembly

VV thermal shield and VV sector sub-assembly are performed in the lay-down and assembly hall building (height 34m, width 46m, length 86m). This building is designed with a smooth and flat floor (DIN 18202) to allow transport of large components, air cleanliness (FED-STD-209E Class 100,000: less than 5 x 10⁶ particles of size > 0.5 μm/m³ [4]) to ensure vacuum compatibility of the assembled components and stable temperature control (±2°C control tolerance at 20 to 25°C, <70% relative humidity) for accurate and repeatable dimensional measurements.
<table>
<thead>
<tr>
<th>Component</th>
<th>Qty</th>
<th>Overall Dims (m)</th>
<th>Mass (tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Base Section</td>
<td>1</td>
<td>Ø 29.3 x 6.0</td>
<td>1166</td>
</tr>
<tr>
<td>Cryostat Lower Cylinder</td>
<td>1</td>
<td>Ø 29.4 x 9.9</td>
<td>667</td>
</tr>
<tr>
<td>Cryostat Upper Cylinder</td>
<td>1</td>
<td>Ø 29.4 x 9.1</td>
<td>591</td>
</tr>
<tr>
<td>Cryostat Lid</td>
<td>1</td>
<td>Ø 28.6 x 4.2</td>
<td>792</td>
</tr>
<tr>
<td>Bioshield Lid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sector 1 (West)</td>
<td>1</td>
<td>27.4 x 7.7 x 1.2</td>
<td>~480</td>
</tr>
<tr>
<td>Sector 2</td>
<td>1</td>
<td>30.5 x 5.0 x 1.2</td>
<td>~450</td>
</tr>
<tr>
<td>Sector 3</td>
<td>1</td>
<td>30.8 x 5.7 x 1.2</td>
<td>~480</td>
</tr>
<tr>
<td>Sector 4</td>
<td>1</td>
<td>30.5 x 5.0 x 1.2</td>
<td>~450</td>
</tr>
<tr>
<td>Sector 5 (East)</td>
<td>1</td>
<td>27.2 x 7.3 x 1.2</td>
<td>~480</td>
</tr>
<tr>
<td>VV Sector (with some separate manifolds and fixtures)</td>
<td>9</td>
<td>14.0 x 8.2 x 6.2</td>
<td>460</td>
</tr>
<tr>
<td>TF Coil</td>
<td>18</td>
<td>17.0 x 9.1 x 3.2</td>
<td>300</td>
</tr>
<tr>
<td>TF Gravity Support</td>
<td>18</td>
<td>2.6 x 2.3 x 1.4</td>
<td>25</td>
</tr>
<tr>
<td>PF1 incl. Clamps</td>
<td>1</td>
<td>Ø 9.6 x 3.7</td>
<td>182</td>
</tr>
<tr>
<td>PF2 incl. Clamps</td>
<td>1</td>
<td>Ø 18.2 x 2.4</td>
<td>184</td>
</tr>
<tr>
<td>PF3 incl. Clamps</td>
<td>1</td>
<td>Ø 25.4 x 3.5</td>
<td>385</td>
</tr>
<tr>
<td>PF4 incl. Clamps</td>
<td>1</td>
<td>Ø 25.3 x 3.5</td>
<td>349</td>
</tr>
<tr>
<td>PF5 incl. Clamps</td>
<td>1</td>
<td>Ø 18.6 x 2.8</td>
<td>329</td>
</tr>
<tr>
<td>PF6 incl. Clamps</td>
<td>1</td>
<td>Ø 11.2 x 3.6</td>
<td>363</td>
</tr>
<tr>
<td>Central Solenoid</td>
<td>1</td>
<td>Ø 4.3 x 18.9</td>
<td>900</td>
</tr>
<tr>
<td>Top Correction Coil</td>
<td>6</td>
<td>7.4 x 2.7 x 0.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Side Correction Coil</td>
<td>6</td>
<td>8.1 x 7.2 x 1.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Bottom Correction Coil</td>
<td>6</td>
<td>7.4 x 2.7 x 0.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Divertor Cassette</td>
<td>54</td>
<td>3.4 x 2.1 x 0.8</td>
<td>12</td>
</tr>
<tr>
<td>Blanket Module (max)</td>
<td>421</td>
<td>(1.3-2.0) x (0.9-1.2) x 0.45</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 1- List of Major Tokamak Components

Components are cleaned in a cleaning facility prior to entry, personnel will be appropriately dressed, and “dirty” processes and tooling specifically excluded from the area.

