JT-60SA TF Coil Manufacture, Test and Preassembly by CEA

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Abstract.

In 2005, when the ITER site decision was made, the French Government decided to participate to the joint Europe-Japan implementation of the so-call "Broader Approach Activities" (BA) in support of the ITER project and DEMO activities [1,2]. The BA comprises the ITER Satellite Tokamak Programme (STP) which consists in upgrading the JT-60U machine into the largest fully superconducting and actively cooled D shaped tokamak JT-60SA before ITER, and in the participation to its scientific exploitation. As collaboration with Fusion for Energy (F4E), the French commitments, in charge of CEA as Voluntary Contributor (VC), are described in the Agreement of Collaboration (AoC) [3]. The CEA contribution related to the Toroidal Field Coil (TFC) procurement is 9 +1 spare of the 18 + 2 spares TFCs, the whole supporting structures, the TFC Cold Test Facility (CTF) and the TFC pre-assembly. The complementary contribution is in charge of Italy.

After the preparation and qualification phases, in these last two years, the industrial production for the procurement of the French contribution to the Toroidal Field Coil manufacture is now well engaged. The first coils were wound and integrated into their casings. The first mechanical structures were produced. These coils were sent to the Cold Test Facility and cold tested for final acceptance before to be assembled with their Outer Intercoil Structures in a dedicated workstation. These assemblies are the first components of the TF magnet which were sent to QST. In parallel the following TFC production, qualification and preassembly are ongoing.

1. Introduction

In 2005, when the ITER site decision was made, the French Government decided to participate to the joint Europe-Japan implementation of the so-call "Broader Approach Activities" (BA) in support of the ITER project and DEMO activities [1,2]. The BA comprises the ITER Satellite Tokamak Programme (STP) which consists in upgrading the JT-60U machine into the largest fully superconducting and actively cooled D shaped tokamak JT-60SA before ITER, and in the participation to its scientific exploitation. As collaboration with Fusion for Energy (F4E), the French commitments, in charge of CEA as Voluntary Contributor (VC), are described in the Agreement of Collaboration (AoC) [3]. The CEA contribution related to the Toroidal Field Coil (TFC) procurement is 9 +1 spare of the 18 + 2 spares TFCs, the whole supporting structures, the TFC Cold Test Facility (CTF) and the TFC pre-assembly. The complementary contribution is in charge of Italy. The report synthetizes the last two years progress in the first CEA coil and structure manufacture, the coil cold test acceptance and the preassembly which constitutes the first TFC delivery to Japan.

2. CEA project organization

The CEA contribution to the JT-60SA TF coils procurement was divided in four projects.

The TF coils consists in the procurement of 9 + 1 spare TFCs, namely C10 to C18 and C20 (the other 9 + 1 by ENEA named C1 to C9 and C19) which includes the winding packs manufacture and their integration in the casings. The conductors as well as the casing components are provided to CEA by F4E.

The structure part consists in the procurement of the 18 Outer intercoil structures (OIS) as well as of the 18 gravity supports (GS).

The CTF consists in the development and construction of a cryogenic test facility at CEA Saclay, able to perform the final coil acceptance tests in relevant cryogenic conditions before the release to send the coils to the final Japan site. The 18 TFCs excluding spares should be tested.

The toroidal field coil pre-assembly consists in assembling the 18 OIS to the 18 TFCs after their cryogenic test at Saclay. After release, these assemblies are packed and installed on a dedicated transport structure before sending to Japan.

This projects organization is globally managed by a CEA project direction to fulfill the CEA commitments in terms of procurement as well as general JT-60SA project time schedule.

3. General TF magnet description

The TF magnet is composed of 18 TF D shaped coils which support the Central Solenoid (CS), and the Equilibrium Field (EF) coils, all superconducting, cooled with supercritical helium at 4.4 K and thermally protected in a cryostat. Each D-shaped TF coil is 7.5 m high and 4.5 m wide and is constituted of a winding pack wound from a cable-in-conduit conductor (CICC) and embedded in a steel casing. The winding pack is constituted by a stack of 6 double pancakes (DPs), of 12 turns each, connected in series by inner joints of praying hand type located outside of the winding. The first and last double pancakes are connected to the feeders by dedicated terminals. The 26 x 22 mm conductor is cooled by a 4.4 K forced helium flow with an inlet at the middle point of the DP near the most loaded conductor and two outlets at the terminals or inner joints, and operates with a current of 25.7 kA under a maximum magnetic field of 5.7 T.

