# Progress in ITER Construction, Manufacturing and R&D

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**Abstract**. Rapid progress is being made in the design, manufacturing, construction and R&D activities for the ITER project, and the facility is now taking shape at St-Paul-lez-Durance, where construction of the major buildings is advancing rapidly. Supported by impressive achievements in fusion technology R&D, manufacturing of major ITER components, such as superconducting magnet systems, vacuum vessel and cryostat, is in full swing. Substantial progress has also been achieved in prototyping and R&D activities in areas such as plasma facing components, in-vessel coils, H&CD systems, remote handling and power supplies in preparation for manufacturing. A wide-ranging physics R&D programme is addressing key issues impacting the finalization of the ITER design and preparations for operation. This paper reviews progress made in developing the advanced technologies required for ITER and in the manufacturing activities for major tokamak components, discusses advances made in experimental and modelling studies of key physics issues, details measures taken to establish a more effective project organization and presents the status of construction of the ITER facility.

## 1. Introduction

The ITER project, established by an international agreement among seven Members (China, the European Union, India, Japan, Korea, the Russian Federation and the United States of America), is a critical step in the development of fusion energy: its role is to confirm the feasibility of exploiting magnetic confinement fusion for the production of energy for peaceful purposes by providing an integrated demonstration of the physics and technology required for a fusion power plant. Rapid progress has been made over the past two years in the design, manufacturing, construction and R&D activities, and the facility is now taking shape at St-Paul-lez-Durance in southern France (e.g. FIG 1).

*FIG. 1: Aerial view of the ITER site at St-Paul-lez-Durance with the construction of the Assembly Hall and Tokamak Complex in the centre of the photograph. The circular form of the bioshield, which will house the cryostat and tokamak core, can be seen in the centre of the Tokamak Complex. A large logistics warehouse can be seen on the hill above the main site.*

A new management structure has been established within the ITER Organization (IO-CT) and its technical activities more tightly integrated with those of the Domestic Agencies (IO-DAs) to provide more effective leadership for the project. The design of critical components has been finalized and stabilized to provide a robust framework for the development of a revised, resource-loaded schedule to First Plasma, now planned for December 2025, and through to DT operation. In preparation for the forthcoming expansion of on-site installation activities, a Construction Organization has been established and 'Construction Management-as-Agent' (CMA) contract signed to provide clear lines of responsibility and to define the interfaces between design and manufacturing activities and on-site installation. In recognition that ITER is a Basic Nuclear Installation (INB-174-ITER) under French law, measures have been implemented to strengthen the nuclear safety culture across the project.

Significant progress has been achieved in the production of major components for the tokamak and plant systems. Over 80% of the superconductors required for the ITER magnets are now complete and coil fabrication activities are underway in 6 of the 7 partners' factories. Manufacture of the sectors, port plug extensions and in-wall shielding for the vacuum vessel is expanding, with 4 of the partners contributing, while the first major elements of the cryostat, 460 t of steel segments for the cryostat base, have been delivered and welding of the base has started on-site. Progress has been achieved in prototyping and R&D activities in areas such as plasma facing components, in-vessel coils, H&CD systems, remote handling and power supplies in preparation for manufacturing. The central control systems (CODAC) are moving from design to procurement, and preparations for on-site instrumentation and control (I&C) integration have been launched. A wide-ranging physics R&D programme, integrated with the ITPA and the Members' fusion facilities, is addressing key issues impacting completion of the ITER design and preparations for operation.

## 2. Construction Progress

### 2.1 Buildings

The complex integration between tokamak, auxiliary and plant systems, and buildings has been a major challenge throughout the life of the ITER project. A streamlined organization, integrating the activities of the IO-CT, EU DA and contractors, has therefore been implemented, with a rapid drive towards the freezing of building design, particularly in the Tokamak Complex. The project has increasingly seen the benefits of these measures over the past 2 years. On-site, the external fabric of the Assembly Building is essentially complete and the internal fitting out, including the successful installation of two 750 t cranes (FIG. 2), is underway. The Tokamak Complex, incorporating the Tokamak Building, the Diagnostics Building and the Tritium Building is advancing (FIG. 3). The lower basement level (B2) of the Tokamak Building is complete, while concrete pouring for the upper basement level (B1) and propping for the ground level (L1) slab are underway. The Diagnostics and Tritium Buildings are progressing at a similar rate. Several captive (water) drain tanks have been installed, the first equipment incorporated in the Tokamak Complex and the first steps in a multi-year on-site installation programme of tokamak and plant systems which is about to be launched.

