The ITER Magnet Systems: Progress on Construction

C. Sborchia 1), A. Bonito Oliva 1), T. Boutboul 1), K. Chan 2), A. Devred 3), S. Egorov 4), K. Kim 5), N. Koizumi 6), S. Lelekhov 4), P. Libeyre 3), B.S. Lim 3), N. Martovetsky 2), H. Nakajima 6), N. Mitchell 3), K. Okuno 6), V. Pantsyrny 4), W. Reiersen 2), I. Rodin 4), F. Savary 3), A. Vostner 3), Y. Wu 7)

1) Fusion for Energy (F4E), European Domestic Agency (EU), Barcelona, Spain
2) US ITER Project Office (US), Oak Ridge, USA
3) ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France
4) Russian Federation (RF) ITER Domestic Agency, Moscow, Russia
5) National Fusion Research Institute, Korean Domestic Agency (KO), Daejeon, Korea
6) Japan Atomic Energy Agency, Japan Domestic Agency (JA), Naka, Japan
7) Institute for Plasma Physics, Chinese Domestic Agency (CN), Hefei, China

E-mail contact of main author: Carlo. Sborchia@f4e.europa.eu

Abstract. Construction of the ITER magnet systems has been started at the end of 2007 following the signature of the first Procurement Arrangements for the Toroidal Field (TF) conductors. Six ITER Members are involved in the share of the ITER magnet components and, to date, eighteen Procurement Arrangements between the ITER Organization and six Domestic Agencies have been signed. Substantial progress towards full scale construction has been achieved with the placement of the first large manufacturing contracts, the production of several tens of tons of advanced Nb_3Sn and NbTi strand, and the set-up of large cabling and jacketing facilities across six ITER Members. The detailed design of the coils and support structures has also been finalized and reviewed. The qualification of the fabrication processes for the Toroidal Field (TF) coils and Poloidal Field (PF) coils has been initiated. The design of the Central Solenoid (CS) coils is being completed by the US. The detailed design of the Correction Coils (CCs) with their support structures has been finalized, as well as for the TF gravity supports and clamps of the PF coils. The manufacture of prototypes of the feeder lines and current leads has been started, while ITER is in charge of the procurement of the required magnet instrumentation.

Keywords: ITER Magnets; Superconductors; Toroidal Field Coils; Central Solenoid; Poloidal Field Coils; Correction Coils; Magnet Feeders.

1. Introduction

The ITER Tokamak requires a superconducting magnet system, which consists of four main sub-systems, as shown in FIG.1: 18 Toroidal Field coils, plus 1 spare; the Central Solenoid; 6 Poloidal Field coils; and 18 (9 pairs) Correction Coils [1]. Additional components are required to form the support structures of the magnets and provide the electrical and cryogenic supplies (feeders, current leads and instrumentation feedthroughs). Like many ITER components, the magnet systems are supplied in-kind by six Domestic Agencies (DAs). The engineering and technologies required to manufacture these systems are very advanced and challenging, as well as the management and coordination needed for the procurement of such large scale components within the tight ITER construction schedule. Extensive qualification work with the manufacture of conductor samples and dummy double pancakes of the coils before start of fabrication of the final components will be carried out, while extensive quality control and assurance will be applied throughout the manufacture of the superconductors and coils.

