The ITER Magnets: Preparation for Full Size Construction Based on the Results of the Model Coil Programme

M. Huguet 1) and the ITER International Team and Participant Teams

1) ITER International Team, Naka Joint Work Site, Naka, Japan

e-mail contact of main author: huguetm@itergps.naka.jaeri.go.jp

Abstract. The ITER magnets are long-lead time items and the preparation of their construction is the subject of a major and coordinated effort of the ITER International Team and Participant Teams. The results of the ITER model coil programme constitute the basis and the main source of data for the preparation of the technical specifications for the procurement of the ITER magnets.

A review of the salient results of the ITER model coil programme is given and the significance of these results for the preparation of full size industrial production is explained. The model coil programme has confirmed the validity of the design and the manufacturer's ability to produce the coils with the required quality level. The programme has also allowed the optimisation of the conductor design and the identification of further development which would lead to cost reductions of the toroidal field coil case.

1. Introduction

The ITER machine is a tokamak with a nominal plasma major radius of 6.2 m and a plasma minor radius of 2 m. The nominal plasma current is 15 MA and the toroidal field at the major radius is 5.3 T [1, 2].

The ITER magnets have been described elsewhere [3]. The ITER magnet R&D programme is focussed on the model coils which consist of the Central Solenoid model coil (CSMC) [4] and two insert coils, the Central Solenoid (CS) insert and the Toroidal Field (TF) insert, and the TF model coil (TFMC) [5]. All model coils use Nb_3Sn conductor. The objectives of the model coils were to test and qualify the conductors and the coil manufacturing procedures. The CSMC and insert coils produce a high field of 12-13 T over a long length (50 m or more) of the conductor and are therefore well suited for conductor testing. The TFMC was essentially intended to qualify the manufacturing procedures and it uses the specific ITER TF coil technology, i.e. a circular conductor contained in spiral grooves of radial plates. It can produce a maximum field of 7.5 T but only over a short conductor length.

All model coils have been manufactured and tests are close to completion. There were three test campaigns with the CSMC and insert coils at the CSMC test facility [6] in Japan, and one campaign for the TFMC at the TOSKA facility in Germany [7]. In addition to these large scale tests, a large number of small conductor samples have also been tested at the SULTAN test facility in Switzerland [8]. Further tests of the TFMC are planned in conjunction with the European LCT coil [9] so as to achieve a higher field (~ 9 T) on the conductor. A NbTi insert coil to test the Poloidal Field (PF) coil conductor is currently under construction in the European Union (EU) and testing is planned in 2003 in the CSMC facility.

This paper gives a brief description of the ITER magnet system in section 2, and in section 3, it describes the envisaged industrial procurement strategy for the ITER magnets. The following sections review the most time critical procurement items, i.e. the superconducting conductors, the TF coil winding packs and the TF coil structures. The other magnet components are less critical and are not included in this review.

2. General Description of the ITER Magnet System

An elevation of the ITER magnet system is shown in Figure 1. The magnet system consists of 18 TF coils, a CS, six PF coils and three sets of correction coils (CCs) [3]. All ITER coils are superconducting. The CS and TF coils operate at high field and use Nb_3Sn superconductor. The PF coils and CCs operate at lower field and use NbTi superconductor. All conductors are of the cable-in-conduit type where a bundle of strands is enclosed in a metal jacket that, as well as containing the helium coolant, contributes to the structural support of the coils [10]. All coils are cooled with supercritical helium in the range 4.4 - 4.7K.