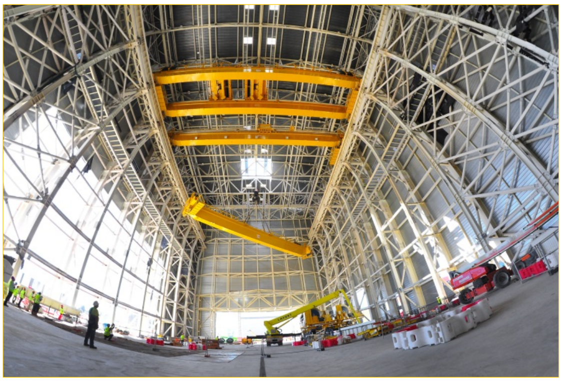
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*FIG. 2: Internal view of the Assembly Building during the installation of the two 750 t cranes (now complete).*

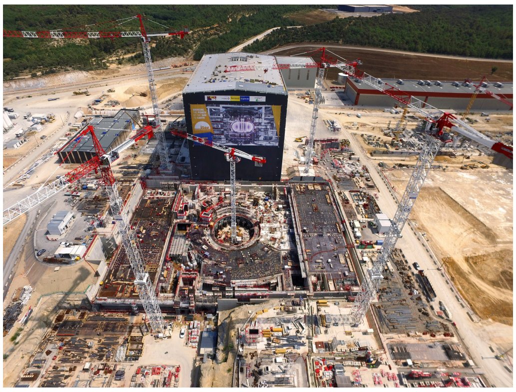
*FIG. 3: A view of the Tokamak Complex construction with the Assembly Building behind. The Tokamak Building is in the centre, with the form of the circular Tokamak Pit (inner diameter ~30 m) visible; the Tritium Building is on the left and the Diagnostics Building on the right of the Complex.*

Construction of a series of ancillary buildings is also progressing rapidly. The structure of the Site Services Building is complete and the installation of services has started, while civil works on the Cryogenic Buildings is advancing, with the erection of the main columns and the completion of the slabs. For the Radiofrequency Building, the pouring of the L1 slab is complete and the cooling water system, civil work and surrounding drainage are progressing on schedule, while the main steel structure for the Cleaning Facility Building has been erected and cladding activities are underway. Construction of the Power Supply Building has also been launched. Overall, the on-site construction is now being driven forward to meet the needs of the installation schedule for tokamak and plant systems, with increasing numbers of components arriving at the ITER site.

## 2.2 Safety

The strengthening of the ITER Organization and the progress towards the assembly phase for the first components is consolidating the realization of the ITER Nuclear Facility (INB-174-ITER), which was awarded the Decree of Authorization of Creation in late 2013. This is the main nuclear licensing step allowing the design, construction and manufacturing, assembly, commissioning and operation of the INB-174-ITER. The full process follows the French nuclear regulation and is subject to inspections by the nuclear regulator (Autorité de sûreté nucléaire - ASN). At each step in this process, demonstration to the regulator of compliance with nuclear safety requirements is mandatory.

The ITER Decree and the associated ‘technical prescriptions’ for release of the main hold points form one important element of the authorization basis: in 2014 the main hold point related to the concrete pouring for the Tokamak Complex basemat, while in 2016 it related to the authorization for construction of the Neutral Beam Cells. For construction of the nuclear buildings (Tokamak, Tritium Building, Hot Cells, Radwaste, including also access control to these buildings), the other hold points are related to the technical prescriptions to be answered before the assembly phase, e.g., results of R&D for demonstration of the efficiency of the detritiation plant, qualification of the detritiation system or qualification for beryllium reception on site. The framework for nuclear safety and environmental protection in ITER is completed by demonstration of respect for ASN decisions and the implementation of corrective actions arising from ASN inspections.

## 2.3 Technical Integration

ITER is by nature a highly integrated device with complex interface issues. ITER’s status as an INB generates additional challenges associated with nuclear integration and safety requirements and procedures. The ‘in-kind’ approach to procurement, with technical responsibilities often distributed across the IO-CT and several IO-DAs, poses further challenges. Effective technical integration across the IO-CT and IO-DAs is, therefore, critical to the design, manufacturing and construction activities. Systems engineering has received increased emphasis over the past two years and the systems engineering team is now focussed on checking and confirming the flow down of safety and other top level requirements, as well as the verification and the validation of these requirements in the systems’ definition.

A Nuclear Integration Unit (NIU), with staff from the IO-CT and IO-DAs, has been created to ensure that performance requirements associated with the nuclear environment are fully incorporated in the design of the buildings and components. Although much design work has already been completed, the NIU team is utilizing earlier, distributed efforts by integration and system design teams. To ensure that, in future, system and overall facility design satisfies all related performance requirements, the NIU has responsibility for all nuclear integration aspects (nuclear analysis, shielding improvements, activation calculations, nuclear heating in magnets, contamination, maintenance, electronics in radiation environment, materials issues and quality control of nuclear analysis codes etc.).

## 2.4 Construction and Assembly

The construction works are separated into ‘Tokamak’ and ‘Plant’, taking into account the geographical distribution and the fundamental differences in work disciplines and skills, between first of a kind and more industrial, standard systems. Assembly of tokamak and auxiliary systems includes many aspects specific to fusion, with leading-edge technologies, superconducting magnets, and handling and positioning of heavy and large-scale components to fine tolerances. In addition, the supply chain is complex, with in-kind components shipped from around the world. Significant uncertainties in delivery schedules can arise due to technical risks during manufacturing, as well as to non-conformities which require adjustment during assembly. The IO-CT has therefore put in place a construction organization that is able to respond and to take into account these issues. The approach to the management of construction aims to maximize the use of expert engineering knowledge in the IO-CT and IO-DAs, while maximizing the use of industrial knowledge in construction management.