There are two 750t SWL(Safe Working Load) twin girder electric overhead travelling (EOT) cranes, each equipped with twin trolleys, each having a 375t main hoist, i.e. a total of four 375t hoists. These Main Cranes are capable of operating in tandem to provide a synchronised, combined lifting capacity. A Dual Crane Heavy Lifting Beam (DCHLB) will be used for connection of heavy loads to the Main Cranes to provide a single, swivelling lifting attachment of approximately 1385t capacity. In addition there are two auxiliary twin girder cranes, each of 50t capacity to support all other lifting activities within the Assembly Hall and Tokamak Building.
The number and variety of lifts, including the preparation time, means that crane usage is a significant constraint which requires careful planning in order to ensure compatibility with the schedule.

Each VV sector and TF coil is upended, ex-vessel diagnostics fitted, thermal shields installed, two TF coils attached. The larger ELM coils may also be temporarily positioned at this stage. The sub-assembly is attached under a radial beam (Figure 3) which serves to support it in the pit. Final alignment and centre of gravity of the sub-assembly must be correctly adjusted in the assembly hall before lifting from the sub-assembly tool into the pit, since neither the sector lifting tool nor the crane can make adjustments at a later stage.

Cryostat sections are manufactured in a workshop located to the south of the assembly & laydown building and are transported on rails through the cleaning facility and into the assembly hall, where they are lifted into the pit. A critical challenge of these lifts is the relative weakness of the cryostat cylinders to radial buckling due to its large diameter and openings for many penetrations.
3.2. In-pit Assembly

Prior to installing the sectors in the Tokamak pit, the VV and TF coil gravity supports (GS), lower cryostat sections, the lower PF coils (5&6) and feeders, Bottom Correction Coils (CCs), the lower CC feeders and the lower pre-tensioning rings, are installed, or placed in temporary locations if they become trapped once the installation of core components begins.

The sector sub-assemblies are transferred into position in the cryostat (Figure 4) in the sequence 6, 5, 4, 3, 2, 1, 9, 8, 7. The sub-assemblies are lowered with a displacement of 55mm radially and 80mm perpendicular in order to ensure a 100mm clearance to the previous sub-assembly. The final sub-assembly is displaced radially 100mm due to having two adjacent sub-assemblies already positioned, and this requires the final sector to be one lying in the axis of movement of the main crane. The sub-assemblies are moved into final position, and the TF positions fixed on their supports using custom-machined shims.

The TF coils and VVTS sectors are connected in the same sequence, whereas the VV sectors are joined (welded) into triplets according to a plan which aims to minimize the effect of welding deformations. Early connection of the TF coils avoids relative movement and degradation of the alignment.

3.3. Vacuum Vessel Field Joint Welding

Full penetration welding between VV sectors is used with custom machined splice plates for outer and then inner shells (performed from inside the VV). The inner splice plate width is 160mm and minimum radii around port stubs are 150mm in order to allow automated welding if desired. Narrow gap welding technology was the assumption during R&D and feasibility studies. This is an established process, welds have limited and predictable distortion and reasonable productivity can be achieved. Manufacture and assembly of the VV must be made according to the French nuclear code RCC-MR 2007 (Règles de Conception et de Construction des Matériels pour les réacteurs Rapides). This code covers welding, non-destructive examination, qualification and cleaning requirements. It references harmonised national standards and special instructions for equipment subject to specific regulations. A mock-up of the VV welding process will be made in the near future to allow full qualification of all processes, including defect repair, before the actual assembly.

RCC-MR requires radiography for volumetric non-destructive examination, and only where “it proves technically impossible to meet the requirements for a specific radiographic examination would the use of ultrasonic examination be permitted”. Feasibility studies have shown that radiological film and Iridium 192 for the outer wall (40 mm or 60 mm thickness) and Cobalt 60 for the inner wall (same radiographic thickness but with another crossing thickness before the radiographic film) can be used for most welds. The curvature of the vessel and source position is critical to ensure adequate detectability. Positioning of the film will require specific tools and techniques. Radiographic examination is not possible for all welds, therefore ultrasonic examination is also required and the necessary mock-ups will be made to demonstrate its application.
Each root and final weld pass, and each completed field joint shall be subject to helium leak testing. Leak rate of root and final passes of a weld shall not exceed $1 \times 10^{-9}$ Pa.m$^3$/s. Leak rate for a completed field joint shall not exceed $1 \times 10^{-8}$ Pa.m$^3$/s.

For leak testing of the root pass and final passes of a weld it is envisaged that a vacuum suction cup (probe) will be used. The suction cup is profiled to the test area and is fitted with a vacuum compliant seal (e.g. silicone, high density neoprene foam). The suction cup is fitted over the test area and pumped with the helium leak detection unit. Leak testing of the suction cup is performed. Helium is sprayed on and behind the test area and the leak rate into the suction cup measured. The weld is tested in sections since the maximum practical suction cup length is approximately 1m, this also allows for localisation of leaks by introducing helium into a small area in case of failure.

Leak testing of the completed field joint is performed by pumping out and monitoring the interspace while spraying helium around the inner and outer welds. Helium gas introduction must be controlled to limit the spread of helium beyond the test area.