Apart from the casing, devoted to support the in-plane loading, the coil structure includes inter-coil components and gravity supports. The inner inter-coil structure (IIS) is constituted by a set of insulated pins and bolts at top and bottom of the coils inner leg to link the inner bore of the coils which is required for the whole magnet mechanical behavior.

The Outer Inter-coil Structure (OIS) is constituted by a set of 18 U steel parts inserted on each coil outer leg and linked each other by insulated shear panels. They are devoted to support mainly the out of plane coils loading by the way of lateral clamping on each coil side.

The 18 gravity supports (GS) are each attached to the bottom of the coils and uses spherical bearing to allow the cool down and movements occurring during operation. They support the whole magnet system including EF coils.

4. TF coils project activities and results

4.1. Coils manufacturing process

Following the conceptual design activity led by the integrated project team CEA, ENEA, F4E and in close collaboration with JAEA, now QST, the French TF Coils procurement was contracted by CEA with Alstom (Belfort, France), now GE, in July 2011 on the basis of the agreed design.

The activities led from 2011 to 2013 were mainly devoted to qualification of the critical processes jointly led by CEA and Alstom [4], definition of the manufacturing procedures, QA documentation, and commissioning of the main tooling. The complete winding production is divided in several successive workstations (WSts). It started by DPs winding and stacking (WSt-1 and 2), their electrical connection in the joints area (WSt-3) and the conductor and ground impregnations (WSt-4 and 5) for final winding pack (WP) acceptance (WSt-6). The coil is completed by WP transfer (WSt-7) for its integration in the casing as well as the embedding impregnation (WSt-8) up to the final machining (WSt-9). The finalization of the manufacture is done by completion of the piping (WSt-10 and 11), the instrumentation and the final acceptance testing prior packing (WSt-12).

4.2. **Coils completion**

The coils production was started early 2014 after validation of the qualification phase. The winding and stacking of the 6 DPs on a reference form including their electrical connection by the joints was already described [5]. These last two years, the WP was completed by the two successive vacuum pressure impregnations (VPI) done horizontally. The conductor impregnation was used to fix the WP geometry using the reference form and allow the wrapping of the 3 mm ground insulation which was fixed by the second one. The first WP was accepted early 2015 after references marks (RMs) bonding and complete geometrical laser survey, tightness and insulation checks in DC and Paschen conditions. After delivery of the first casing elements mid-2015, the insertion was done vertically with the casing straight leg of the D shape part lying horizontally, the curved part being installed by the top. The WP to casing gap was filled with a mix of dry glass, sand and G10 plates checking the correct WP positioning and the straightness of the straight leg. A final embedding VPI in the same position has fixed the coil before to send it to a subcontractor for final interfaces machining [6]. This operation was done using a specific tooling to allow all the machining without any handling. Back to Belfort, the coil was completed by welding and insulation of the piping and instrumentation. The final acceptance tests including complete WP and interfaces geometrical survey, DC and Paschen insulation as well as tightness and flow distribution checks were successfully passed end 2015 (Fig 1).

The splitting of this manufacture in successive WSts has demonstrated an achievable 40 days period each. So, in September 2016, C10, C11, C12 and C13 were already delivered to the CTF and the successive coils all entered into the manufacture process.

Figure 1 : Coil 10 completed

4.3. Experience and issues encountered

During manufacture, the main technical issues encountered were first the radius changes during bending as the winding machine cannot be driven for an instantaneous radius change. In particular, this induced systematic bending defect at the transition between the smallest coil curvature radius and the straight leg with infinite curvature radius. As consequence, an overgrowth of the pancakes wound in the curved to straight part direction was experienced. Even if the transition from the finite to the infinite curvature radius was anticipated in the winding machine software, the stress relaxation after impregnations results in a systematic inboard bending of the straight leg associated to a reduction of the equatorial diameter.

A second issue was the final straight leg straightness. Due to cover to casing weld shrinkage, a global coil deformation from the D to somewhat a O shape was experienced. To correct this point discovered on Coil 10, a variable wedging between WP and casing was used on the successive coils in order to apply a straight leg outboard pre-bending at insertion. The final WP bending inside casing was then reduced to be closer to the ± 1 mm tolerance.