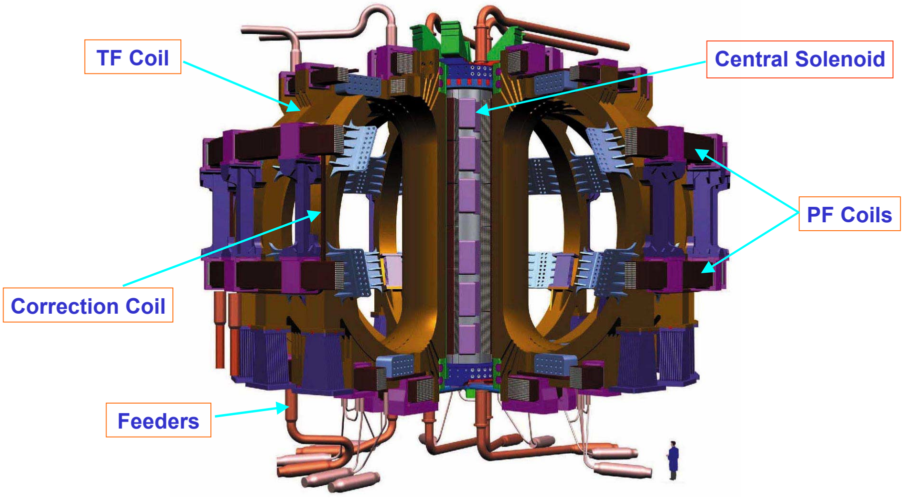

FIG. 1. Elevation of the ITER Magnet System.

The TF coil winding packs are enclosed in cases which constitute the main structural component of the magnet system. These winding packs use the concept of a conductor with a circular cross section contained in grooves of so-called “radial plates” which provide mechanical support for the conductor and protection for the conductor insulation. This concept has been selected due to the greater insulation reliability despite cost and radial build penalties [3]. The CS assembly consists of a vertical stack of six electrically independent modules. The six PF coils are mechanically attached to the TF coil cases through flexible plates allowing radial displacements. The three sets of CCs are located above, at, and below the equator of the machine. Table I lists some of the main magnet parameters.

TABLE I: MAGNET SYSTEM PARAMETERS

Number of TF coils	18
Magnetic energy in TF coils (GJ)	~ 41
TF coil current (kA)	68
Maximum field in TF coils (T)	11.8
CS current, initial magnetization, [end-of-burn] (kA)	41.5, [45.2]
CS peak field, initial magnetization, [end-of-burn] (T)	13.5, [12.8]
PF coil current, normal operation, [backup mode] (kA)	45, [52]
Correction coil current (kA)	10
Weight of TF coils including structures (t)	5,621
Weight of CS including structures (t)	926
Weight of PF coils including clamps (t)	2,835
Weight of CCs including clamps (t)	80
Total weight of magnet system (t)	~ 10,135

3. General Procurement Schedule and Strategy for the ITER Magnets

A procurement strategy has been established for the ITER magnets. Six major procurement packages, each of which can be broken down into sub-packages, have been defined for the conductors, the TF coil winding packs, the structures including the TF coil cases, the PF coils and CCs, the CS and the magnet feeders. The guiding principle for the definition of these packages has been to ensure that the package scope of work matches expertise available within industry. As a consequence of this procurement philosophy, the TF coil winding packs, which require expertise in winding, insulation and vacuum impregnation, and the TF coil cases and radial plates, which require expertise in heavy mechanical engineering, are in different packages. This approach, which makes optimum use of industrial experience, relies on strong coordination of the ITER construction organization and a very precise definition of the interfaces in terms of the responsibilities of the respective industrial suppliers.

The ITER magnets are long-lead time items and preparation for their procurement must start early in order to meet the ITER construction schedule. Figure 2 shows that the conductors and the TF coil winding packs are the most critical items. Supply contracts for them must be placed 15 months before the time when the license to construct is issued by the regulatory authorities. This is considered possible since the magnets are not directly related to licensing issues. The TF coil structures and the PF coils are also close to the critical path and supply contracts for them must be placed no later than the regulatory approval. The CS is somewhat less critical due to its late assembly into the tokamak. Early procurement, as shown on Figure 2, assumes that procurement sharing among the ITER partners has been agreed at the appropriate time thus allowing call for tender actions to be initiated by the ITER procurement organization. A time of 9 to 12 months is considered reasonable for the call for tender process of such large and complex supplies. For a successful tender process, it is necessary to ensure that a sufficient number of potential contractors have been informed and qualified for the ITER type of supply. This emphasizes the importance of an early and coordinated plan for the preparation of the tender process and a qualifying programme for industry.

