Testing of the Toroidal Field Model Coil (TFMC)

E. Salpietro on behalf of the ITER-TFMC Team

EFDA-CSU, Garching,, Germany

ettore.salpietro@tech.efda.org

Abstract

The paper shortly describes the Toroidal Field Model Coil (TFMC) design, fabrication choices and issues with respect to technological and management aspects.

The experience gained during the assembly and disassembly of the TFMC for phase 1 testing, as well as the assembly with the LCT coil for phase 2 testing will be reported.
During phase 1 the TFMC was energised at 80 kA and was fast discharged several times without changes in the coil performances. The first test campaign has demonstrated the feasibility and operability of the ITER Toroidal Field coils including the joints. An in depth analysis of the test results will be presented in the paper.

The goal for phase 2 testing is to determine the actual margins which have been achieved in the design and manufacture of the TFMC in selected areas.
For this purpose, the TFMC will be operated beyond the design conditions in terms of current, temperature and parameters related to coil protection (discharge time constant, quench detection time).

This second phase has started in September 2002 and will last about four months, therefore the test results can be used to optimise the ITER design, in particular on the conductors and insulation system.

1. TFMC Layout

The Toroidal Field Model Coil (TFMC) has been conceived to demonstrate the feasibility of the ITER-TF coil system: therefore its design follows the same design principles and criteria. [1, 2]
The TFMC consists of five racetrack-shaped double pancakes. The circular conductor is composed of a cable made of 720 Nb_3Sn- and 360 Cu-strands inserted in a thin 316 LN steel jacket (similar to the full size ITER conductor). {Fig. 1}

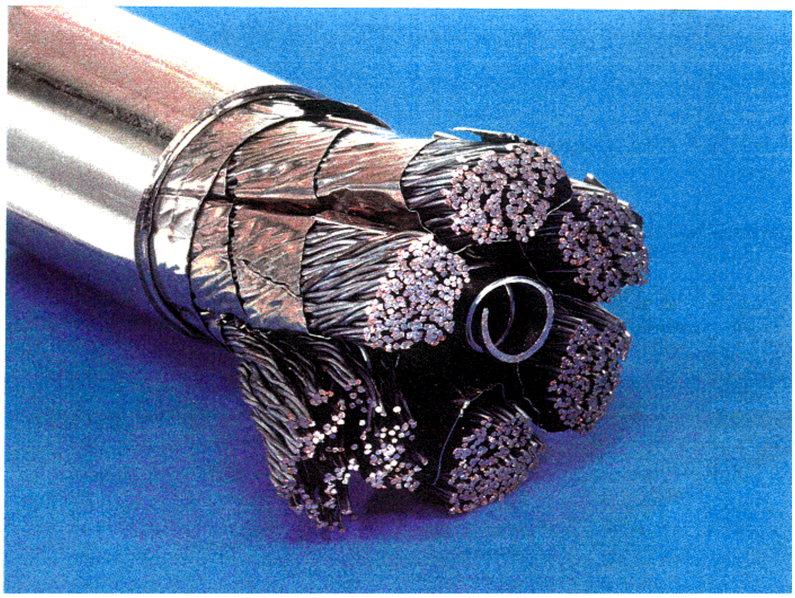

Fig. 1 TFMC Conductor

The conductor is placed in machined grooves of a radial plate ("react and transfer process"). Before insulation and insertion the conductor was wound to a racetrack shaped spiral and reaction heat-treated for 200 h at 650°C in a rigid mould.
The insulated conductor is held in place by covers which are laser welded at the corners of the groove.

The single pancake terminations are formed by compaction of the cable inside a box. The box is formed from steel with a copper sole plate machined from a copper steel composite sheet formed by explosive bonding. The single pancake joints are soldered to form a continuous double pancake which is wrapped with glass-Kapton tape and then vacuum impregnated. The five double pancakes are assembled and insulated to ground with a combination of glass fabric and polyimide tapes and then epoxy vacuum impregnated.
The impregnated coil was then placed inside a stainless steel case and the gap between the coil and case is filled with silica sand and glass felt and impregnated again with epoxy resin. The weight of the finished coil is 35 t. The test of an integrated system, namely the model coil, is the only way to fully qualify the techniques used during the manufacture which are relevant for the full size coils.

2. TFMC Construction

A contract was placed with the AGAN Consortium made of four companies (Accel, Alstom, Ansaldo, Noell) for the engineering design and construction of the TFMC.
The project was managed via regular meetings devoted to different aims:

- Working meetings involving industry and experts from EFDA and research laboratories for monitoring the progress and solving daily problems.
- Planning/Management meetings every two months between AGAN and EFDA dealing mainly with administrative and management matters.
- Project Progress Meetings with all involved institutions and industries every two months focusing on specific technical issues and in particular on integration.
- Project Review Meetings every six months with all involved industries, laboratories, ITER joint central team and home teams to keep informed all team members and assess the progress.

