ITER Magnet Systems - from Qualification to Full Scale Construction

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Abstract. The ITER organization and 6 Domestic Agencies (DAs; China (CN), European Union (EU), Japan (JA), Korea (KO), Russia Federation (RF), and United States of America (US)) have been implementing the construction of ITER superconducting magnet systems. The JA, RF, CN, and KO/EU have already started full scale construction of Toroidal Field (TF) coil conductors. The qualification of the radial plate manufacture for TF coils has been completed by both EU and JA, and both DAs are ready for full scale construction. JA has also qualified full manufacturing processes of the winding pack with a 1/3 prototype prior to the qualification with the full scale one. Preparation and qualification of the full scale construction of the TF coil winding is underway by EU. Two full scale mock-ups of the basic segments of TF coil structure were also manufactured to optimize and industrialize the manufacturing process by JA. Preparation of the manufacture of the Correction coils is progressing fairly well by CN as well as the TF coil. Procurement of the manufacturing equipment is near completion and qualification of manufacturing processes has already started. The constructions of other components of the ITER magnet systems are also going well towards the main goal of the first plasma in 2020.

1. Introduction

ITER requires superconducting magnet systems, which consist of 18 Toroidal Field (TF) coils, one Central Solenoid (CS), Poloidal Field (PF) coils, 18 (9 pairs) Correction coils (CC), and additional components such as feeders, current leads, instrumentations, and so on. Six Domestic Agencies (DAs), China (CN), European Union (EU), Japan (JA), Korea (KO), Russia Federation (RF), and United States of America (US), are involved in the sharing of the procurement of the components of the ITER magnet systems and their manufacturing activities have been implemented under more than 20 Procurement Arrangements (PAs) signed between the ITER Organization (IO) and 6 DAs [1, 2]. During recent years, qualification activities including optimization and industrialization works have been performed and full scale constructions have been started for the TF conductors. This paper is highlighting the activities on TF coil system, which is one of the most progressive ITER magnet systems and one of the most important components in the ITER tokamak system.

2. Progress of manufacture of TF coils

The TF coil (TFC) is D-shaped coil with a height of 14 m and a width of 9 m. The maximum magnetic field is 11.8 T. The TFC consists of three main components; TF conductors, winding pack (WP), and TF coil structures (TFCS) composed of sub-assemblies to be welded to make the main coil case, as shown in Fig. 1. A TF conductor is wound into a D-shape and heat-treated to form Nb_3Sn superconducting material. It is then transferred into a radial plate (RP) followed by the insulation process to make a double pancake (DP) winding. Seven double pancakes (5 regular and 2 side double pancakes) are stacked and insulated to complete a WP. The WP is encased into a coil case, which consists of four segments called sub-assemblies (AU, BU, AP, and BP) to construct a TF coil. The sharing in procurement of the TF coils is the most complex. All the TF conductors produced by EU, RF, US and 8 ones produced by CN will be provided to EU manufacturer to make 10 TF coils, while the other ones from JA, KO and 3 ones from CN will be transported to JA manufacturer to make 9 TF coils.