Following a year-long international tender process, an industrial consortium has been selected as Construction Management-as-Agent contractor (CMA). The scope of CMA services includes contract management, change management, project management, construction preparation, site coordination, works supervision and activities leading up to mechanical completion. IO-CT will, in addition, place three main work contracts for the assembly of the tokamak machine and the mechanical and electrical installation of plant systems. IO-DAs will also place contracts for some plant installation works.

Significant manufacturing and R&D activities are underway to support on-site construction and assembly work. A key purpose-built tool for ITER construction is the sector sub-assembly tool (SSAT), scheduled for delivery to the ITER site in the second quarter of 2017 by KO DA. This heavy structure (see FIG. 4) will support the assembly of a 40° sector of vacuum vessel (VV), vacuum vessel thermal shield (VVTS) and two pairs of toroidal field (TF) coils. Two SSAT sets will be used to integrate 9 tokamak sectors in the Assembly Hall prior to their installation in the Tokamak Pit. Manufacturing of the first SSAT set was launched in March 2016 and is progressing satisfactorily to allow delivery to the ITER site on-schedule. KO DA and its major supplier are preparing to launch sub-component manufacturing and are preparing a facility for the factory acceptance test (FAT).

A contract for Vacuum Vessel Assembly Welding was launched in 2012 to weld and test the 9 VV sectors and 53 port structures on-site and to develop, supply and qualify all related tools, procedures and personnel. Specific welding tools for all geometries and locations have been designed, manufactured, commissioned and rigorously tested. The robot and welding control systems have been fully integrated and extensive welding trials carried out on a series of test plates and mock-ups. The feasibility of the final (on-site) VV assembly is being demonstrated through several types of mock-up, designed to be fully representative of the most difficult areas (e.g. FIG. 5). Welding tests of the final 1:1 mock-ups are planned over the next year, with completion expected by the end of 2017.

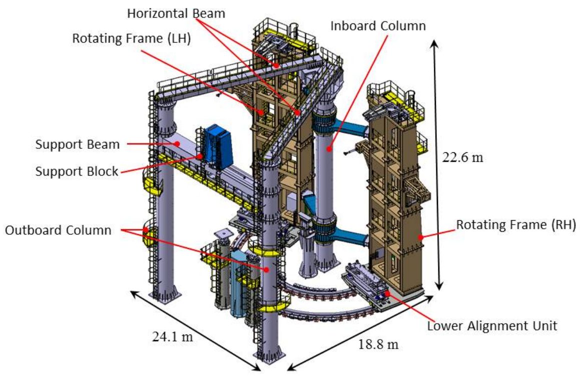

*FIG. 4: Diagram of the Sector Sub-Assembly Tool (SSAT).*

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*FIG. 5: Welding trials on a mock-up of the VV triangular support area.*

## 3. Progress in Tokamak and Plant Systems

### 3.1 Tokamak Core Components

The international collaboration formed around the production of superconducting magnets for the ITER tokamak has produced over 600 t of $Nb_3Sn$ (increasing annual world production by approximately a factor of 10) and almost 250 t of NbTi superconducting strand during an eight-year campaign. At a final Conductor Meeting at ITER Headquarters, held in September 2015 and involving the procuring IO-DAs - CN, EU, JA, KO, RF and US – as well as representatives of the applied superconductor community, the many factors contributing to the campaign's success were recognized.

Manufacturing of the TF coil windings and structures is now well underway - the first EU TF winding pack was completed in April 2016 (FIG. 6). TF coil activities under JA DA scope also advanced, with double pancake series manufacturing underway and coil structure sub-sections in fabrication (FIG. 7). Over 4,500 tonnes of high-strength ITER-grade steel will be required to produce the 19 massive encasements required by the TF coils. In the on-site Poloidal Field (PF) Coils Winding Facility, the winding table and equipment for fabrication of PF coils #5 and #2 has been installed in preparation for the first qualification activities with dummy conductor in 2016 (FIG. 8). Manufacturing of PF coil #1 is advancing in the RF (FIG. 9), while tooling and component qualification is underway for PF coil #6, to be manufactured in China under an agreement with the EU.

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*FIG. 6: The first complete TF coil winding pack at the EU manufacturer (fabricated from $Nb_3Sn$ superconductor, with dimensions of 13.8 m × 8.7 m).*

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*FIG. 7: Inboard section of TF case manufactured in Japan.*

The winding of the first module for ITER's central solenoid (CS) was completed in the US following the successful commissioning of 11 tooling stations. Fabrication was also launched on elements of the structural support, including the first lower key blocks and three prototype tie plates, and a cold testing facility was built for the final testing of each module at 4 K. The US closed out the Final Design Review (FDR) on assembly tooling and awarded contracts for the initial set. In a US-Japan collaboration, the performance of the CS conductor was tested through an 'insert coil test' in Naka which confirmed that the conductor performed as predicted, with no degradation.