Defects must be repaired, and feasibility studies have shown that 2-stage milling is feasible, the 2$^{nd}$ stage being required to remove stepping and ensure a suitable welding surface.

### 3.4. Tokamak Alignment

Toroidal Field requirements ($B_{3\text{-mode}}/B_{\text{to}} < 5 \times 10^{-5}$) drive the positional tolerances of the current centre line and therefore TF radial position to be ±3mm. The inner leg inter-coil structure gaps must be 2mm ±0.5mm. Currently tolerance analyses predict that the former can be achieved (to a tolerance of ±2.8mm) while the latter can only be achieved within ±7mm (i.e. with clashes) and therefore studies continue on alternative concepts.

Following installation of the final sector, the TF coil pre-tensioning rings are installed and the preload applied to each of the coils. A detailed dimensional survey at this stage will determine the as-built position of the TF coils from which the magnetic centre of the TF coils shall be derived. This operation will define the alignment reference datum for all subsequent assembly tasks on the Tokamak machine.

The VV is closed toroidally, with the welding of the three final joints between the triplets (VV sectors 1 to 9, 4 to 3, 7 to 6). Tolerance requirements on the overall vertical position of the VV are driven by port alignment needs. Positioning is achieved by jacking of the radial beams and fixed through custom toroidal and radial shimming of the VV gravity supports (Figure 5).

Clean conditions are then established inside the vessel, and the installation of the in-vessel systems is completed. The completion of the installation of the ex-vessel components proceeds in parallel.

### 4. Assembly Challenges

The installation tolerances for the Tokamak components are extremely tight, considering their large size and weight. To achieve these tolerances, the assembly plan must follow sequences and processes which optimize component alignment and ensure that residual stresses in the
components are kept to a minimum. Deviations within the assembly process shall be corrected as they occur, so as to ensure that alignment errors do not accumulate;

Routing of components through the building and between or through other pre-positioned or installed components is complex and must be carefully considered to avoid potential conflicts, including activities that are carried out in parallel. This activity will include the routing of systems which must be transferred via the assembly facilities, and be installed elsewhere in the building, such as in the galleries.

Figure 6 shows an example of clash detection made using 3-d simulation (now solved). In such cases design changes to the component are requested only if alternative installation paths cannot be achieved. Integration studies typically use nominal collective envelopes; however assembly studies must be performed using maximum individual envelopes (nominal dimensions + manufacturing tolerances + assembly tolerances). The next phase of studies will also consider deformations (dead weight) and margins of calculations to further increase confidence.

During assembly it is necessary to use temporary supports and assembly tools, for example to allow custom shims to be inserted. Load transfers from such temporary to final supports are studied to ensure stability, accuracy and maintenance of tolerances.

4.1. Tolerance Management

With the alignment tolerances close to the limit of what is achievable, the accumulation of deviations must be strictly controlled. The assembly plan is therefore designed to correct alignment deviations at each step of the assembly sequence ([3], [5]). Contributions to variation will come mainly from: TF coil and VV sector manufacturing, alignment accuracy and precision, measurement uncertainty and weld shrinkage. In-vessel the key alignment requirements are derived from the required alignment of first wall panels relative to the magnetic centre of the machine. The global position required is ± 10mm with respect to the magnetic centre, Toroidal and Poloidal gaps between modules shall be ± 4mm from nominal and the maximum step between the plasma face of adjacent components 5 mm.

The strategy relies on using a sophisticated Optical Metrology System (Figure 7) running dedicated metrology software to measure analyse the complex 3D survey data. This will provide a complete, evolutionary database of the as-built (i.e. assembled) components and of the overall Tokamak geometry. As an example, the blanket system includes 4000 interfaces which will require a minimum of 12,000 targets to be fully defined in 6 degrees of freedom plus many volume targets to link the camera images.
Mock-ups of the blanket support system survey target layouts have been constructed, along with trials of the necessary custom machining, to ensure that these alignment targets are achievable. 48/50 components were aligned to within ±0.1mm with a standard deviation of 0.035mm over 350 measured points.

With respect to the major components, it is essential that most geometrical interfaces have the provision for adjustment (generally shimming) included in their design. A graded approach has been taken to defining requirements on components by assigning an Alignment & Metrology Classification ([10]) according to the risk to assembly success, schedule and cost.

5. Summary

Assembly of the ITER machine is extremely challenging, however extensive studies, simulations and feasibility trails have been undertaken and continue in order to increase confidence in the design and to reduce risk.

The complex interfaces, tight tolerances, confined spaces and component dimensions and weights mean that careful preparation and execution of the assembly process will be required to ensure successful and safe machine integration within the planned timescales. The schedule is extremely challenging (approximately 4 ½ years) for what is one of the most complex machine construction projects ever.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

6. References