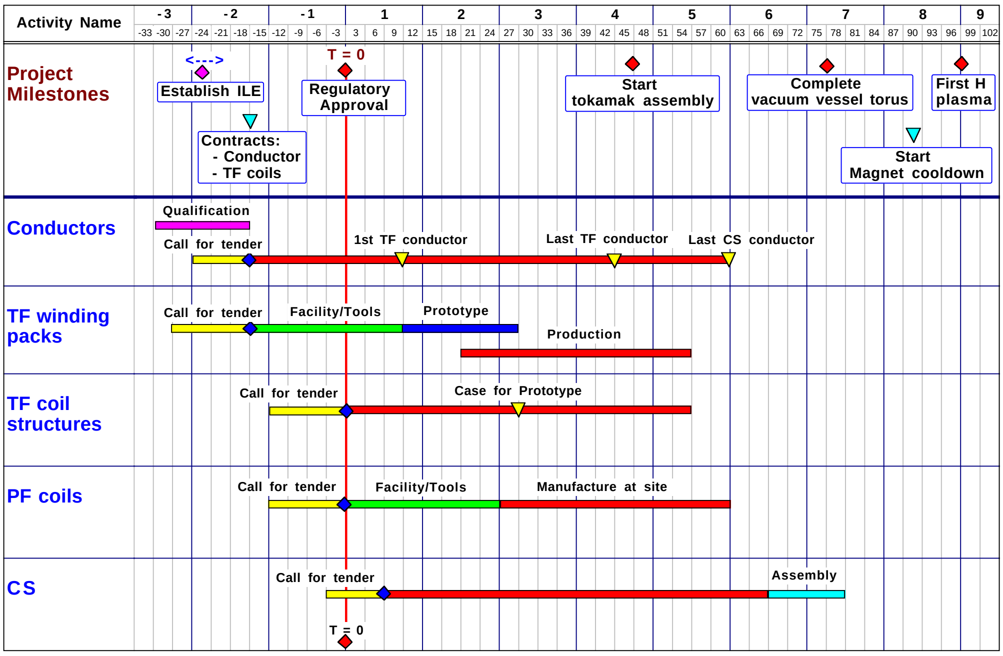

FIG. 2. ITER Magnet Procurement Schedule

The sharing of procurement among the ITER partners has an impact on the procurement strategy. This sharing may be imposed by the need to share the cost, the desire to access the technology or by time schedule requirements. For example, the TF coil winding pack and the case manufacture are likely to be shared between the EU and Japan for technology and cost sharing reasons.

The preparation of the technical specifications for the procurement of the most critical components is the subject of a major and coordinated effort of the ITER International Team and Participant Teams. In view of their complex design, the ITER magnets are categorized as "build-to-print" components, which means that the ITER organization takes full responsibility for their design and performance. The specifications must, therefore, be very detailed and must, in particular, describe in full the quality assurance (QA) requirements at each manufacturing step. The results of the ITER model coil programme constitute the basis and main source of data for these detailed procurement specifications.

4. Results on Nb_3Sn Conductor Performance and Implications for the Design

The model coil programmes have validated the design choices and qualified most of the manufacturing processes proposed for the ITER coils. All coils have reached their full performance in terms of field and current and have performed satisfactorily as regards the structural and electrical characteristics. Attention has therefore been focussed on the most innovative part of the model coil development programme, i.e. the conductor design and the verification of its nominal performance and operation margins. Since the conductor cost represents 46% of the total magnet cost and almost 13% of the total ITER direct capital cost, the conductors have been designed with the smallest possible margins to cover operational disturbances and performance uncertainties. Verification of these operation margins is therefore a critical issue.