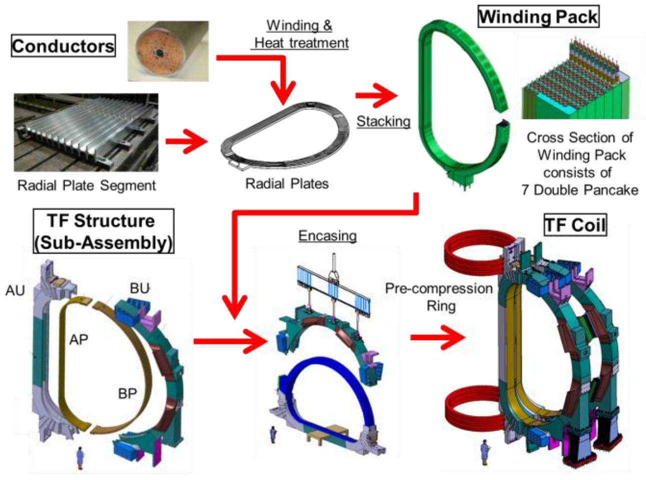

Fig.1 Manufacturing Process of TF Coil

2.1. TF conductors

Manufactures of 133 conductors total including 7 ones for a spare TF coil are underway in 6 DAs. The procurement sharing between CN, EU, JA, KO, RF, and US includes the manufacture of 11, 27, 33, 27, 26, and 9 conductors, respectively. There are two lengths of TF conductors with Cr-plated Cu and Nb_3Sn strands, one is 760 m for a regular double pancake and the other is 415 m for a side one. Over 300 tons of strands have been produced by 8 suppliers as of the end of August 2012. Since KO uses EU jacketing line, five jacketing lines have been prepared in the world. Four jacketing lines have been set-up and qualified in CN, EU, JA, and RF, and one jacketing line has been constructed in US. The JA, RF, CN, and KO/EU has already started full scale construction of TF conductors, especially, JA has completed 26 conductors by the end of March 2012. The latest achievements are the delivery of the 760-m dummy conductors manufactured by EU, CN, and KO. They have been received by EU and JA in July and August 2012, respectively, in order to start winding trials and qualification of wining facilities. The dummy conductor of CN was the first ITER component completed in CN and also the first shipment between DAs under cooperation with the IO and DAs. The latest status of TF conductor manufacture is summarized in Table 1.

TABLE 1 LATEST STATUS OF TF CONDUCTOR MNUFACTURE

Supplying DA	CN	EU	JA	KO	RF	US	Total
Receiving DA	3:JA, 8:EU	EU	JA	JA	EU	EU	
Amount of TF strands (tons)	28.0	95.3	108.0	93.0	97.0	44.7	437.5
Completion as of 2012.8	0.8	58.7	87.6	68.5	66.0	39.5	306.6
Number of TF Cables	11	27	33	27	26	9	133
Completion as of 2012.8	0	3	26	13	7	0	49
Number of TF Conductors	11	27	33	27	26	9	133
Completion as of 2012.8	0	2	26	7	4	0	39

2.2. TF coils

The TFC procurement is shared by EU (10 TFC) and JA (9 TFC). JA procures 19 TFCS and provides 10 TFCS to EU. The manufacturing strategy is different between EU and JA. EU uses 3 main manufactures for RP, WP, and encasing work with 10 TFCS from JA. On the other hand, JA plans to use 2 main manufacturers, one is for 9 TFC including RP, WP, TFCS, and encasing, and the other is for 10 TFCS to be delivered to EU. The manufacture of the TF C is a challenging work because of their extremely large size and required tight manufacturing tolerances. The manufacturing process is subdivided into 4 phases; evaluation of manufactures (phase I), qualification and/or industrialization (phase II), the first production (phase III), and series production (phase IV).

Qualification of radial plate in EU and JA: The EU and JA, have completed qualification of the full scale RP manufacture in 2011 and are ready for full scale construction. The EU successfully qualified two different manufacturing processes for radial plates by manufacturing two prototypes. One has been utilized to manufacture a regular RP. Straight plates produced by Hot Isostatic Pressing (HIP) are roughly machined to generate groves on the RP segments except for both edges of the plates. Then, the pre-machined segments are welded each other by Narrow Gap Tungsten Inert Gas (TIG) welding, and finally the whole RP is machined to the final dimension by a portal machine (Fig. 2 (a)). The other technique has been utilized to produce a side RP. Shaped plates produced by free forging process are fully machined to generate groves on the RP except for both edges of the plates. Then, they are welded together by local vacuum Electron Beam Welding (EBW), and final machining of welded areas is performed by means of a local milling machine after welding connection (Fig. 2 (b)). Both prototypes have shown good qualification results including fitting of cover plates, which satisfy the ITER requirement such as achieved flatness of 1 mm. On the other hand, JA manufactured a RP prototype for regular DPs with hot rolled plate, precise grove machining, connection of grooved RP segments by Laser Welding (LW), and local grinding of welded parts after welding connection (Fig. 2 (c)). However, JA has encountered a hot cracking

(a) EU RP prototype for regular DP with assembled covered plate at EU premises.

(b) EU RP prototype for side DP with assembled covered plate at EU premises.

(c) JA RP prototype for regular DP at JA premises

Fig. 2 Three full scale prototypes of the radial plate manufactured by EU and JA problem due to full austenitic structure weld enhanced by the complicated laser welding conditions to weld cross-shaped cross-section from 4 sides. Since JA has found a solution of the problem that constant thickness is welded by using hybrid laser technique followed by TIG or MIG welding, JA is performing additional qualification work for the new welding procedure towards the full scale construction. These trials have demonstrated that the target flatness of 1 mm for RP is achievable because the long wave distortion over the entire RP can be easily corrected through application of small forces.