A very effective quality assurance (QA) system has been implemented to control especially the interfaces between the companies and laboratories. It has allowed to detect many non-conformities and related responsibility during the coil construction and assembly. The original quality control plan needed to be improved only in few cases.
The TFMC was originally to be manufactured and assembled on a very tight time schedule of 30 months from start of the contract (end of March 96) to the cold acceptance test of the coil in TOSKA at Forschungszentrum Karlsruhe (FZK). A few contract amendments were made to take into account some changes or modification in concept which had to be introduced as a result of the engineering design. This led to an extension of the contractual date of the cold acceptance test to June 2000. The test took place in July 2001, which gives an overall delay of 13 months.
Analysis of the main contributory factors delaying the manufacture do not show any single item as a major factor, but rather a series of factors. These were largely unrelated to any of the novel technical aspects of the coil, such as the radial plates or the transfer of the reacted conductor, but concerned problems with standard industrial processes (e.g. case welding), with setting up and taking into service special purpose equipment such as that associated with the winding and heat treatment.

3. TFMC Testing

The TOSKA facility at FZK {Fig. 2} was originally constructed for the test of the Euratom LCT coil. In addition to a new cryogenic system added for the TF model coil test, it has been upgraded in several other areas:

Fig. 2 TFMC & LCT in the Toska Hall

- The power supplies and fast discharge system have been extended from 30 kA to provide a 80 kA steady state capability (at 50 V maximum)
- Two 80 kA current leads have been manufactured and commissioned as part of the TFMC test.

A trial assembly of the auxiliary structure and the intercoil structure has been carried out before the coil delivery to Forschungszentrum Karlsruhe. This has proved very useful and it allowed a smooth final assembly of the TFMC. [3]