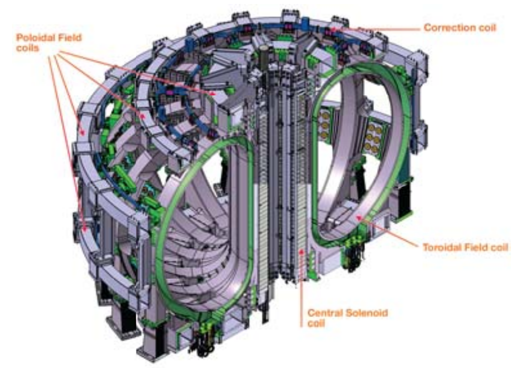

FIG.1. Iso-view of the main ITER superconducting magnet systems

2. Procurement Sharing and Schedule

The complex procurement sharing between the ITER Domestic Agencies is shown in Table I. The manufacture of the advanced Nb_3Sn superconductors is shared between six Domestic Agencies. This provides redundancy in case one DA would fail to deliver. The TF conductors produced by EU, RF, US and some of the CN ones will be provided to manufacture the 10 European TF winding packs, while the other ones from CN, KO and JA will feed the 9 JA TF coils. A good part of the PF conductors will be produced by CN, while EU and RF will share the ones for the smaller diameter coils PF1 and PF6. The PF coils will be produced by EU, except for the upper PF1 fabricated in RF. JA will produce all the conductors for the CS, but the CS coils and their support structure will be built by US. Another organizational and interface challenge is represented by the TF coil cases, which will all be produced in JA, but 10 sets of them will be delivered to EU for the insertion of their 10 TF winding packs and completion of the coil structure.

TABLE I: SUMMARY OF MAGNET SHARING BETWEEN ITER DOMESTIC AGENCIES.

Component	**IO**	**CN**	**EU**	**KO**	**JA**	**RF**	**US**
TF Conductors		7%	20%	20%	25%	20%	8%
TF Windings + Insertion			10 coils		9 coils		
TF Case Sections					100%		
Pre-compression Rings			100%				
TF Gravity Supports		100%					
CS Conductors					100%		
CS Coils + Structure							7 coils
PF Conductors		65%	21%			14%	
PF Coils			5 coils			1 (PF1)	
PF Supports		100%					
CC Conductors		100%					
CC + Supports		18 coils					
Magnet Feeders		100%					
Instrumentation	100%						

On top of the complicated in-kind scheme described above, FIG.2 shows the second major challenge: the Integrated Project Schedule (IPS), agreed in July 2010, foresees, after a 2 years qualification programme, the delivery of the first conductors in 2010, the start of installation of the first PF and TF coils in 2015 and completion of the deliveries with the last PF coil and the CS coils due in 2017: a true management and technological challenge.

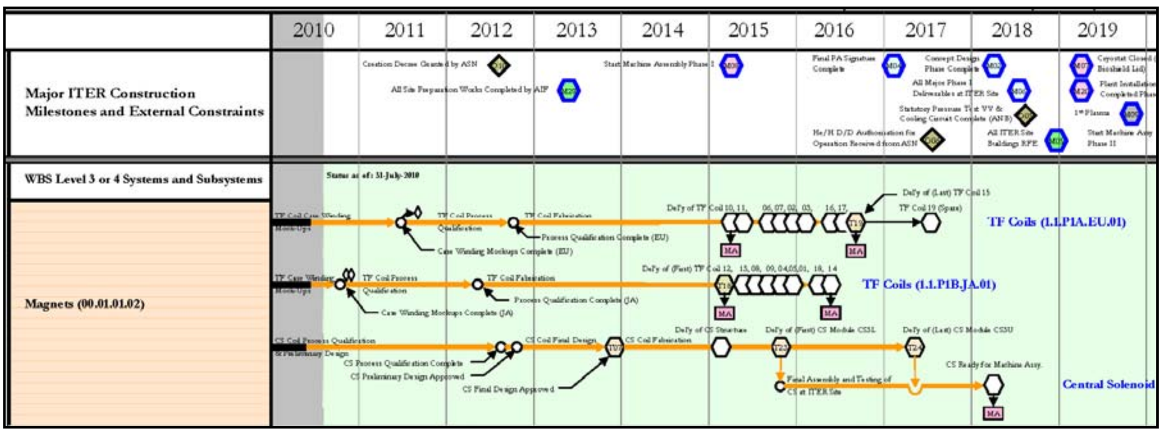

FIG.2. Reference Schedule of Delivery of Main Magnet Components

3. Superconductors

The TF conductor is a Cable-In-Conduit Conductor (CICC) composed of co-twisted, multifilament Cr-plated Cu and Nb_3Sn strands forming the cable, which is then inserted in a circular jacket, as shown in FIG.3 [2]. The TF system requires the production of ~400 tons of advanced Nb_3Sn strand in about four years, including the qualification and ramp-up phase, which typically should last about 9 months. This alone leads to a scale-up of an order of magnitude from the previous worldwide production of Nb_3Sn strand. Since 2007 the qualification of the candidate suppliers of strand, cables and finished conductors with the final design by ITER has been carried out with a series of full size samples provided by the DAs and tested in the reference Sultan facility in Villigen, Switzerland [3].

