THE ITER TOROIDAL FIELD MODEL COIL (TFMC) DEVELOPMENT PROGRAMME

E. SALPIETRO[1], R. MAIX[1], G. BEVILACQUA[1], N. MITCHELL[2], B. TURCK[3], A. ULBRICHT[4], M. SPADONI[5]

[1]The NET Team, Boltzmannstr.2, D-85748 Garching, Germany
[2]ITER Naka JCT, Naka , 311-0193 Japan
[3]Association Euratom-CEA/Cadarache, F-13108 Saint Paul lez Durance, France
[4]Association Euratom-FZK, Forschungszentrum, D-76021 Karlsruhe, Germany
[5]Association Euratom-ENEA, I-00044 Frascati, Italy

Abstract

The TF coils for ITER will use the concept of a circular thin walled Nb_3Sn cable in conduit superconductor completely enclosed in an insulated groove in steel plates to form the coil pancakes. These are then stacked together to form the winding pack and supported by a AISI 316LN stainless steel case.

The concept is being demonstrated by the fabrication of a racetrack shaped model coil (TFMC) which is designed to operate mecanically, electrically and hydraulically in conditions representative for the ITER TF coils. For this purpose the TFMC will be assembled in the TOSKA facility at FZK Karlsruhe, together with the EURATOM LCT coil which provides an external field. The objectives of the TFMC are as follows:

- to develop and verify the full scale TF coil manufacturing techniques;
- to establish realistic manufacturing tolerances;
- to bench-mark methods for the ITER TF coil acceptance;
- to gain information on the coil's behaviour, operating margins and in-service monitoring techniques.

The TFMC is actually in an advanced state of manufacture. Thus a large part of the first three objectives is reached. The TFMC will be delivered to FZK in summer 1999 to be prepared there for testing in TOSKA.

Connected wit the ITER TFMC two other progammes are running in parallel, namely:

- a joint development programme which foresees the production and test of three full size joint samples;
- the fabrication of full size sections of the ITER TF coil case and radial plate.

1. DESIGN DESCRIPTION

The design of the ITER Toroidal Field Model Coil (TFMC) [1,2] follows the design of the full size ITER TF coils [3, 4]. The coil parameters are reported in Table I and the coil layout is shown in Fig. 1. The conductor used corresponds to the one developed for ITER. The conductor is reacted after winding to form the Nb_3Sn compound in a mould at 650°C for about 200 hours, then insulated with a glass/Kapton tape interleaved and transferred to the radial plates. The shape of the radial plate is a racetrack having different radii of curvature. The grooves of the radial plate are closed with a cover laser welded to the plate. After glass-Kapton insulation is applied the double pancake (DP) modules are vacuum impregnated. The 5 DP's forming the winding pack are assembled together, then the ground insulation is applied and the winding pack is vacuum impregnated. To be able to connect the pancakes the conductor ends are provided with terminations according a technique developed at CEA Cadarache [5]. The terminations of the two pancakes forming a DP module are joined at the inner circumference by soldering and clamping them together. The inter-DP joints are located at the outer circumference. They are made by electron beam welding copper pins between the two terminations. The winding pack is inserted in the case, the space in between filled with graded silica grains and finally epoxy resin impregnated.

TABLE I. Coil Parameters	**ITER TF**	**TFMC**
Conductor diameter [mm]	45.7	40.7
Conductor insulation thickness [mm]	2.5	2.5
Ground insulation thickness [mm]	8	8
Number of double pancake modules	7	5
Total number of turns	192	98
Winding min/max radius [mm]	2705/9600	600/1161
Case thickness [mm]	75-240	70 - 80
Overall dimensions [m]	18.7x12x1.4	3.8x2.7x0.77
Weight per coil [t]	695	40

An inter-coil structure (ICS) allows the assembly of the TFMC and the LCT with an angle to have in addition to the attracting forces between the coils also a pressure on the front part of the coil (Fig.2). The TFMC is supported on the ICS by four wedges to simulate, during testing, mechanical stresses similar to the one experienced by the ITER TF coils during operation. The TFMC case and the ICS are provided with cooling channels. A large number of sensors will be mounted as co-wound voltage taps, strain gauges, temperature and displacement sensors etc., to be able to operate the coil safely and to monitor the behaviour of the assembly during testing.

