CONFERENCE PRE-PRINT

ITER CORE MACHINE ASSEMBLY PROGRESS

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Abstract

The ITER (International Thermonuclear Experimental Reactor) project is a global collaboration aimed at demonstrating the feasibility of nuclear fusion as a large-scale and carbon-free energy source. The ITER facility will feature a large 'tokamak', a doughnut-shaped magnetic confinement device, which will contain the plasma through magnetic confinement. The project is led by seven international partners: China, India, Japan, the European Union, Russia, South Korea, and the United States. Construction began in the mid-2000s, and while there have been challenges and delays, ITER represents a major step toward advancing the scientific and engineering capabilities needed to make fusion energy a practical and reliable energy source in the future. The assembly of the ITER tokamak machine is a technical challenge due to the size and weight of its components. To achieve the predicted plasma inside the torus through precise magnetic field, to ensure vacuum integrity, and to accomplish proper distribution of heat loads, all components must be positioned within tight tolerances, well beyond usual practical requirements for this size of machine. Special handling tools were developed and proven while assembling. From the construction organization standpoint, the construction of ITER machine is a joint effort starting from technical specifications written by ITER Organization (IO) engineers, transversal work site coordination and supervision by IO supported by partner MOMENTUM (Construction Management as Agent) and execution of work in the field by installation contractors (Consortium CNPE-C). The scope of the paper is to report on the progress of the ITER machine construction and to describe how the assembly was brought back to schedule after a period of necessary repair works. Upfront work organization, detailed short- and long-term planning and communication to stakeholders, daily onsite meetings, close supervision with real-time reactivity to solve issues, and qualification of workers and equipment, are points which will be described.

1. INTRODUCTION

The ITER Tokamak, under construction in Cadarache, Southern France, is the largest Fusion project at present. Already by the size and the weight of its components, the assembly of this machine is a challenging task.
As the largest fusion project in the world, ITER is a "first of a kind" project, not only in terms of its scientific ambition but also in the complexity and scale of its assembly. The machine components are massive – some weighing over 400 tons – and must be positioned with extraordinary precision to ensure the integrity of magnetic fields and heat distribution essential for plasma generation.
This paper provides a detailed overview of the technical and organizational challenges involved in assembling the ITER core machine. It highlights the innovative tools, techniques, and coordination efforts that have enabled progress in this highly demanding environment.

2. COMMON ASSEMBLY SEQUENCES FOR THE CORE MACHINE ORIGINALITY

In fact, Assembly of the core machine started already long time ago. As an example, one of the heaviest single component lifts of the machine assembly program was conducted already five years ago. The Cryostat base with its approximately 30 m diameter and about 1200 tons weight was located by 2x 750 tons gantry cranes in tandem mode with less than 2.2 mm (x/y/z) directions positioning tolerance.

Comparable to a space docking stations, for the last final steps before landing, a special engineered and custom-made jacking systems was developed to reach the required position.

It is rested on 18 support bearings which take massive loads (e.g. dead weight, operational loads) and distribute them to the building slab. The overall net weight of all installations is calculated with about 23.000 tons. An equal distribution must be ensured via ITERs whole lifetime.

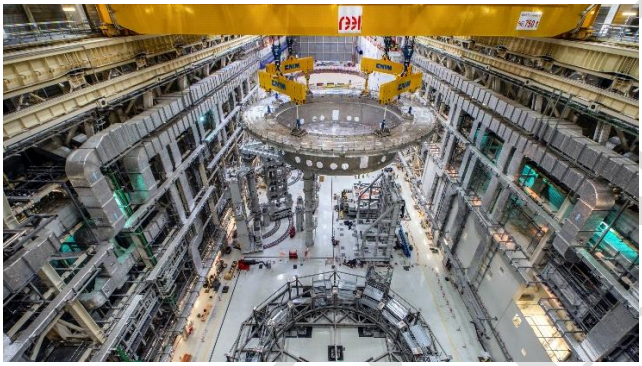

FIG. 1 Cryostat base being lifted from Assembly Hall to Pit

FIG. 2 Cryostat base landing in Tokamak Pit

The Cryostat base serves as a fundament for all future components of the core machine. Starting from nine so-called sector modules, which will form the complete torus ring. Each of the nine modules is composed of a Vacuum Vessel sector surrounded by two Toroidal Field coils (TFC), and Vacuum Vessel Thermal Shield (VVTS) elements. Furthermore, first diagnostic systems are installed on the outer vessel surface.