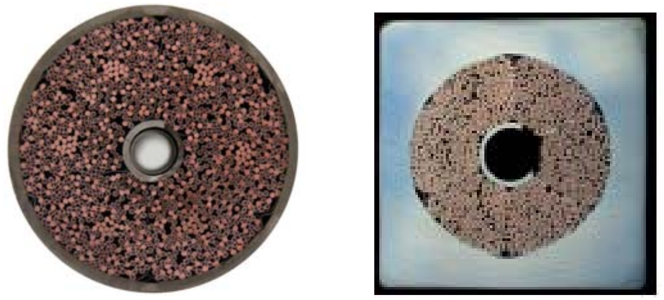

FIG.3. Cross sections of typical ITER CICC conductors (TF left, CS/PF right)

The current distribution of the production of the Nb_3Sn strand between the DAs is illustrated in FIG.4. About 90 tons have already been produced, ~60% of which by two JA companies, Hitachi and JASTEC, which have started production since 2008. Mass production has also started at other DAs, like KO (Kiswire Advanced Technologies) or RF (Chepetsky Mechanical Plant). Supply contracts have also been placed with two companies by EU, with OST (Oxford Superconducting Technology) and Bruker EAS (60-40% share), and by US, with an 80-20% share between OST and Luvata. Two fabrication routes for the Nb_3Sn strand, Bronze Route or Internal Tin diffusion, are used. Moreover, large quantities of pure copper strand for the dummy lengths and the segregated copper have been produced.

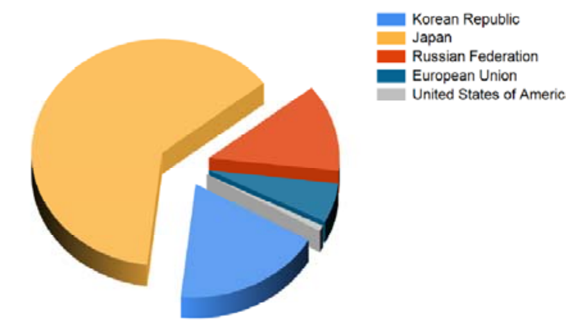

FIG.4. TF strand billet distribution (by weight)

Six cabling production lines and five jacketing lines are being set-up for the TF conductors. Two jacketing lines in JA and RF (VNIIKP, see FIG.5) are completed and the JA one has already delivered the first full 760 m length of dummy copper conductor shown in FIG.6, while five actual superconductors have been successfully manufactured. Korea might use the Nippon Steel jacketing facility in Japan for their TF lengths.

For the CS conductors, JA is preparing to place the contract for the manufacture of about 120 tons of advanced Nb_3Sn strand and setting up the cabling and jacketing facilities. Some issues with the fatigue behaviour of the jacket material for the CS conductors are still open and qualification of two candidate steels (316 LN and JK2 LB) is in progress.

FIG.5. Views of Russian TF jacketing line

The PF conductors are made of co-twisted Ni-plated NbTi cables (due to the lower magnetic field) inserted in a square jacket. In the PF2-PF5 conductors produced by CN the cable also contains segregated copper strands. The first few tons of NbTi strand are being produced in RF and CN to start cabling, while jacketing facilities are being set up in CN and EU (for TF and PF conductors). A synergy in the production of the conductors has been agreed between RF and EU, where Russia will provide the complete cables for PF1/PF6 and EU will carry out their jacketing.