Pre-qualification of WP and qualification of tooling for WP in JA: More challenging technologies in the ITER TFC are come from the extremely large size and tight tolerances compared with the previous developed coils such as TF model coil (approximately three times in scale). Since it is required a high accurate winding system for the D-shaped double pancake, JA focused on the development of prototype winding system and demonstration of the manufacturing process of the D-shaped double pancake prior to the qualification with the full scale prototype in the phase II activities from 2009 to 2011 [3]. JA has successfully developed a high precision winding system with 3-point bending rollers, which has an optical measurement device using a laser marker and CCD cameras to measure the straight conductor length with accuracy of ±0.01%. JA has also demonstrated the full manufacturing process with the developed system including precision winding, heat treatment, insulation, and impregnation from the trial manufacture of the 1/3 prototype DP shown in Fig. 3.

Fig. 3 1/3 scale prototype of TF winding pack manufactured by JA

JA has concluded a contract in August 2012 for tooling preparation and their qualification with full size DP winding in the phase II to be completed by September 2013. This contract also includes the first manufacture of the TFC including the manufacture of radial plates, manufacture of WP, fabrication of the TFCS, and assembly of WP and coil case. The first TFC will be completed by July 2015.

Qualification of tooling for WP in EU: The EU has placed a contract for winding of 10 TFC in 2011 and is currently in the qualification period of the tooling for WP manufacture. The EU has completed the construction of a new building to fabricate WPs and prepared all the necessary tooling such as a vacuum chamber for conductor acceptance test, winding facility, heat treatment furnace, loading carriage, radial plate insertion device, conductor insulation facility, and cover plate laser welding facility. The winding line consists of winding table, unspooling unit, straightening unit, measuring bench, and 3-roller head bending machine has been completed and assembled in the premises of the EU company as shown in Fig. 4. The commissioning tests of the winding line with preliminary copper dummy conductors have also been successfully

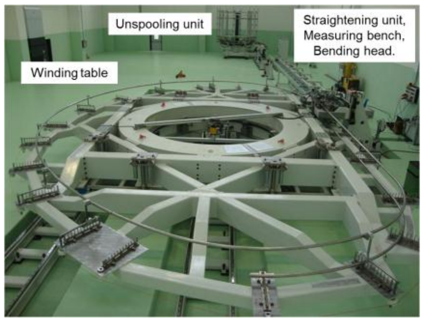

Fig. 4 TF coil DP winding line during winding of the first full size turn

Fig. 5 Heat treatments furnace installed at EU premises.

completed in July 2012 and the first trials of full size manufacture of one turn winding with two types of EU 100-m Nb_3Sn conductors have been started. The heat treatment furnace has been newly installed (see fig. 5) and will be commissioned soon. The qualification with full size DP winding utilizing copper dummy conductor, small turns DP winding utilizing superconductor, and their heat treatment will be completed by the beginning of 2013. A pre-qualification phase of the transfer operation with the RP prototype and dummy turns is underway and the final qualification of transfer with DP prototype will be performed at the beginning of 2013. Impregnation trials are also on-going to assess resin soaking speed in turn and DP insulation as a function of the pressure used in the impregnation of the resign. A pre-qualification phase of the impregnation with 3-m DP mock-up will be performed, followed by cutting to observe the cross-sections of the mock-up to demonstrate no presence of voids. Other technologies such as gap filling between coil case and WP, and ultrasonic testing for the closure welding are also being developed. The EU first TFC will be completed at the almost same time as JA one.

Pre-compression Rings manufacture in EU: The EU is responsible for providing the upper and lower pre-compression rings (PCRs, shown in red in Fig. 1), which each consist of 3 rings each having 5 m inner diameter and 288 x 337 mm^2 cross-section. In addition, a set of 3 spare rings is to be provided and stored in the pit to allow possible replacement of the lower rings in case needed during the ITER operation life. The PCRs, which are made of glass-fibre/epoxy composite material, apply centring force of about 30 MN on top and bottom of each TF coil in order to avoid separation of the TF coils during operations. The feasibility of design was demonstrated by manufacturing and testing of 1/5 scale samples. The EU placed a 5.5-year qualification and manufacturing contract in July 2012, to provide the needed 9 Pre-compression rings including 3 spares by 2017.

2.3. Progress of manufacture of TF coil structures

The manufacture of the TFCS is also as challenging work as the one required for the TFC. The main objectives in Phase II of the TFCS are qualification of material, and optimization and industrialization of the manufacturing process to reduce the technical, schedule, and cost risks associated with the series manufacturing of the TFCS in Phases III and IV.