Fabrication of the correction coils (CC) is progressing satisfactorily in China, where the first bottom coil was wound, several key manufacturing steps were qualified, and the raw material for the coil cases was hot-rolled and extruded in prototype trials. The first manufacturing readiness assessment for a magnet feeder component was successfully held for a cryostat feedthrough (for PF coil #4), bringing five years of work on the design and qualification of this key feeder component to a successful close. High temperature superconducting (HTS) current lead prototypes were also successfully tested at 10 kA (CC-type) and 68 kA (TF-type).

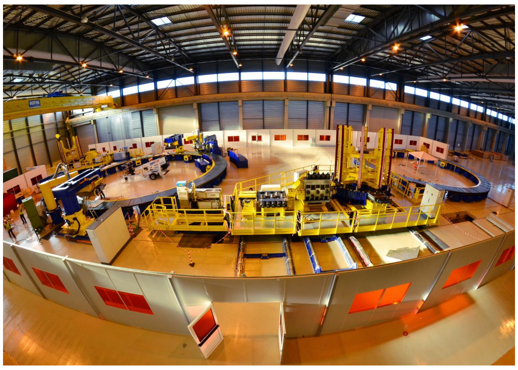

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*FIG. 8: View of the PF Coil Winding Facility on the ITER site, with tooling being installed.*

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*FIG. 9: Winding of a double pancake for PF coil #1 in the Russian Federation.*

R&D on the modified design and reference conductor for the in-vessel coils demonstrated a significant reduction in fatigue and increased manufacturability, robustness and reliability. Development continues on a new bracket concept and on bending and welding mock-ups, while the feasibility of long-length conductors was demonstrated through the manufacture of two 40-metre prototypes.

Within the Vacuum Vessel Project Team, formed in 2015 as part of the Action Plan to strengthen action and decision-making in critical areas, staff of the IO-DAs responsible for VV procurement work in tight coordination with IO-CT staff to improve manufacturing performance. The team's early successes include a marked acceleration in document review and approval time, the establishment of a baseline schedule for all procuring IO-DAs and much-improved resolution of interface issues. As a result, the VV sector design has been fully frozen with fixed interfaces. The sectors, in-wall shielding (IWS), ports, and gravity supports are now being manufactured in Korea, the EU, India, and Russia.

The technically challenging fabrication of the ITER VV has been advancing in both Korea and the EU. Material for all plates and forgings was procured for the two VV sectors under Korean procurement responsibility, manufacturing drawings were finalized and ~50% of the fabrication activities for the first VV sector have been completed (e.g. FIG. 10). In the EU, manufacturing activities continue on VV sector #5, including cutting, forming, machining and welding. All materials for sector #5 have been delivered to factories and progress of manufacturing for the first sector is 15%. To optimize the delivery schedule of sectors, sectors #7 and #8 have been transferred from the EU to Korea. In India, manufacturing of the IWS is ~20% complete, while manufacturing of the upper ports, under the responsibility of the RF DA, is ~ 25% complete.

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*FIG. 10: VV Sector #6 under manufacture in Korea, illustrating that the welding of the flexible supports (for the shielding blanket modules) is complete.*

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*FIG. 11: Manufacturing of the VV Thermal Shield underway in Korea.*

Manufacturing of the thermal shield (TS) is also progressing well in Korea (FIG. 11): the VV TS and Cryostat TS have reached about 50% and 25% completion respectively. Leak testing of the first segment of the VV TS has been successfully completed in June 2016 with no leakage detected.

### 3.2 Plant Systems

ITER will require extensive and large scale 'plant systems' to provide electrical power, cooling water, cryogenics and gas supplies to the tokamak and auxiliary systems. Significant progress has already been made in the manufacturing of most of these systems, and, indeed, on-site installation of the first large scale components has occurred.

The ITER Electrical Power Distribution System receives power from the French 400 kV power transmission grid, which is capable of providing approximately 120 MW of steady-state power (SSEN) to the standard industrial auxiliary loads and 500 MW of pulsed power (PPEN) required for plasma operation and control. Several large electrical components have been delivered to the ITER site and the four main step-down transformers are installed (FIG. 12). The 400 kV sub-station is expected to be completed by the end of 2016 and energized in early 2017. Qualification of the main components for the Switching Networks and the Fast Discharge units has been completed and the mass production of the same is anticipated. The global mass production for the large power converters (FIG. 13), the DC busbars and the 66 kV power cables of the Pulsed Power Electrical Network is at an advanced state.

*FIG. 12: Main 400 kV step-down transformers installed at the ITER site.*

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*FIG. 13: Mass production of large power converters.*

The ITER vacuum system will be one of the largest, most complex vacuum systems ever built. It involves several large volume systems, including: the cryostat (~ 8500 $m^3$), the torus (~1330 $m^3$), the neutral beam injectors (~180 $m^3$ each) and several lower volume systems. There are more than 400 vacuum pumps of 10 different technologies. The most demanding vacuum pumping applications are served by 18 large cryogenic pumps of 3 distinct custom designs. All of the vacuum systems are progressing from design, validation and into manufacturing. The VV and cryostat are to be directly pumped by a total of 8 cylindrical cryosorption pumps with integral 800 mm all-metal vacuum valves. The 'build-to-print' design of these pumps is complete and manufacturing of the first pump is well advanced. All component parts have been manufactured, qualified and are being assembled, with completion expected in 2017. FIG. 14 shows the 8 tonne flange of this cryopump (the 'pump plug').