The CC and feeder conductors are procured by CN. The same NbTi strand as for the PF2–PF5 conductors will be used. The CC conductor is the only one being jacketed into a circular tube and compacted to a square shape. Due to the lower operating current of the CCs, a different type of busbars is used for those coils.

FIG.6. First TF dummy from JA

4. Toroidal Field Coils

The TF conductors will be shipped to EU and JA for the manufacture of the 19 TF coils by winding, heat treatment at temperatures up to 650 ˚C, transfer to the radial plates, final insulation and vacuum pressure impregnation. A major challenge is the wind, react and transfer process, never experienced before in such large Nb_3Sn coils, which require extensive qualification work, especially to develop the transfer of reacted superconductors in the radial plates (see FIG.7). Other challenges are caused by the required manufacturing tolerances [4].

Major contracts have been placed in Europe and Japan for the development and qualification of the relevant fabrication processes for the TF windings. EU has chosen the strategy to split the supply, to reduce risks and costs, into three main areas: radial plates, winding packs, assigned to an Italian-Spanish consortium formed by Iberdrola/ASG/Elytt, and case insertion. In parallel, JA has placed a common development contract with Toshiba as prime contractor for the manufacture of the prototypes of the coil radial plates, windings and cases, the final qualification of the fabrication processes and the assessment of cost vs. schedule. In total, three full scale prototypes of the radial plates are being manufactured, two by EU (CNIM, France, and Simic, Italy) and one by Toshiba in JA. In order to mitigate risks all three prototypes employ alternative technologies for sub-segment production (FIG.8), welding and assembly procedure. The series production will use the most successful technologies and might be shared, if cost can be reduced.

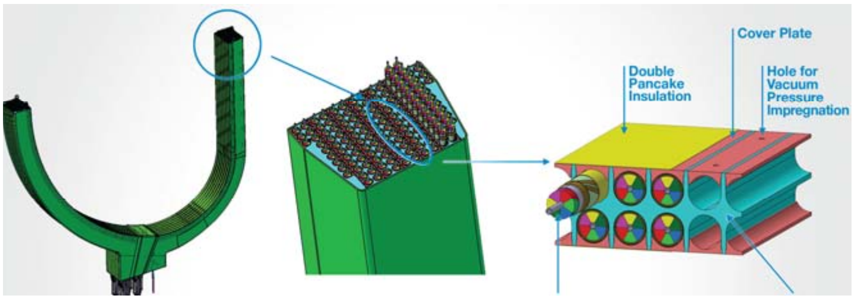

FIG.7. Construction of TF winding pack

The winding pack procurement has been divided into three stages: in stage I development tasks and the production of a full scale double pancake prototype with copper cable will be carried out

FIG.8. Radial plate mock-ups fro HIPping and forging (EU)

(see FIG.9 for the first winding system for a reduced scale dummy [5]), in stage II development tasks and production of the first winding pack, and in stage III the series production of the other winding packs. The staged approach will minimize risks and, to ensure continuity, the three stages will be carried out by the same supplier.

FIG.9. Tooling for 1/3 scale dummy winding (JA)

Most probably, the winding pack insertion activities will be common for all 19 TF coils. It is also proposed to make an integrated leak and high voltage test of each WP at low temperature in a common facility equipped with one/two cryostats, each able to accommodate two WPs and with a shared refrigeration system, in order to maximize flexibility whilst minimizing capital outlay. The scope of this integrated test is still under discussion and might be reduced to integrated tests at room temperature only. The insertion activity will follow and consist in the fitting of the WPs into their respective coil case sections and closure welding, followed by final impregnation under vacuum. This operation will probably be carried out at an EU location closer to the ITER site.