5. Structures manufacturing and results

5.1. Contract preparation

The structures preliminary design, minimizing the cold mass, done by F4E rely on original solutions as friction joints for the OIS and ball and socket sliding joint for the GS. Following the detailed design and several qualifications on critical points, such as bolted joints for the OIS and bearings working at cryogenic temperature, done by CEA, several contracts have been awarded in 2013 and 2014.

For the manufacturing of the 18 OIS, a contract was signed in March 2013 with SDMS (St Romans, France) and for the 18 GS, a contract was signed in April 2013 with Alsyom (Tarbes, France). In addition, a contract was signed in July 2014 with RWG Germany (Höchstadt a. d. Aisch, Germany) for the procurement of the bearings for the OIS and GS.

5.2. OIS manufacturing progress

The manufacturing of the OIS is made by SDMS in 4 main phases. Three consists in electron beam welding the body of an OIS (walls, walls to the backplate, and shear panels to the body), and the last one consists in TIG/MIG welding the ribs to the OIS, doing the final machining of the complete OIS and the final assembly and acceptance tests.

The first OIS has been delivered at Saclay the 3rd of December 2015 (Fig. 2), and the production of the other OIS is progressing in line with the needs of the project. 4 have been already delivered to Saclay, and the manufacturing of the other ones is ongoing. The 2 first phases are complete for all the OIS and more than 50% of the OIS are in the phase 4, at different steps.

Figure 2 : First OIS delivered at Saclay

5.3. GS manufacturing progress

The company RWG manufactured the spherical bearings for the GS and the OIS in time, and did the delivery in December 2014.

Alsyom, the company in charge of manufacturing the GS, encountered in 2014 and 2015 some difficulties to qualify at cryogenic temperature the welding processes used to weld the 2 legs of the GS. Several improvement of the process has been done in 2015 and 2016, and, in order to shorten the manufacturing schedule, half of the lower welds have been done by electron beam. In addition, a specific ultrasonic inspection of the welds has been developed with the help of external experts in order to control the TIG/MAG welds of the GS. Once the qualifications were completed, the manufacturing of the GS progressed rapidly, and the manufacturing of the GS was completed in July 2016 (Fig. 3). They all have been sent to Japan end of September 2016.

Figure 3 : packing of one completed GS

6. CTF activities and results

6.1 First phase commissioning: tests at 25.7 kA with a shunt [7]

After the cold test facility completion end of 2014, the first commissioning phase began. The aim of this first phase was to demonstrate that the electrical system of the facility was able to reach the nominal current of 25.7 kA. To make this, a superconductive shunt was connected to the superconductive busbars of the facility. The whole system was cooled to 5 K and the current was ramped up to 25.7 kA in the shunt. This test was successful and allowed to fully commission:

– The HTS current leads of the facility cooled at 50 K by gas helium. The current were energized at 25.7 kA with no quench problems. The HTS/Cupper and Cupper/busbars joint resistances and the voltage drops in the current leads have also been checked and are all within the specifications.

– The electrical system including the power supply, the water cooled cables, the current leads and the superconducting busbars cooled with 2 g/s of SHe at 5 K.

6.2 Second phase commissioning: tests with a prototype W7X coil [7]

Once the first phase commissioning was completed, the W7X demo coil was installed in the cryostat and connected electrically and hydraulically to the facility. The aim of this second phase commissioning was to test the cooling down process and demonstrate that the helium refrigerator had the required power for cooling the JT-60SA TF coils at a rate of 2 K/h. Another goal of this phase was to test the Magnet Safety System (MSS) of the CTF against a quench. These tests were successful and allowed to:

– Demonstrate that the CTF cooling power was higher than 4 kW at 300 K and 500 W at 5 K which is enough for achieving the required cooling rates on the JT-60SA TF coils

– Estimate the static heads loads falling on the facility at 5 K. These ones are within the specifications

– Quench the W7X demo coil and demonstrate that the MSS detected the quench within the required threshold of 100 mV / 100 ms and triggered of fast discharge on a dump resistor with a time constant of about 10 s.