The ITER Cooling Water System is composed of four main systems: the Tokamak Cooling Water System (TCWS), the Component Cooling Water System (CCWS), Chilled Water System (CHWS) and the Heat Rejection System (HRS). The TCWS is in the Final Design Stage, with the FDR scheduled in late 2017 for First Plasma systems and in early 2019 for systems required for the subsequent phases of plasma operation. Procurement will begin immediately after the FDR, although some components (5 TCWS Drain Tanks) have already been fabricated and delivered to the ITER site (FIG. 15), since they are captive and their installation must be integrated into the building construction. Delivery of several captive (non-nuclear) piping spools started in September 2015 (to date 188 spools have been delivered to the site). Delivery of other main components will start in 2021.

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*FIG. 14: Machined flange of the first Torus Cryopump.*

*FIG. 15: Arrival of TCWS Drain Tanks at the ITER site.*

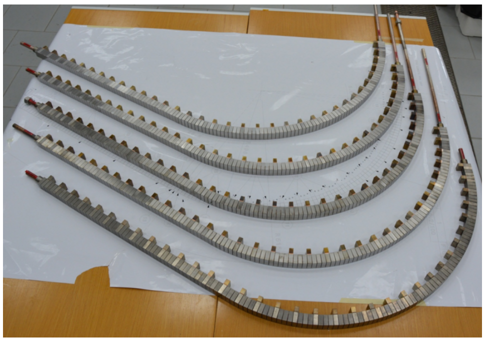
Two large nitrogen refrigerators and three large helium refrigerators form the Cryoplant, which provides cryogenic cooling power at a variety of temperatures. The principal clients of the cryogenic system are the superconducting magnets and the cryopumps, operating at ~4 K, the magnet current leads at 50 K and the thermal shields at 80 K. Helium at 80 K and 300 K is also used for the regeneration of the cryopumps. A complex system of lines and distribution boxes connects the various clients to the Cryoplant. The warm lines, cryolines and cryodistribution boxes are within the scope of the IN DA. These systems are currently in the final phase of engineering design. Fabrication is scheduled for the period 2016 to 2019, while deliveries will start in 2017 and installation is scheduled for the period 2017 to 2020. The three helium refrigerators are procured by the IO-CT and are in the final phase of manufacturing. Delivery to the ITER site is foreseen by the end of 2016 and installation will be complete in 2018. The nitrogen refrigerators, 80 K plants, storage tanks, recovery and purification systems, together with the quench tanks and air separation plant, are procured by the EU DA. Manufacturing will largely be completed in 2016 and delivery is scheduled for 2016 - 2017.

The Tritium Plant, essentially a nuclear gas processing plant, receives deuterium-tritium (DT) gases from torus and neutral beam vacuum systems, removes impurities, separates isotopes, and delivers $D_2$, DT and $T_2$ to the fuelling systems. The Tritium Plant also includes equipment for detritiating gases and water. Experience with the relevant technologies exists, but not at the scale and processing demands required by ITER. The Atmosphere Detritiation System is entering the final design phase and key R&D on scrubber column tritiated water collection efficiency has been completed. Six of the largest tritiated water storage tanks for the Water Detritiation System are captive, and therefore they have already been installed in the Tokamak Complex. The remainder of the system is currently completing preliminary design. R&D on recovery of tritium from impurities using waste-free technologies has been completed to support the Tokamak Exhaust Processing system design, which is in the preliminary design phase. The Storage and Delivery System, Isotope Separation System and Analytical System are all the subject of ongoing design and R&D studies.

## 3.3 In-Vessel Components and Auxiliary Systems

### *3.3.1 In-Vessel Components*

Manufacturing activities for the ITER tungsten divertor progressed in 2015 and 2016 through a number of significant qualification milestones. Fabrication began on three full-scale divertor cassette body prototypes; contractors completed the manufacturing design of the divertor dome and began manufacturing a prototype in Russia. The EU and JA DAs successfully produced full-scale, full-tungsten plasma facing units in conformance with the IO's tight tolerances and stringent acceptance criteria (FIG. 16). Four of the outer target units manufactured by Japanese industry performed well under high heat flux tests at the Divertor Test Facility in Russia, demonstrating excellent tungsten-copper alloy bonds and material behaviour. A tungsten material characterization programme has also been launched aimed at correlating the high heat flux performance of the material with its physical properties. This will allow an optimization and refinement of the tungsten material specification.