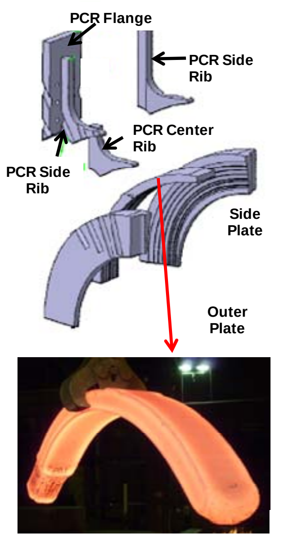

FIG.10. Forging of TF case

The qualification work on the TF coil case manufacture is underway in Japan with the production of several full-scale mock-ups, to validate the forging techniques for the reference structural materials (see FIG.10 [6]), such as 316 LN and JJ1 high strength alloys, and develop the TIG welding qualification procedures for the construction joints of the various sub-assemblies. A similar study for the qualification of various welding processes (TIG/MAG) and non-destructive examination techniques of the closure welds is in progress by EU.

Other components, which are included in the TF coil system and for which construction will start soon, are:

- TF gravity supports (CN) – the detailed design has been completed and production of sub-size mock-ups has been started to qualify the manufacture, welding and assembly of the flexible plates used in these supports;
- Pre-compression rings (EU) – these are composite rings used to pre-load the TF system. The detailed design and specifications have been finalized following the successful qualification of the candidate S-2 glass fibre, which showed satisfactory tensile and stress relaxation behaviour, and the tender for the fabrication of nine rings is being launched.

5. Central Solenoid

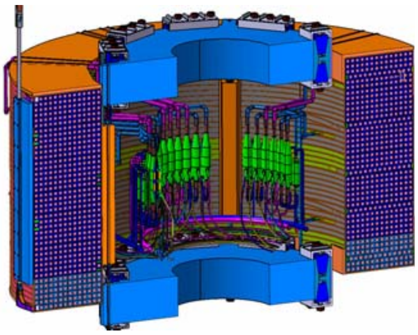

FIG.11. Iso-view of a CS module

The Central Solenoid will be fabricated by the US with square CICC conductors supplied by JA. The conductors will be wound into multiple pancakes and heat treated before insulation. In this case the heat treated conductor spirals will be opened (transfer operation) to apply the glass-polyimide insulation. Then, a vacuum pressure impregnation will be carried out. As illustrated in FIG.11, the CS is subdivided in 6 large coils (or modules), which are then assembled and pre-loaded by a large external steel structure made of tie-plates attached to thick upper and lower flanges [7]. Some critical components need special attention, first of all the superconductor which cannot be fully tested in Sultan under relevant (hoop tension) conditions. For this reason US has started the design of a CS Insert coil to be tested in the JAEA Naka CS Model Coil test facility. Also the interpancake joints or the connections to the coil terminals have to be located at the outer radius of the coil in the lower field region and, due to the space constraints inside the bore of the TF system, they have to be "butt joints" exposed to the high cyclic hoop load of the coil. Extensive design and analysis, supported by qualification tests, are being carried out to validate the design. Other critical items are the design and assembly of the pre-loading system, the layout of the helium manifolds and electrical breaks inside the coils (as shown in FIG.11) and the magnet feeder connections. For the above reasons the PA for completing the design and manufacture of the CS coils and structures has been signed by the US with a functional specification and is now underway.

In parallel, US is preparing for construction and progressing on the preparation of the manufacturing bids. Vendor meetings have been organized to attract qualified suppliers and increase competition. The plan is to manufacture a mock-up coil, consisting of only two hexa-pancakes (instead of six) and a quad-pancake wound with dummy conductor. The mock-up coil will qualify the manufacturing stations and procedures and allow the start of production. Also in this case it is proposed to cold test the mock-up coil and the production coils before delivery to the ITER site. The CS structures will be fabricated by industry and delivered directly to the ITER site.

6. Poloidal Field Coils

The design of the PF conductors and their performance, especially for the high magnetic field coil PF6, has been demonstrated with the testing of the PF Insert coil at Naka in 2008 [8]. The design of the coils has been finalized in 2009 [9], but the design of some critical items, like helium inlets, tails, joint and termination supports is still ongoing. The PA for the manufacture of the five large PF coils to be fabricated by EU in a dedicated on-site facility has been signed in 2009, while the one for the manufacture of PF1 in RF is under preparation and should be signed by the end of 2010. While the call-for-tender for the EU coils is in progress and the contract should be started in early 2011, RF has started the preparation of the facilities for winding, insulation and impregnation of the PF1 coil in 2008.