Qualification of material: It is very important not only to qualify mechanical properties at 4K but also to develop material quality control (QC) techniques at room temperature because it is almost impossible to measure 4K mechanical properties of all materials during mass production phases from schedule and cost point of views. JAEA has proposed the relation between strength and temperature from room temperature to 4K, which was introduced from many data obtained in JAEA [4] and authorized by the Japanese Society [5]. Several actual size large forgings shown in Fig. 6 were tested in Phase II and measured data successfully satisfied the relations. From these results, use of the relation has been approved by IO and QC at room temperature can be realized in the series production.

Optimization and industrialization of manufacturing process: The activities regarding TFCS performed in Phase II were carried out in such a way that companies can be confident to minimize and control both the technical and commercial risks by themselves. Two full scale mock-ups of basic segments shown in Fig. 6 were manufactured in Phase II to optimize and industrialize the manufacturing process of the TFCS. The main objectives in phase II is to qualify the welding procedure with new full austenitic welding wire containing high nitrogen and to get engineering data on welding deformation with the actual size segment. The measured maximum opening distance between side plates were 15.3 mm and 9.8 mm in A1 and B3 segments, respectively [6]. These values are a little bit larger than the expectations; however, they are within a manageable level by additional machining in the following process. The final manufacturing plan and drawings will be prepared by early 2013 prior to start of actual manufacture based on further engineering trials. The first manufacture of the TFCS to be delivered to JA and EU manufacturers will be completed by November 2014 and March 2015, respectively, in the frame work of contract placed in August 2012.

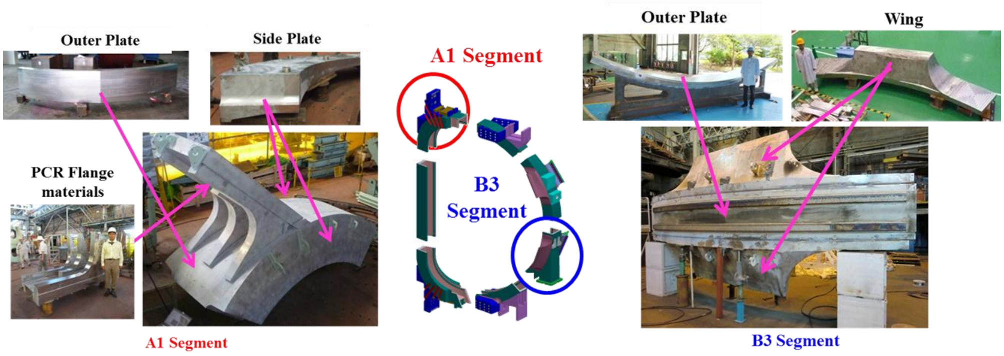

Fig. 6 Trial manufacture of A1 and B3 segments for TFCS industrialization in JA.

3. Progress of manufacture of Central Solenoid

The Central Solenoid (CS), which is composed of 6 modules assembled and pre-loaded by a large external steel tie-plates attached to thick upper and lower flanges. The maximum magnetic field is 13 T. The CS will be manufactured by the US with square CICC conductors supplied by JA. The CS module consists of six hexa-pancakes (HP) and one quad-pancake (QP). Two lengths of conductors, 918 m and 613 m, will be wound in HP and QP, respectively. A high manganese stainless steel material, JK2LB, which has been specially developed for the CS jacket by JAEA and the JA steel company, is used for the jacket of the CS conductor. It enables to maintain the pre-load during the cool down and to withstand cyclic separating load generated by pulsed operations in the CS without production risk experienced in Incoloy 908, which was used as a jacket material in the CSMC Program [7].

JA manufactured in 2010 a 200-m dummy conductor to confirm a design of jacketing line for the CS conductors, as shown in Fig. 7. Three contracts to manufacture strands, jackets, and the conductors for the first module have been concluded in April, July, and August 2012, respectively. JA has been manufacturing a 900-m Cu dummy and 150-m superconductor for CS insert (70m) and winding trial (80m) by US to be shipped by July 2013. The US has completed bending trials, joint trials, impregnation trials, and is building the winding facility and started development and qualification activities towards completion of the CS in 2020.

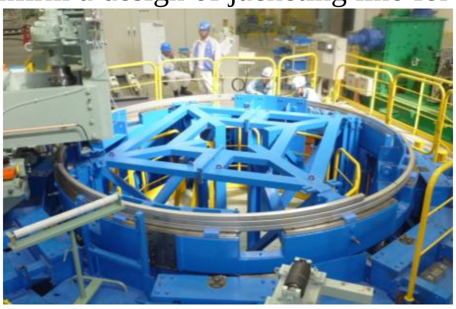
Fig. 7 200-m dummy conductor manufactured in JA.