A considerable amount of data on the Nb_3Sn conductors has been accumulated with the tests on temperature margin, AC losses, stability, thermohydraulic behaviour, quench behaviour. From this data, two salient results can be extracted.

- The transient behaviour has been found to be as expected and in some respects, better than expected. The so-called ramp-rate limitation, a severe instability experienced in some coils before the ITER model coils, has not been observed. AC losses due to field changes have been measured at, or lower than, the expected level.
- The transition from superconducting to resistive behaviour has been found to occur more gradually and at a lower temperature than expected from measurements on individual superconducting strands. This means that a resistive voltage develops and resistive power is dissipated in the conductor at a lower than expected temperature. Although the temperature difference is not large, typically less than 1K, it is very significant for the ITER conductors which have been designed with a temperature margin of 1K.

The later result means that the operation margin has been reduced and interpretative analysis has been focussed on it. Explanations are in two areas: non-uniform current distribution among the about 1000 strands forming the cable, and strain effects in strands [11]. The non-uniform current distribution can arise from inductive non-uniformity among strands or from non-uniform resistance distribution at joints. Nb_3Sn strand performance is known to be sensitive to strain and there is a complex behaviour resulting from strain induced by thermal contraction, strain induced by coil hoop stresses and strain induced by the transverse Lorentz forces acting on the strands in the cable.

The performance of the Nb_3Sn conductors for the full scale ITER CS and TF coils has been re-assessed on the basis of the model coil results [12]. Some modification of the conductor design has been found necessary to restore adequate operation margins. In the case of the TF coil conductor, one option is to increase the quantity of superconducting strand in the conductor. This is feasible but leads to some cost increase and other options which would mitigate, or altogether avoid, any increase in cost are being investigated. The use of superconducting strand with a somewhat higher critical current J_c is one possibility. A J_c of 800 A/mm^2, rather than the present specification of 650 A/ mm^2, would be adequate. The manufacturing feasibility of such strand is not an issue but the industrial production capability to meet the ITER delivery schedule must be checked. Another possibility is in the use of a conductor jacket material with a low contraction coefficient instead of steel. Experience on such materials (Incoloy, titanium) is also available from the model coil programme since the CSMC and the CS insert coil use an Incoloy jacket and the TF insert coil [13] uses a titanium jacket.

5. Procurement of ITER Conductors

The conductor requirements for all the ITER coils and feeders are shown in Table II.

TABLE II: CONDUCTOR QUANTITIES FOR ITER MAGNETS

Coil type	**TF**	**CS**	**PF1, 6**	**PF2, 3, 4**	**PF5**	**CCs**	**Feeders**
Strand	Nb_3Sn	Nb_3Sn	NbTi	NbTi	NbTi	NbTi	NbTi
Jacket	Circular	Square	Square	Square	Square	Square	Circular
Length (km)	88	40	18	32.5	11	5	< 1

The manufacture of the cable-in-conduit conductor can be broken down into two main types of activities leading to two types of supply package:

- Superconducting cables including the manufacture of Nb_3Sn or NbTi superconducting strands and the cabling work to produce finished cables;
- Conductor jacketing including the procurement of jacket sections, the butt welding of these sections to form the full jacket length and the jacketing processes consisting of the introduction of the cable into the jacket and compaction of the jacket onto the cable.

It is expected that the conductors will be the subject of multiple cable and jacketing supply contracts with specialist industries of the ITER Partners. These conductors will be delivered by ITER to the various coil suppliers.

For Nb_3Sn strand, the total production is 480 t and the peak production rate must reach 162 t/year. These requirements are well above the current industrial production for which there is only a very limited market, and also well above the 29 t production for the ITER model coils. This situation makes it essential to organize a pre-production qualification in order to prepare potential suppliers, enlarge the supplier list and promote competition. The limitations in production capacity mean that multiple procurement contracts will be necessary and it is important that all ITER Partners with industries involved in Nb_3Sn strand manufacture contribute to the Nb_3Sn strand production.