Two of these sector modules (please see figure 3) are already installed on the Cryostat base. The next modules are in preparation; a kind of series production for all nine modules is foreseen.

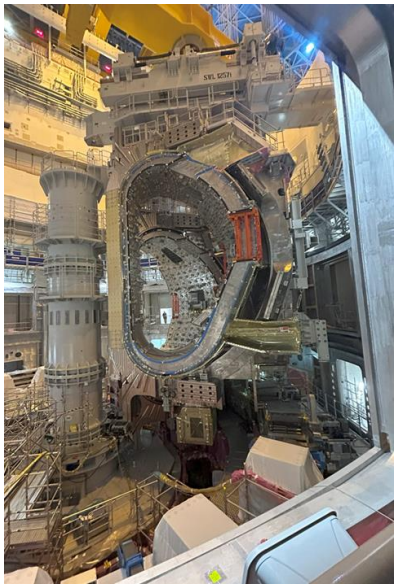

FIG. 3 Two sector modules installed in their final location in Pit

But installation of the Vacuum Vessel and TF coils is not the end of the assembly story. Many more components and systems must be positioned in close vicinity of the major components like other coil systems (e.g. Poloidal Field Coils, Central Solenoid), Cryostat Thermal Shield, cooling water and cryogenic pipes and instrumentations.

Finally, in-Vessel installations with components protecting the Vacuum Vessel surfaces while operating the plasma will be installed inside the vacuum vessel torus. In-Vessel installations are quite sensitive to their final position inside the Vessel as they must comply with the tight space between future plasma and inner wall of the Vacuum Vessel.

3. CHALLENGES DURING MACHINE ASSEMBLY

The current assembly focus is on sector module activities. These sector modules are pre-assembled in a so-called Sector Sub-Assembly Tool (SSAT). The SSAT has on the ground curved rails allowing the rotation of two side arms on which the components are pre-positioned (figure 5). While rotating the arms, the TS and the TF coils will be pulled over the vacuum vessel segments.
This technique, while not entirely new, is being applied at an unprecedented scale and accuracy and provides the base for our sector module assembly.

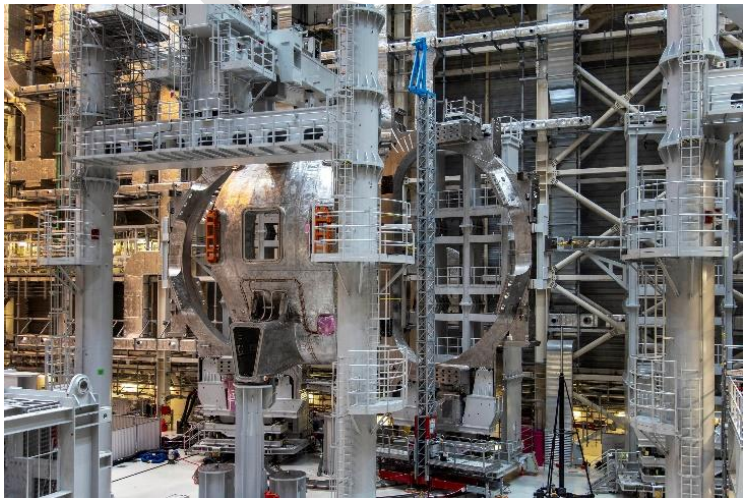

FIG. 4. Sector Sub-Assembly Tool with Vacuum Vessel in middle position and Toroidal Field coils on rotating arms

FIG. 5. Sector Sub-Assembly Tool with curved rails to allow rotation

Positioning of all systems is constantly checked by metrology. Without high precision measurements in the range of tens of millimetres (accuracy of the laser tracker systems), the machine assembly would not be possible.
Gaps of just a few millimetres must be kept during rotation of these components, otherwise serious damages on surfaces or first installed diagnostic systems could occur.