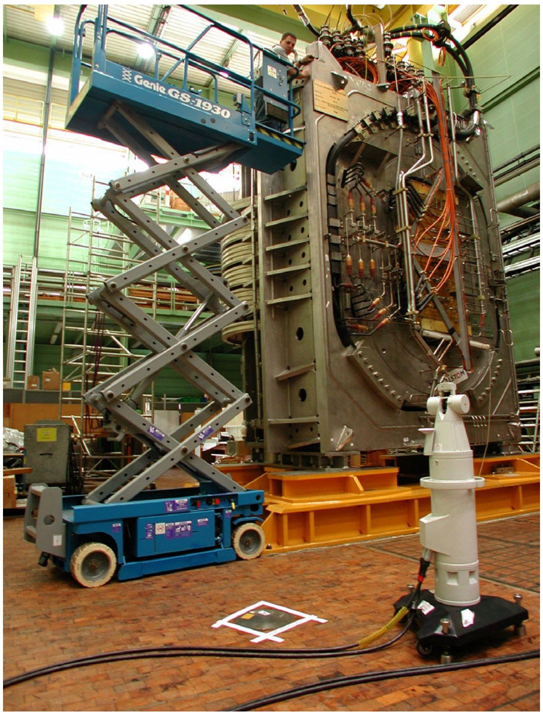

Fig. 3 Laser Tracker measurements

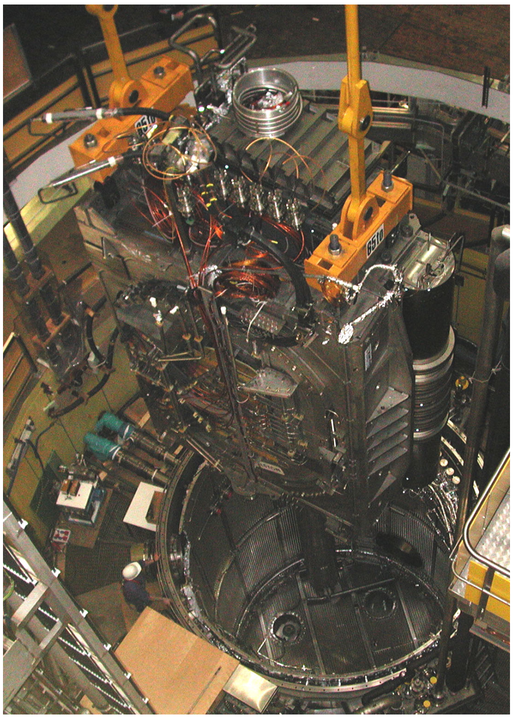

Fig. 4 Installation of the ITER TF model coil into the TOSKA vacuum vessel

The geometry during all manufacturing and assembly steps were checked by ENEA using a laser tracker system, which has proved to be very useful for the final assembly. {Fig. 3, Fig.4}
The coil was cooled down in two week within the specified temperature difference. [4]
The coil was ramped up in steps of 10, 20, 30, 40, 56.6, 69.3, 75.9 and 80 kA. {Fig. 5}
No spontaneous safety discharge has been experienced. The joints resistance were determined in the range 1-2 nΩ by electrical and calorimetric measurements. All design codes (electrical, thermohydraulic, mechanical) have been validated and proved suitable for the ITER design. Refinements are required for Quench propagation codes and coupled field (thermal, mechanical, hydraulic, electromagnetic) codes for the cable current distribution analysis.

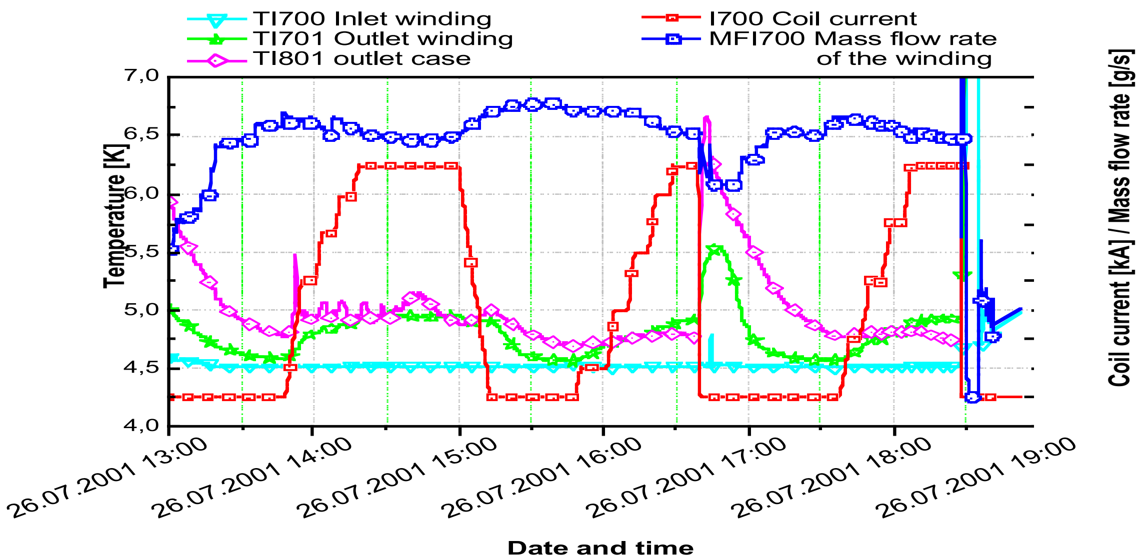

Fig. 5 TFMC reaches 80 kA

In order to improve the understanding of the cable current distribution, novel diagnostic based on Hall Probes has been installed in the electrical bus-bars which should allow a proper measurement of the current distribution in the six bundles of the cable.
Using the optimum scenario based on the multiple-step strategy, the measurement of the Tcs at 80 kA was successfully performed. {Fig. 6}
A normal zone was originated first in the DP12 conductor, with an inlet helium temperature in DP12 of about 8.6 K just before the transition, as expected from previous analysis. [5]