6.3 First JT-60 SA TF coils tests [8]

The first JT-60 SA TF coil (C10) has been delivered to the CTF end of December 2015 and has been followed by 5 other coils up to September 2016 (C11, C12, C13 and C1, C3 respectively from French and Italian procurement). C10, C11, C1, C12 and C3 have already been tested. The main results of these first coils tests are the following:

– The warm tests (wire and sensors check, coil resistance, leak test) have all been positive. Only one coil showed an important DC insulation problem. This coil has been successfully repaired and re-tested

– The cooling down of the coils has reached its nominal rate of 7 to 8 days of cooling down beginning from the 4th coil tested. This is due to some unexpected pollution inside the coils that had to be evacuated during cooling down and to unexpected temperature gradients problems between winding and casing that had been solved.

– All the coils were successfully energized to 25.7 kA. The quenching temperatures are all around 7.46 K which is higher than the required value of 7.3 K. The joint resistance measurements are all within the specifications below 2 nΩ.

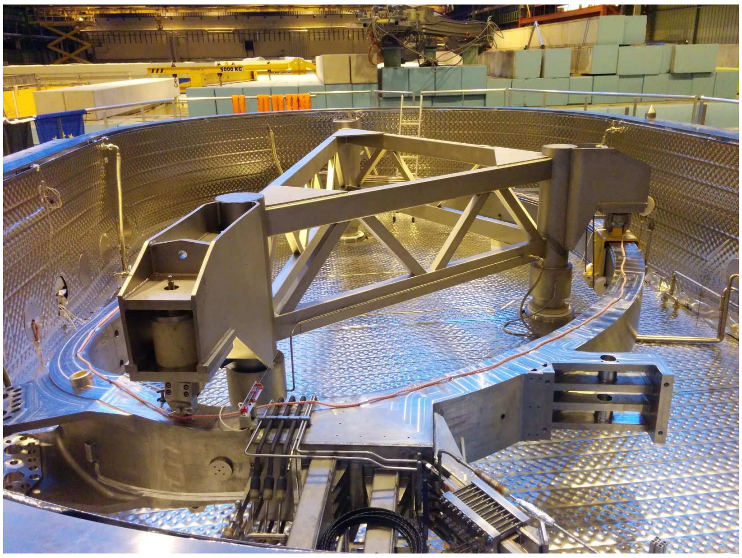

Figure 4: The first TF coil in the CTF cryostat

7. Pre assembly activities and results

After testing at 4 K each TF coil has to be equipped its OIS. This "preassembly" work is performed by CEA Saclay just after the coils leave the CTF. First, the coil is transferred to an adjacent building on a dedicated trolley frame. In order to ensure that the geometry of the coil was not affected by the cryogenic test, the mechanical interfaces of the first coils are measured again by a laser tracker. In order to efficiently fit the OIS onto the coil, the coil is raised to an "on-edge" position using a dedicated rotating tool (Fig. 5). Then the OIS, already equipped with alignment legs, is lowered down on the coil. Special scaffolds allow access to the top part of the assembly where the pinned link must be mounted between the OIS and the coil. The precise movement of the OIS, assured by pushing systems and sliding areas under the leg bases, allows the OIS to be located with an accuracy of about 1 mm. The location of the OIS is measured by laser tracker before fixing it to the coil, and the lateral bearing pads are fitted between the sides of the OIS and the coil. After a back rotation to a 10° inclination needed by the OIS presence, the pre-assembly is laid down inside its frame, the one used for the coil delivery to Saclay, stiffly fixed to it and packed with waterproof foil before the shipment to Japan.

In September 2016, three pre-assembly (C10, C11 and C1) were completed and sent to Japan. The delivery rate is 1 set per month.

Figure 5 : OIS installation onto a TF coil

8. Summary

In these last two years, the production and validation program led by CEA on the TF coils and structures enter into its regular phase. In particular, the TF coils and structures production is now well engaged with 5 TF coils, 4 OIS and the full set of 18 GS already manufactured. The others TF coils and OIS are all entered into production. Three of the first French TF coils were validated by their cold test and two of them were successfully pre-assembled with their OIS. As a major milestone, the two first coil + OIS assemblies were delivered in Japan in July and August 2016 respectively and the third assembly and the full set of GS were shipped to Japan in September 2016. These first successful achievements as well as the quality control implemented by CEA to follow these activities give confidence in the good achievement of the project. The paper describes extensively all these results.

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