3.1. Upending Techniques

Components are getting transported horizontally into the Assembly Hall, consequently, they must be rotated into an upright position for further installation works. The upending of heavy components – sometimes exceeding 400 tons – is a critical operation. Specialized upending tools facilitate this transformation, ensuring stability and control throughout the process. The two 750 tons overhead cranes, available in the Assembly Hall, must be brought into a simultaneous mode to lift and rotate the tool with the components together (figure 6).
Special care must be taken to the exact pre-alignment of the components in the tool to match both horizontal and vertical supporting positions. Before final rigging, the centre of gravity is determined in the range of few centimetres, allowing the prior adjustment of the lifting tools together with the cranes. This is essential to avoid any unexpected movements while upending.

FIG. 6. upending of heavy components with the Upending Tool (UT)

3.2. Required Accuracy

To achieve the predicted plasma inside the torus through precise magnetic fields, and to accomplish proper distribution of heat loads, all components and systems must be positioned in a very accurate manner with gaps well below normal practical requirements for this size of machines. Major components are in the scale of 15 m in height, 6-7 m in width with a deadweight spanning from serval up to 440 tons. The required accuracy for the final alignment is driven by the interfaces between various systems. As an example, in the case of TF coils the inboard nominal gap between the two coils shall be aligned within 2 mm+- 0.5 mm (see figure 7).

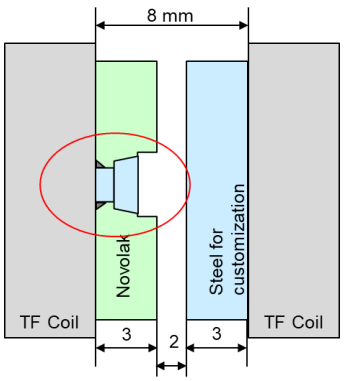

FIG. 7. Gap requirements between two Toroidal Field Coils (TFC)

Overall, the inboard gap between all 18 TFC shall have a uniform gap distribution with all modules in place at their final position. This is coming from the strict magnetic centreline requirement [1] on the magnetic systems.
In practice, it is essential to align first the two TF coils to each other in the SSAT. Once the module transportation into the pit has been completed, the TF gap between adjacent modules must be measured again and, and if necessary, adjusted.

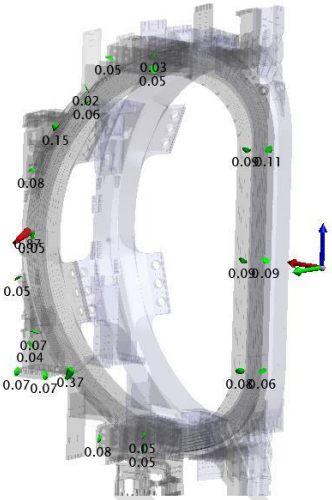

FIG. 8. Inboard area of a TF coil in the Sector Sub-Assembly Tool (SSAT)

FIG. 9. Measured TF coils after alignment in the SSAT

3.3. Assembly Schedule Opportunities

The assembly of the core machine is following an extremely tight time plan. In spring 2033 the Cryostat and as such the core machine assembly shall be finished. Keeping this in mind, all opportunities are used to optimise the assembly process. A more industrial execution rather than a scientific approach had to be established.

In 2024 a bottleneck was identified with the preparation of components in the Assembly Hall. A thorough sequence study was done at that time with the result that IO decided to procure a second upending tool. Immediate efforts were done to identify a possible manufacturer with capacities to test this tool afterwards. Only few companies were able to fulfil these requirements.
Finally, after performance of acceptance test with about 600 tons, the second upending tool arrived in time for the onsite installation needs, in spring 2025. After additional functional tests, the now two tools were used in Summer 2025 to upend and then transfer two TF coils into the SSAT. The availability of this second upending tool was allowing the use of the required crane rigging twice. A time saving of about two weeks was achieved which represents a massive optimisation in terms of operational costs.
Please see the picture below for the current set up of the two upending tools in the Assembly Hall.

FIG. 10. Two Upending Tools installed in the Assembly Hall for optimization of processes

4. WORK SITE ORGANIZATION - HUMAN EXPERTISE AND COORDINATION

The complexity of ITER assembly extends beyond machinery and tools. Human expertise plays a vital role, particularly in tasks requiring high-end technical know-how. Coordination among various stakeholders is equally crucial. The assembly process is the result of technical specifications issued by ITER Organisation (IO) engineers, executed on site by installation contractors such as the CNPE-Consortium, under the site coordination and supervision ensured by IO and its external partner MOMENTUM who acts as Construction Management as Agent. Success hinges on synchronized planning, clear communication, and a shared understanding of assembly goals.