For NbTi strand, the total production is 244 t and the peak production rate must reach 93 t/year. These production targets can be readily met by industry.

6. The TF Coil Winding Packs: Technological Development and Preparation for Procurement

One of the main objective of the TFMC was to verify the feasibility of manufacture and qualify the manufacturing processes for the full size TF coils. The TFMC uses, therefore, the same design concepts and manufacturing procedures similar to those of the full size coils [14].

In order to achieve a high quality coil insulation, and therefore improve the magnet reliability, the ITER TF coils (and also the CS) use an unconventional manufacturing process (wind-react-insulate) where the Nb_3Sn conductor is wound and reacted before the application of the conductor insulation. This is to allow the use of insulation materials, such as polyimide tapes, with intrinsic dielectric properties, rather than rely solely on the insulation barrier provided by the epoxy resin after vacuum impregnation. One of the difficulty of this wind-react-insulate process is the handling of the reacted conductor: Nb_3Sn is brittle and mechanical strain during all post reaction handling must not exceed 0.2%. The model coil and insert coil fabrications have demonstrated the feasibility of this unconventional process and qualified all manufacturing procedures.

The TF coils use the concept of a conductor with a circular cross section contained in grooves of so-called “radial plates”. One manufacturing issue is the transfer of the wound, reacted and insulated conductor into the grooves of the radial plate. A high dimensional accuracy is required on both the radial plate grooves and the conductor shape to ensure a good fit between the conductor and the radial plate. Although at a smaller scale, the TF model coil manufacture has helped establish the QA requirements for full size construction.

The full scale production includes a total of 18 winding packs plus one prototype winding pack. The prototype winding pack will be used to make a prototype coil which will not be assembled into the tokamak but kept as a spare. Each finished winding pack weighs 106 t and requires the winding of 4.6 km of conductor. The ITER construction schedule requires to complete the winding pack fabrication contract in no more than 6 years. To meet this tight schedule, two production lines running in parallel are required. This situation, together with the desire to access the technology and share the cost, has led the EU and Japanese partners to consider sharing the TF coil manufacture. Under this scheme, industrial suppliers from the EU and Japan will enter a technological collaboration. One of the two suppliers, the “lead” supplier, will drive the development work and tool design and produce the prototype winding pack in collaboration with the second, or “follower”, supplier. Each supplier will then manufacture 9 production coils. It should be noted that almost all components of the winding packs, including the TF coil conductors and the radial plates, are expected to be manufactured by specialist industries and provided, under ITER responsibility, to the winding pack suppliers.

7. The TF Coil Cases: Technological Development and Manufacturing Processes

The TF coil cases are massive structures with a finished weight of 200 t and their manufacture offers a special challenge due to the wall thickness of 200-400 mm in some regions and the quality requirements. The development programme in the EU has focussed on the production of forged and cast basic elements to be joined by welding to form the full case [14]. Results have shown that for the most stressed regions of the cases at the inboard legs, the use of forged pieces and plates will satisfy all requirements. The mechanical properties of the forged material have been verified on a 40 t model which is a relevant size when compared to the

200 t of a full size ITER casting for the TF coil cases. The properties meet the requirements of 1,000 MPa yield stress and 200 MPam$^{1/2}$ fracture toughness with a low fatigue crack growth rate. For the outboard legs, where stresses are lower but the shape is more complicated, the use of forged pieces and plates is also possible but castings appear promising as a more economical manufacturing route. The mechanical properties of the cast material have been investigated on a 25 t model. Properties have been found to be adequate but there are severe limitations in material QA. Ultra-sonic inspection of the base material and welds is not possible with austenitic castings. Further qualification of inspection procedures is therefore required, and is planned, before the casting method can be selected as the reference production process.