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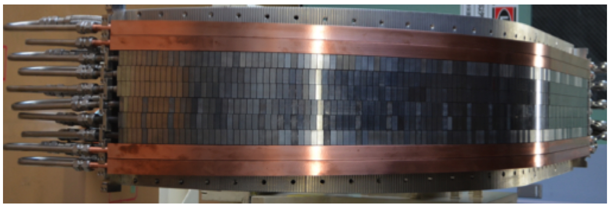

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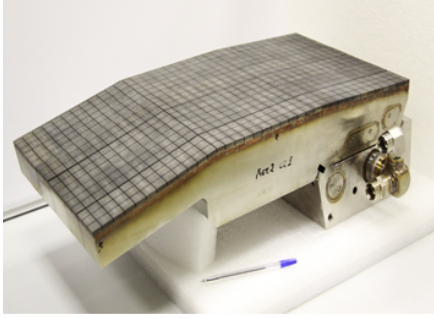
*FIG. 16: Full-tungsten divertor, full-scale plasma-facing units manufactured by European (top) and Japanese (bottom) industry.*



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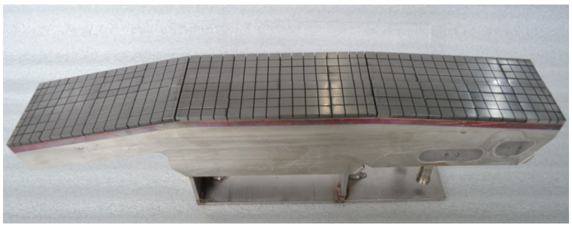

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*FIG. 17: Blanket First Wall semi-prototypes manufactured by Russian (top) and Chinese (bottom) industry.*

The IO-CT created a Beryllium Management Committee in June 2016 to establish the rules and best-practice guidelines for the safe handling of beryllium. Successful qualification activities for the beryllium first wall were achieved in Russia and in China (FIG. 17), where semi-prototypes were realized, and in the EU, where a beryllium-copper bonding technique was selected for the procurement of blanket first wall panels. In December 2015, a final design review was held for the complex array of piping that will feed cooling water to the blanket modules - the blanket manifold system. As part of the procurement of blanket connections, the RF DA launched a test programme to verify the robustness of various ceramic coatings for the keypad interfaces between the blanket shield blocks and the VV walls. Work has also accelerated on the design of First Plasma Protection Components, a set of temporary structures to be installed inside the VV in the absence of the blanket and divertor for First Plasma operation.

With the signature in March 2015 of the sixth and final Test Blanket Module (TBM) Arrangement with India, the framework governing the TBM program up to delivery and site acceptance tests is now complete. Conceptual design reviews (CDRs) were held for Japan's water-cooled ceramic breeder, Korea's helium-cooled ceramic reflector, China's helium-cooled ceramic breeder, India's lithium-lead ceramic breeder and the EU's helium-cooled lithium-lead and helium-cooled pebble bed systems, as well as for associated IO-CT activities, such as common maintenance tools and port cell components. Significant R&D activities on TBM technologies are also being conducted in Russia and the US.

### *3.3.2 Auxiliary Systems*

At the Neutral Beam Test Facility (NBTF) in Italy, an ITER-scale negative ion source (SPIDER) and a full-scale neutral beam injector (MITICA) will be tested for ITER's heating neutral beam system (33 MW injected at 1 MeV $D^o$). The SPIDER system is being installed: the vacuum vessel has been installed inside the bioshield (FIG. 18) and the transmission line connected through the HV bushing. In addition, the high voltage deck, transmission lines, ion source and extraction power supplies have passed the site acceptance tests, and the remaining 100 kV power supply, procured and delivered by the IN DA, is currently being installed. The beam source, the most critical component of the SPIDER system, is in the assembly phase with the supplier and is due to be delivered to the site in 2017. Once installed, integrated commissioning and operation of the SPIDER testbed can start. For the MITICA testbed, the JA DA power supply components are currently being installed on-site and the HV bushing has been assembled, allowing the first set of voltage holding tests to be performed in January 2016.

The design and validation of the electron cyclotron system advanced in 2015 and 2016 through successful FDRs for the Japanese and Russian gyrotrons, a manufacturing readiness review of the high voltage power supplies in the EU, and the fabrication of prototype diamond disks for the launchers. The Russian gyrotron demonstrated 1 MW operation for 1000 s with reliability that exceeded requirements. The master models of the equatorial and upper launchers were updated to reflect changes to VV port plug dimensions and encouraging results were achieved in the US on the analysis of electron cyclotron transmission line performance against requirements.

The ion cyclotron antenna design was revisited to accommodate evolving requirements for the VV port plug dimensions due to the latest VV tolerance model, the installation procedures and the implementation of shielding to minimize the shutdown dose rate. Prototypes of high heat flux front-face antenna components have been validated by the EU. A preliminary design review of the transmission line equipment design was conducted, and successful prototyping tests were performed for long-pulse high power tests in the US. Technology qualification for the radiofrequency sources, procured by the IN DA, is progressing well, with one candidate already achieving ITER performance.

Approximately one hundred projects are underway for the design and development of ITER's diagnostic systems (e.g. FIG. 19). Through annual coordination meetings involving all seven IO-DAs, the IO-CT encourages synergies, promotes problem solving, and seeks to resolve common concerns such as the integration of diagnostic systems, safety requirements, and instrumentation and control. Nearly all diagnostics have reached either the intermediate or the final design phase, and the first system - continuous external Rogowski (CER) coils that will be integrated into a toroidal field coil - should be completed in 2016. In March 2015, elements finalized for the micro-fission chamber became the first completed diagnostic components.