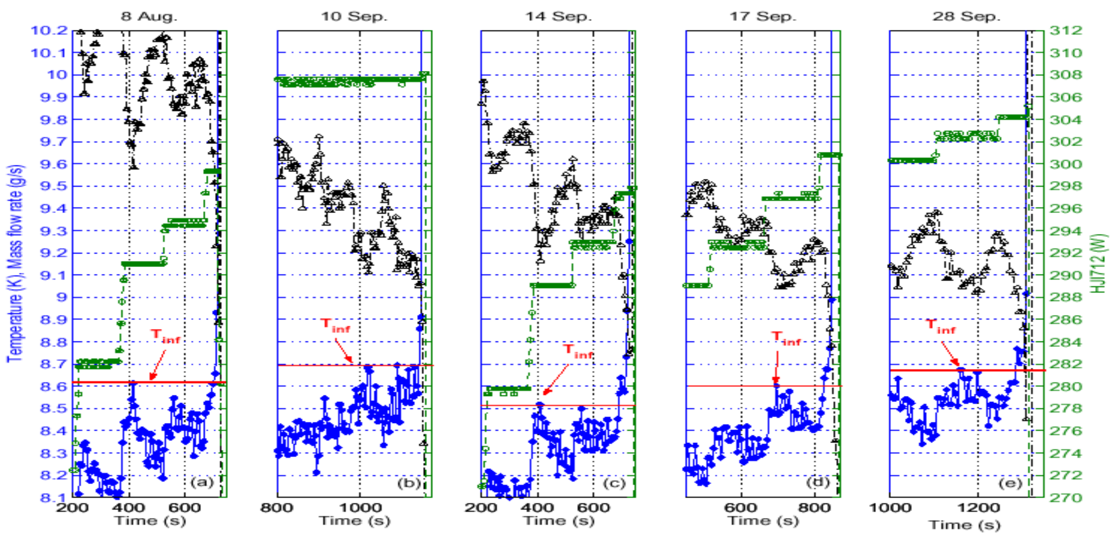

Fig. 6 Comparison between different tests multiple step strategy at 80 kA

Six Quenches at full current were made with no changes in the Tcs and the measured Tcs at different current levels is in agreement with the expectation from strand values, contrary to what was experienced in the Central Solenoid Insert Conductor. {Fig. 7}

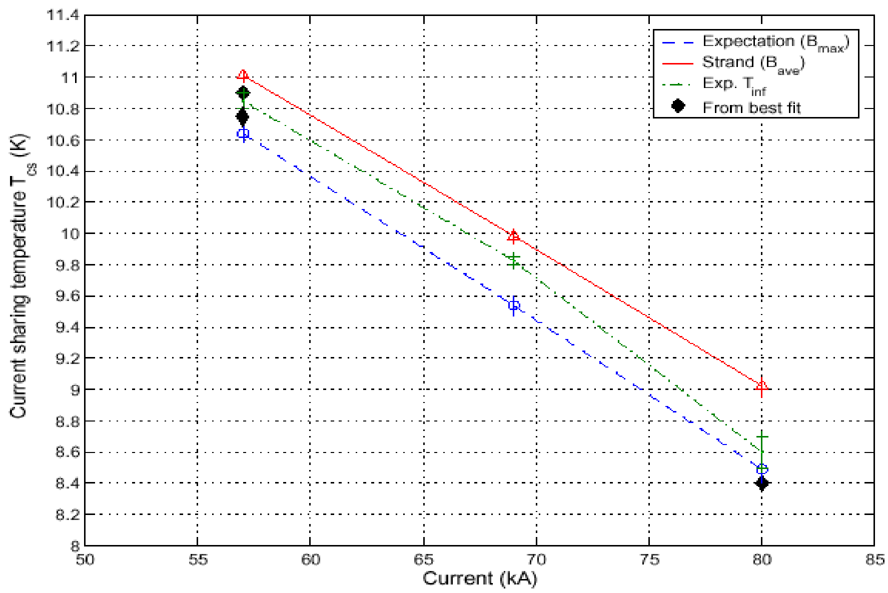

Fig. 7 *Tcs expected and measured from T_{inf}*

A possible explanation is that the bending strain reduces the critical current of the strand when jacketed in an Incolloy or Ti Jacket, while it has no influence when jacketed in stainless steel [6]. The phase 1 testing campaign went on very smoothly, minor problems were encountered. Only the Partial Discharge test could not be completed as planned, due to a weak electrical point in the cooling pipe region. At present the coil is assembled with the LCT coil and the testing started in September 2002.

From the TFMC project the following conclusions can be drawn:

- The construction and testing of the TFMC has proven the feasibility of the ITER TF Coils
- The TFMC coil performance is in agreement with the expectations
- The new technologies were mastered in an excellent way

References

[1] E. SALPIETRO, "Research and development for the ITER Toroidal Field Coils", 18th IAEA Fusion Energy Conference Sorrento, October 2001
[2] H. MITCHELL, E. SALPIETRO, "ITER R&D: Magnets: Toroidal Field Model" Fusion Engineering and Design, Volume 55 (2001).
[3] H. FILLUNGER, F. HURD, R.K. MAIX et al. "Assembly in the test facility, acceptance and first test results of the ITER TF Model Coil", 17th International Conference on Magnet Technology, CERN, September 2001
[4] A. ULBRICHT and the ITER L2 PROJECT TEAM, "Test results of the ITER Toroidal Field Model Coil (TFMC) experiment in the Toska facility of the Forschungszentrum Karlsruhe", 22nd SOFT in Helsinki, October 2002
[5] L. SAVOLDI, R. ZANINO, Predictive study of current sharing temperature test in the TFMC without Lct coil using the M2M code, Cryogenics 40 (2000), 539 – 548
[6] EKIN, Strain scaling low and prediction of unaxial and bending strain effects in multifilamentary A15 Superconductors, Cryogenic Materials, Plenum Press