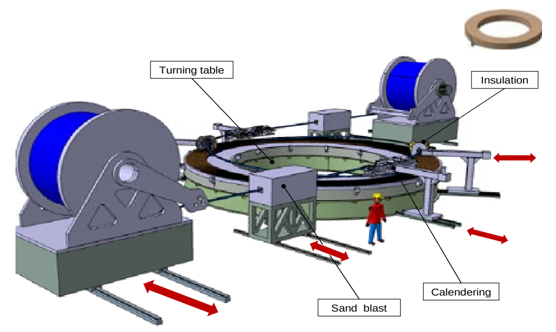

FIG.12. Fabrication of a PF DP

FIG.12 shows a schematic view of the two-in-hand winding of a typical PF double pancake in EU. The manufacture of the PF coils will evolve in three stages too, starting with the manufacture of prototype dummy double pancakes, followed by a second stage for the manufacture of the lower trapped PF6 and PF5 coils, the most critical ones since they have to be delivered first to start the assembly of the machine, followed by the manufacture of the other three coils in the third stage.

The contract for the PF winding facility (~240 m long x 40 m wide) to be built by EU in Cadarache has been placed in early 2010 and the detailed design and definition of the interfaces with the coil supplier are almost complete. The building should be handed over by the end of 2011 to start hosting the winding and impregnation facilities of the 5 EU PF coils.

FIG.13. Winding shop of the PF1 DPs (RF)

RF will use one of the workshops of a shipyard placed near the river to allow for the coil transportation. The winding/insulation facility of the PF1 double pancakes [10] is practically assembled and put into operation (FIG.13). The first trials were performed using some preliminary PF1 conductor mock-ups and showed the substantial impact of the material properties on the trial results. The final checking and set-up of the tooling is supposed to be performed by using the real jacket of the PF conductor. The vacuum pressure impregnation equipment of the double pancakes has been designed and is under manufacture. The first fabrication trials are supposed to be performed in 2011. Other facilities are under design based on the PA technical requirements. It is also proposed to carry out a cooldown test of all 6 PF coils, including PF1, at Cadarache, either in the PF winding building or in an adjacent facility.

CN has signed the PA for the manufacture of the PF coil clamps, for which the design is almost complete. Preparation work for the purchase of the base plates, forgings and tie-rod material is in progress, but this is not a critical activity on the schedule.

7. Correction Coils and Magnet Feeders

CN is also responsible for the detailed design and manufacture of the Correction Coils and the feeder lines of the magnets [11]. Final design reviews of these systems have been carried out and the manufacture of prototype components is being started.

The CCs are subdivided in 9 pairs of multi-turn windings made of a smaller NbTi conductor, which are then inserted inside stainless steel cases. CN is in charge to manufacture all the components of these coils, including conductors, cases and support clamps.

The same is also applicable to the feeder lines of all the magnet system components [12], which are carrying the electrical and cryogenic supplies to the magnets, as well as all the high and low voltage instrumentation cables. CN is also in charge of the High Temperature Superconductor (HTS) current leads, the S-bend boxes, where expansion of the feeder conductor is allowed, and the coil terminal boxes, as well all the auxiliary equipment and cubicles required to interface with the power supplies busbars, cryolines and data acquisition system. At present, the detailed design of the in-cryostat lines, their interfaces to the cryostat and the layout of the coil terminal boxes and their satellites in the outer galleries of the building is still under development, including assembly aspects, and IO design reviews are in progress. It is expected that the related PA can be finalized by the end of 2010.