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*FIG. 18: SPIDER vessel installed in the bioshield at the NBTF at RFX in Padua.*

*FIG. 19: Prototype in-vessel magnetic pickup coil support assembly (IO-CT, EU DA, Consorzio RFX).*

With over 100 plasma parameters relying on optical diagnostic systems, a reliable mirror surface recovery system is essential. R&D continues to confirm that radiofrequency discharge cleaning is the most suitable technique for the cleaning of diagnostic first mirrors. Five repetitive mirror cleaning cycles were achieved without noticeable degradation in the EU, Russian researchers simulated radiofrequency discharges, and the US plans a real-geometry first mirror mock-up. A life-size mirror cleaning mock-up was tested in the EAST tokamak in China and the results appear very positive.

Manufacturing was launched in 2015 for a mock-up of the diagnostic first wall based on the generic design; in parallel the port-specific final design phase is underway. The interfaces with blanket shield cut-outs and the first-wall panel interfaces for distributed diagnostic systems have been clarified and significant progress has been achieved in the VV weld interface and designs for the in-vessel diagnostic attachments, including acceptance by the Agreed Notified Body (ANB) of a strategy for qualification. Engineering activities for the integration of diagnostic systems into the port plugs are shared by the IO-CT and IO-DAs. Work progressed strongly in 2016, with a focus on simplifying the design and optimizing performance. Following the adoption of a common approach to the manufacture of ITER's 22 port plug structures, the technical specifications were finalized and the call for tender launched. Design, resource and budget plans were also established for port plug test facility activities in 2016. Four test stands (two at ITER, one in the EU and one in the US) will enable testing of port plugs before their installation in the tokamak.

## 4. Progress in Control and Physics R&D

### 4.1 Control Systems

The ITER Control System performs the functional integration of the ITER plant and enables integrated and automated operation. As ITER is both a scientific experiment and a nuclear installation, there is a clear segregation in the architecture between conventional control, machine protection and safety. Normal operation is carried out by conventional control, while the machine protection system guards against risks which might damage the tokamak and facility, and the safety systems guard against any nuclear or occupational safety risks. The central control system, comprising conventional control (CODAC), central interlock system (CIS) and central safety systems (CSS), interfaces to around 200 local control systems, called plant system I&C (instrumentation and control), which are grouped in eighteen subsystems. These local control systems, are developed around the world under contract from the seven IO-DAs and must then be integrated into the overall facility control system, an activity considered to be the major challenge for the successful implementation of the ITER control system.

Mitigation of the integration risk has been pursued by standardization, provision of hardware (I&C integration kit) and provision of software (CODAC Core System). Plant system developers build each plant system application on the basis of this standard infrastructure, guaranteeing inter-operability. To date, 89 I&C integration kits have been shipped and 62 organizations are actively using the CODAC Core System. The first plant systems will arrive on site, and I&C integration will start, in 2018. A pre-requisite for I&C integration is a network infrastructure connecting the various buildings on the site which will house the plant systems. The installation, starting at end of 2017, will follow the progress of the civil construction and last for 10 years. The current focus is to set up the detailed organization, schedule and procedures to deal efficiently with interface problems and to facilitate rapid solutions. In parallel to the preparation of I&C integration, the detailed design of operation applications, such as supervision and automation, scheduling, plasma control, data handling and remote participation, is proceeding. The central interlock system has passed the FDR and is in manufacturing, while the central safety systems for nuclear and occupational safety are in the final design phase.

### 4.2 Physics R&D

A wide-ranging physics R&D programme, closely integrated with the International Tokamak Physics Activity and the Members' fusion facilities, is addressing key issues impacting the finalization of the ITER design and the preparations for ITER operation. Comparative studies have been launched of the efficiency of massive gas injection and shattered pellet injection for disruption mitigation (e.g. [1]), the suppression of runaway electrons in the post-disruptive plasma being of particular importance. Adequate mitigation of disruption loads in ITER requires a comprehensive approach to disruption detection, avoidance and mitigation, and the implementation of a highly reliable disruption and runaway electron mitigation system [2]. Extensive experimental and modelling R&D has been undertaken in support of this goal, and an international collaboration has been established to install a shattered pellet injector in JET to test this technique in an environment similar to that in ITER. An integrated strategy for disruption prediction, avoidance and mitigation will be implemented within the ITER plasma control system, scheduled for its preliminary design review in late 2016 [3].

Investigations of ELM control by magnetic perturbations are being pursued to support the design analysis of the in-vessel coil system for ELM control in ITER, with a particular focus on the spectral requirements, control of divertor heat loads in the perturbed field topology [4] and losses of energetic particles due to 3-D effects. Experiments on plasma scenarios for the non-active and nuclear phases of ITER operation have continued to explore physics issues and performance optimization. Particular emphasis has been given to the study of fuelling, particle transport and impurity control during plasma transient phases such as H-mode transitions (e.g. [5]).