This is ensured by a continual review and adjustment of long-, mid- and short-term schedules, trickled down to the operational level.

Sequences and schedules are being reviewed on a long-term basis (~5 to 8 years), to look for opportunities to optimize the schedule. This could be through anticipation of some activities, or optimizations of tooling to give more flexibility in the installation sequence. As an example, in-vessel bosses, used to attach the diagnostics systems inside the Vacuum Vessel, were initially planned to be installed after the completion of Vacuum Vessel torus welding. A schedule opportunity was identified and seized to anticipate a large portion of their installation gradually as the sectors are being placed inside the Tokamak Pit, or even during sector module sub-assembly. Another example is the decision to redesign the tooling for equatorial port stub extension in order to enable an earlier installation of Side Correction coils. The long-term schedule analysis enables us to spot these opportunities upfront and to launch potentially long-lead actions, such as redesign and procurement of tooling. The long-term schedule is reviewed regularly with ITER Organization project leaders from a technical standpoint and is published once per month to all stakeholders.

This long-term schedule feeds into a mid-term schedule (~6 months to 1 year span). The level of details of the mid-term schedule is much higher than the one of the long-term. Resources are further detailed, particularly with regards to tooling allocation (e.g. overhead cranes) and space allocation, which are two key factors for the assembly of the Tokamak machine large and heavy components. Sequences are re-arranged to level the use of these resources and to eliminate any possible bottleneck. Also, the granularity of this schedule is high and enables to perform in-depth analysis of the duration of each task. As an example, suggestions were made in the initial schedule of the second Upending Tool assembly, enabling to gain ~20% in duration. The mid-term schedule is reviewed with each technical stakeholder every week and published to everyone on a weekly basis.

Both, the mid and long-term schedules are also reviewed using 4D support. Basically, the 3D model and the schedule are linked together to visually set in motion the 3D components of the Tokamak machine, as per the actual programme of works. Beyond the mere purpose of creating an animation for communication purpose, this visualization has several benefits (figure 11):

- It is visually engaging, therefore increasing communication between stakeholders and improving the feedback loop.
- It helps to spot potential clashes and validate sequences;
- It helps to better identify the space available and the needs for accesses;
- It can be used to validate/dismiss alternative proposals through ‘digital rehearsal’;

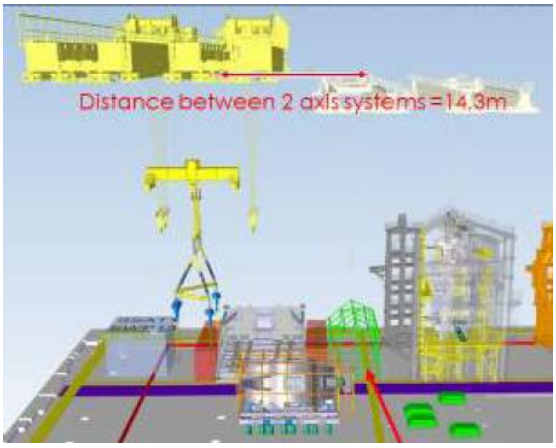

FIG. 5 4D study of components movements in Pit

At the site operational level, on a three-week look-ahead span, the mid-term schedule is turned into a coordination schedule. This very detailed schedule is used by the site teams to book the necessary support services (e.g. crane drivers, material deliveries) and organize the work areas (safety exclusion zones, ad hoc measures to preserve cleanliness, etc.). It is reviewed on a weekly and on a daily basis, with all the involved contractors, in each area. Beyond the digital communication, dedicated boards are set on site to increase visual management and foster maximum alignment on project targets.

FIG. 6 Coordination boards in Assembly Hall

These mechanisms operate continuously, so that the schedule is constantly refined and optimized, and the plan is cascaded down to the teams on a permanent basis.

5. QUALIFICATION OF PROCESSES

Workers must know upfront how they have to assemble components and systems together and shall not discover any uncertain situation. That is why qualification of processes and anticipation of any possible disturbances during the work execution is given a special focus (e.g. specific processes such as superconducting coil connections, welding of special shaped components or instrumentation laydown in specific constraint environments).
Mock-ups for training and qualification must be planned from the beginning of the contract. The contractor must announce suitable qualified and experienced persons (SQEP) with matching skills required for the special work.
Main challenges on specific processes are:

- Complex integration with existing fusion technology systems;
- Strict safety and nuclear environment requirements;
- Limited physical access and confined installation spaces.