A manufacturing scheme has been developed, based on design and manufacturing studies with input from specialist industries. The case is composed of 7 basic segments along the poloidal contour. Depending on the segment shape and the operation stress level, the segments can be obtained as cast or forged pieces or as a welded fabrication from plates. Each segment is a U-shaped piece comprising the case outer and side walls. These segments are joined by welding to form sub-assemblies of the inboard and outboard regions. This U-shaped geometry implies a "radial" insertion of the winding pack as shown on Figure 3. After insertion of the winding pack, the inner wall of the case is installed and welded. The U-shaped geometry and radial insertion present the advantage of minimizing the amount of welding, and the associated distortions, after insertion of the winding pack. The final operations include precision machining of the coil interfaces such as the inboard wedged surfaces and the shear key slots.

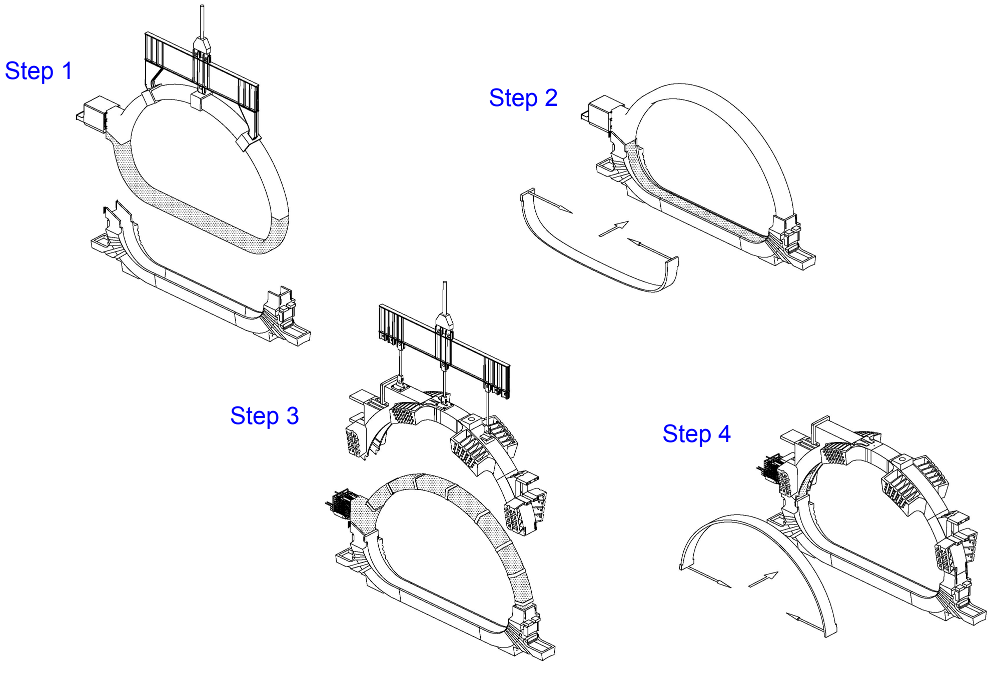

FIG. 3. Insertion of the Winding Pack in the Case

7. Conclusions

The model coil programme has validated the design choices and qualified most manufacturing processes proposed for the ITER magnets. All model coils have reached their full performances in terms of field and current.

The ITER conductors are the most innovative part of the model coil programme and one of the main results concerns the conductor performance. The transient performance of the conductors has been found to be as, or better than, expected but the transition from superconducting to resistive behaviour has been found to occur more gradually and at a lower than expected temperature. The causes of these results have been identified and the conductor design is being optimized to take these findings into account.

The technical specifications for magnet procurement are being prepared jointly by the ITER International Team and the Participant Teams. This ensures that all the experience gained during the model coil programme is fully incorporated in these specifications. The specifications for the time critical components are expected to be ready to initiate pre-procurement action in 2003.

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