Divertor physics and plasma-wall interaction studies have focussed on issues of leading edge power loading and melting of metallic PFCs, higher fidelity models for material migration and fuel retention, and improved understanding of dust production. Considerable effort has been invested in the expansion of the boundary plasma simulation capability at the IO-CT with the launch of SOLPS-ITER [6, 7] to the ITER Member institutions. Hosted at IO-CT within the Integrated Modelling Analysis Suite (IMAS) [8], this code incorporates all recent improvements in physics models and is now the subject of intense further development. The key remaining physics design issue for the ITER tungsten divertor is the question of monoblock front surface shaping in the divertor high heat flux areas. An extensive and successful R&D programme, including a multi-device collaboration through the ITPA, has been established by the IO-CT to study the power loading in shaped and unshaped geometries and to investigate the consequences of component melting [9]. The result is a significant improvement in the understanding of leading edge power loading [10], quantitative and experimentally validated estimates of the likely melt damage to ITER monoblock surfaces under ELM transients, and a conclusion that the front surface shaping concept proposed for the ITER divertor is appropriate [9].

## 5. ITER Baseline Revision

In March 2015, the ITER Council accepted an Action Plan to substantially improve the ITER project management and operations, and requested ITER management to develop a realistic resource loaded schedule. The Updated Long-Term Schedule was presented to Council in November 2015 and Council implemented an independent review of this proposal, which was conducted by an ITER Council working group, the ICRG. In parallel, a 'staged approach' was developed in response to the resource constraints of ITER Members. The ICRG recommended to Council in April 2016 that the IO-CT, the IO-DAs and the Members adopt the staged model in the development of the revised baseline. Therefore, within this 'staged approach' framework, the IO-CT is resource loading the so-called Master Schedule (a high level schedule summarizing the approximately 250 000 activities in the detailed schedules) and is putting in place Risk Management, Key Performance Index and Earned Value Management systems for presentation to the ITER Council meeting in November 2016.

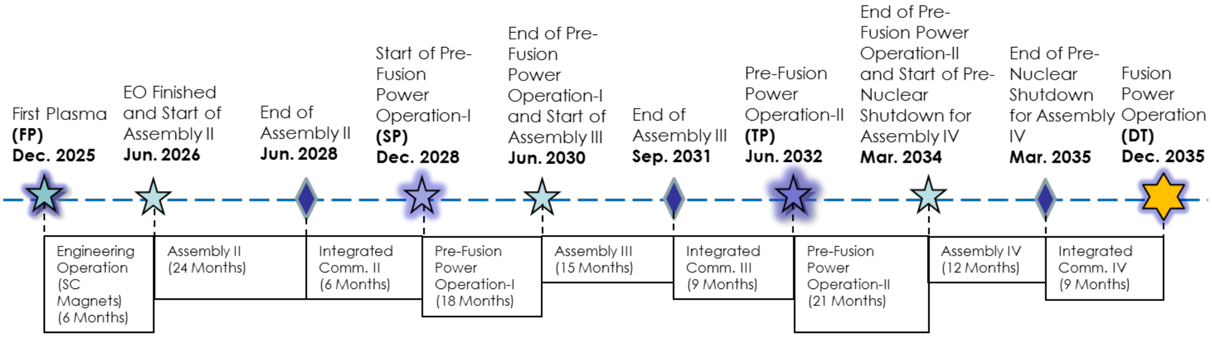

*FIG. 20: Schematic of the four-stage strategy from First Plasma to DT operation within the revised ITER baseline schedule.*

The ‘staged approach’ envisages several assembly phases and plasma operation campaigns before the start of DT operation, as depicted in FIG. 20. In advance of First Plasma, the core tokamak systems will be assembled with minimum auxiliary systems (H&CD, Diagnostics, Fuelling) required to support plasma breakdown: First Plasma is essentially a demonstration of the successful integration of the tokamak core and principal plant systems (power supplies, cooling, cryogenics, vacuum, etc.) and is the conclusion of the first phase of integrated commissioning of the ITER facility. Subsequently, the Magnet systems will be commissioned to full current, the full set of in-vessel components (including shielding blanket, first wall and divertor) will be installed, together with a subset of the H&CD and Diagnostic capability. Two periods of experimental operation with hydrogen and helium plasmas will follow, with a 3rd assembly period to complete the H&CD and most of the remaining Diagnostic capability. These two experimental periods are intended to commission all tokamak and auxiliary systems with plasma and to demonstrate full technical performance (15 MA/5.3 T) of the ITER device before the transition to D and DT operation in the 4th stage of the experimental programme.

## 6. Conclusions

Following a major reorganization of the IO-CT management and organizational structure in early 2015 and the implementation of an Action Plan to streamline and better integrate the IO-CT and IO-DA activities, the ITER project has moved forward rapidly in the key areas of design completion, advancing on-site integration and preparing the framework for the forthcoming installation activities. In preparation for this last activity, a new internal organization has been implemented to ensure that on-site installation work is managed efficiently and on schedule. Impressive progress is being made in the production of components for the ITER tokamak, plant and auxiliary systems, and a steadily increasing volume of components is arriving at the ITER site. Within the revised baseline schedule to be presented to the ITER Council in November 2016, First Plasma is foreseen for December 2025, followed by a staged approach to the development of the tokamak and auxiliary system performance and to the experimental exploitation, culminating in the transition to D/DT operation in late 2035.

## References

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