8. Magnet Instrumentation

The ITER Organization is also completing the detailed design and launching qualification programmes for the instrumentation systems to be used in all magnets, such as temperature sensors, voltage and pressure taps, strain gauges, etc., as well as the qualification of the high potential insulators which will be installed on the cooling pipes and used to break the high voltage. Another important activity is the detailed design and analysis of possible systems for the quench detection in each type of magnet.

Following this qualification, the instrumentation will be purchased by IO and delivered to the magnet manufacturers. An adequate number of spares will also be purchased, to allow for prompt replacement in case of damage during fabrication or testing.

9. Conclusions

This paper has provided a brief overview of the progress in construction of the ITER magnet systems, especially for conductors and TF coils which are the most advanced ones.

For the conductors most of the manufacturing lines and production facilities in 6 Members are either ready or almost complete, and mass production of superconducting strand is established. The first qualification stage of the TF coil manufacture has been started and full scale mock-ups of radial plates and windings are being manufactured.

While the design and assembly of the CS coils and their support structure needs to be completed, especially for some critical items, start up of several qualification and preparation activities has taken place. For the PF coils some manufacturing equipment has already been prepared for PF1, while the contract for the EU coils will be placed in early 2011.

Manufacture of the Correction Coils and the TF/PF supports is starting, while the design of the magnet feeders still needs to be finalized due to the complicated interfaces.

It is important to note the very tight delivery schedules the six DAs have to work with, while solving impressive challenges on components, whose technical complexity and size have not been exploited before, and (least but not last) meeting the required quality standards.

DISCLAIMER

REFERENCES

[1] N. Mitchell, D. Bessette, *et al.*, "The ITER Magnet System", *IEEE Trans. Appl. Supercond.*, Vol. 18(2), pp. 435-440, 2008.

[2] D. Bessette and N. Mitchell, "Review of the Results of the ITER Toroidal Field Conductor R&D and Qualification", *IEEE Trans. Appl. Supercond.*, Vol. 18(2), pp. 1109-1113, 2008.

[3] P. Bruzzone, B. Stepanov, *et al.*, "Results of a New Generation of ITER TF Conductor Samples in SULTAN", *IEEE Trans. Appl. Supercond.*, Vol. 18(2), pp. 459–462, 2008.

[4] C. Sborchia, Y. Fu, *et al.*, "Design and Specifications of the ITER TF Coils", *IEEE Trans. Appl. Supercond.*, Vol. 18(2), pp. 463-466, 2008.

[5] K. Matsui, *et al.*, "Progress of Mock-up Trials for ITER TF Coil Procurement in Japan", presented at 26th Symposium on Fusion Technology, Porto, 2010.

[6] Y. Chida, *et al.*, "Validation of Welding Technology for ITER TF Coil Structures", presented at 26th Symposium on Fusion Technology, Porto 2010.

[7] P. Libeyre, N. Mitchell, *et al.*, "Detailed Design of the ITER Central Solenoid", *Fus. Eng. and Des.* Vol. 84, pp. 1188-1191, 2009.

[8] D. Bessette, L. Bottura, *et al.*, "Test Results from the PF Conductor Insert Coil and Implications for the ITER PF System", *IEEE Trans. Appl. Supercond.*, Vol. 19(2), pp. 1525-1531, 2009.

[9] F. Simon, Y. Ilyin, *et al.*, "Reliability Considerations for the ITER Poloidal Field Coils", *IEEE Trans. Appl. Supercond.*, Vol. 20, pp. 423-426, 2010.

[10] S.A. Egorov, A.A. Mednikov, *et al.*, "Winding Shop of the PF1 Coil Double Pancakes", presented at Applied Superconductivity Conference, Washington, 2010.

[11] A. Foussat, P. Libeyre, *et al.*, "Overview of the ITER Correction Coils Design", *IEEE Trans. Appl. Supercond.*, Vol. 20, pp. 402-406, 2010.

[12] Y. Song, P. Bauer, *et al.*, "Design of the ITER TF Magnet Feeder Systems", *IEEE Trans. Appl. Supercond.*, Vol. 20, pp. 1710-1713, 2010.