Required key competences for the completion of qualification processes are:

- **Cross-cultural collaboration** – Navigating the multinational work environment and communicating effectively with stakeholders from diverse technical and cultural backgrounds;
- **Procedural discipline** – Following qualified procedures exactly, even under schedule pressure, and resisting shortcuts;

— **Questioning attitude** – Noticing deviations from the approved procedure, subtle signs of defects, or missing documentation before it becomes a non-conformance;
— **Problem-solving mindset** – Identifying root causes and proposing corrective actions when qualification trials fail or parameters drift.

A representative case is the qualification for connecting superconducting magnet coils and related feeder systems. IO and CNPE-C established a dedicated and highly efficient qualification team composed of IO engineers, IO Quality Control, CNPE-C Construction Work Package (CWP) Leader and Quality Control engineer, and candidate workers. At Corbières off-site facility, the team used full-scale mock-up samples, reproduced the same physical constraints as the actual site, and applied identical process procedures planned for live execution. Through this setup, over 20 teams for joint connections and insulation wrapping with dielectric performance qualification were completed efficiently. This preparation ensured that, during the peak on-site phase, up to ten parallel special-process activities could be executed while fully meeting the stringent schedule and quality requirements.

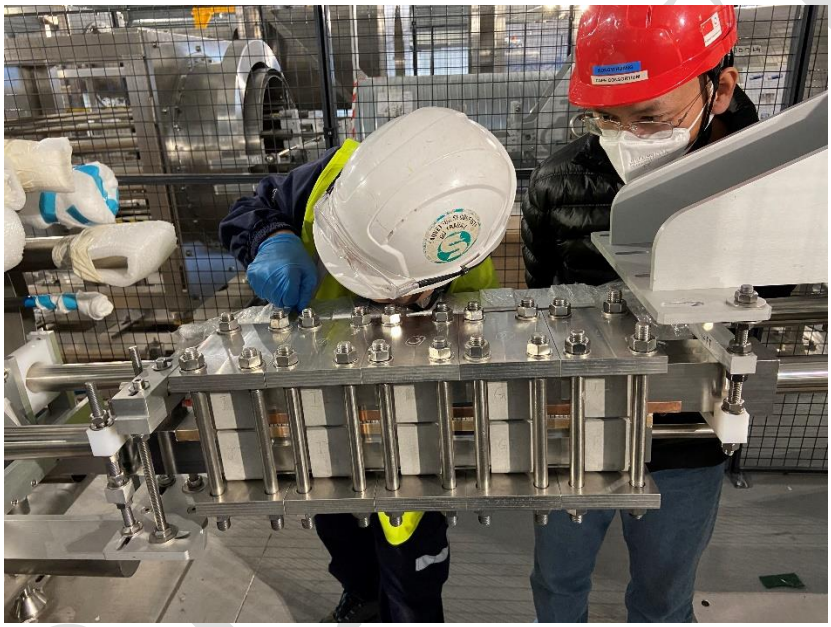

FIG. 13. Full-scale mock-up used for operator qualification at Corbières

6. SUMMARY

The ITER project, the world largest fusion energy experiment, is advancing through a highly complex and precisely coordinated assembly process. This paper outlines the technical achievements and logistical strategies behind the installation of massive components like the Cryostat base and Vacuum Vessel modules. It highlights the use of custom-engineered tools and laser-based metrology to achieve sub-millimetre accuracy in positioning. The assembly process also relies heavily on human expertise, including specialized workers and a multi-tiered coordination structure involving engineers, contractors, and management agents. Looking ahead, ITER roadmap includes completing the machine assembly, achieving first plasma, and transitioning to deuterium-tritium operations, all of which are critical steps toward demonstrating the viability of fusion as a large-scale energy source.

7. REFERENCES

[1] ALIX B. and al., UNDERSTANDING OF THE ILIS GAP REQUIREMENTS, internal report, ITER Organization, Saint-Paul-lez-Durance, 2025 https://user.iter.org/?uid=E6DCZB