4. Progress of manufacture of PF coils

Six PF coils are ring coils with Nb-Ti strands, which are located at the outside of the TF coils and the largest PF coil has an outer diameter of 25 m. The maximum magnetic field is 6.5T. The EU and RF are responsible for manufacture of the PF1 and PF6 conductors, and CN is responsible for manufacture of the PF2 - PF5 conductors. Five large PF coils (PF2 - PF6) will be fabricated by EU in a dedicated on-site facility and the upper PF1 coil will be manufactured by RF and transported to the ITER site. The contracts for EU PF coils with industries are ongoing in EU. A building for the PF coil manufacture of the EU PF coils has been constructed at the ITER site in February 2012. A qualification program of the most critical components and their fabrication procedure for the EU PF coils will be performed before the series production. The component qualifications regarding helium inlet, dummy joint, full size joint, turn insulation 3x3 mock-up sample, turn insulation material, and so on will be performed followed by a full dummy DP for the PF6 coil, and 5 turns of dummy coils for PF5 and PF4. The tooling and critical fabrication processes will be qualified by these prototype manufactures.

The RF has started the preparation of the winding, insulation and vacuum pressure impregnation (VPI) facilities for the PF1 coil at one of the workshops of a shipyard since 2010. At this moment the winding/insulation facility of the PF1 double pancakes is practically assembled and put into operation. Through the trials performed using different kind imitators of the PF conductors the winding/insulation facility is ready for the qualification with PF1 dummy conductor lengths, which will be delivered from EU. The VPI equipment of the PF1 double pancakes has already been manufactured. The vacuum test of the VPI mold has been performed and VPI equipment is waiting for completion of the PF1 DP mock-up to complete the qualification activity.

5. Progress of manufacture of Correction coils

The Correction Coils (CC) include three sets of six coils each, the Bottom Correction Coils (BCC), the Side Correction Coils (SCC) and the Top Correction Coils (TCC), distributed symmetrically around the tokamak and inserted between the TF and PF coils. The maximum magnetic field is 4.1 T. The CCs are subdivided in 9 pairs of multi-turn windings with a smaller NbTi conductor, which are inserted inside stainless steel cases. The CN is responsible for the manufacture of these coils, including conductors, cases and support clamps in addition to the magnet support structures and the feeder lines of the magnets.

Preparation of the manufacture of the CCs is progressing fairly well as well as the TFC [8]. Procurement of the manufacturing equipment is near completion and qualification of manufacturing processes has already started. The winding equipment, which was developed based on winding tests using dummy conductor, has been installed and is now under commissioning with a 920-m CC dummy conductor. The development of a manufacturing procedure for the helium inlet and outlet, and terminal joints are carried out by manufacturing prototype samples. A prototype sample having a different manufacturing route for each joint has been tested in DC conditions in June 2012. The results of the DC tests for this sample show a resistance in the range of 1 to 2 nΩ, which satisfied the required limit resistance of 5 nΩ. Qualification of the VPI procedure has also been carried out by manufacture of several mock-ups. The final VPI test was carried out by manufacturing a curved mock-up featuring the terminal area of a SCC. The ground and turn insulation were tested up to 50 kV and 15 kV, respectively. No breakdown was observed and the leak current was measured to be less than 40 µA at 50 kV and 10 µA at 15kV for the ground and turn insulation, respectively.

Prototype segments of the coil case for the BCC and SCC have been produced and assembled by using TIG welding process to build a reduced size model with full-size cross-section of each type. Qualification of the TIG welding process with hot rolled 316LN plates has been successfully completed including nondestructive and destructive examinations. Procurement of two 4 kW fiber laser machines, which are used for the final closure welding of the case after installation of the winding, has been performed and qualification trials are underway.

6. Conclusions

The qualifications and constructions of ITER superconducting magnets including components are going well in collaboration between the ITER organization and 6 Domestic Agencies (DA). The stage of TF conductors has moved into full scale construction from qualification phase in 6 DAs. The manufacture of TF coil and structures are also ready for full scale construction in both EU and JA. The final qualification using actual size prototypes are under way in EU and JA industries, and constructions will be started in 2013. Preparation of the manufacture of the correction coils is progressing fairly well as well as the TF coil. Procurement of the manufacturing equipment is near completion and qualification of manufacturing processes has already started. The qualification processes in other magnets and components are also underway towards the main goal of the first plasma in 2020

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

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