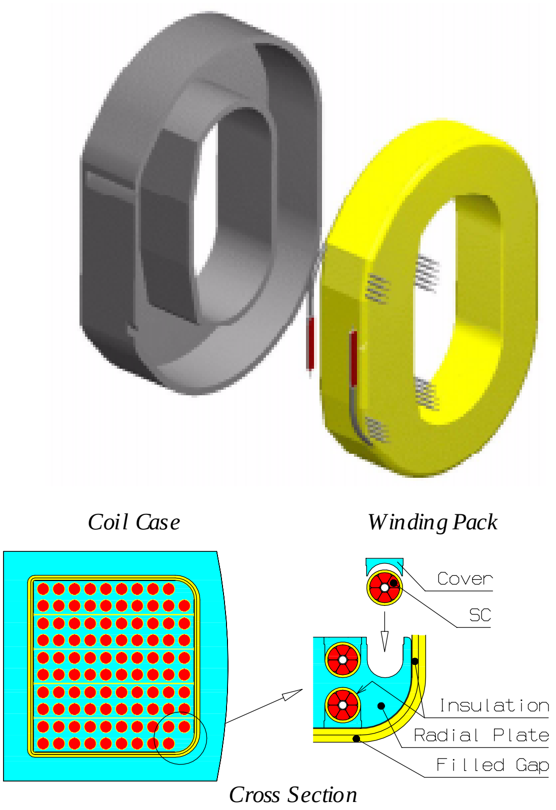

FIG. 1. Layout of the ITER TFMC.

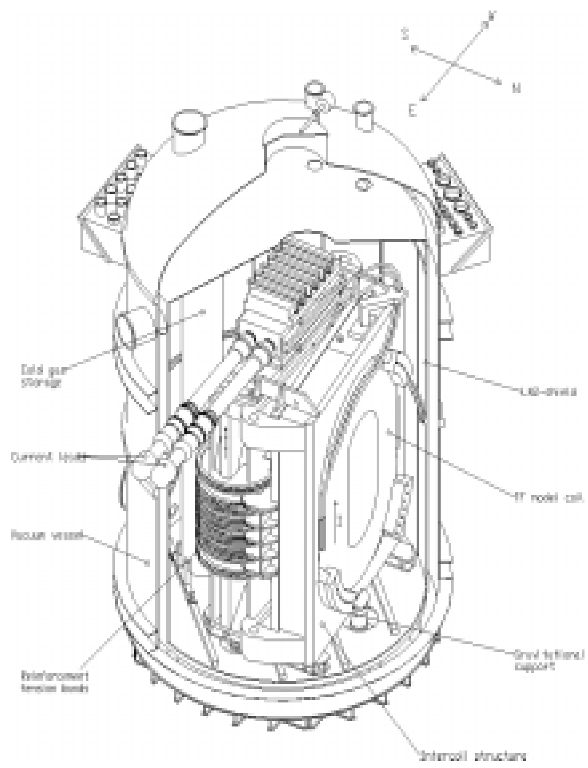

FIG. 2. TFMC and LCT in the TOSKA facility.

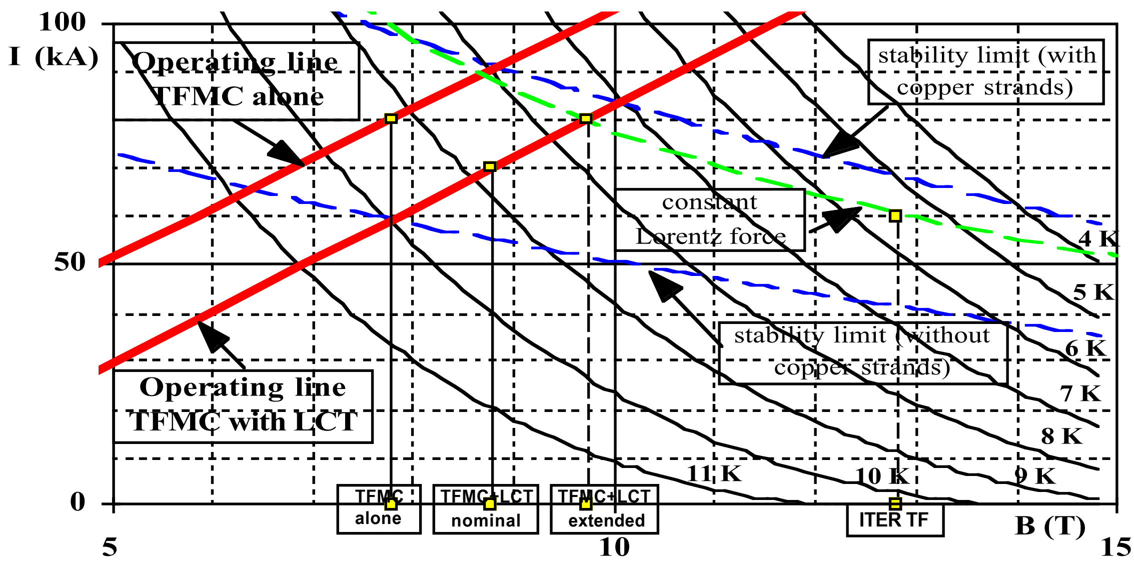

FIG. 3. Ic(B) curves, operating lines and stability limits of the TFMC. The two stability limit curves correspond to the well-ill cooled stability transition taking the copper strands into account or not.

2. THE CONDUCTOR PERFORMANCE

The conductor [6, 7] used for the ITER TFMC consists of 720 “internal tin” Nb_3Sn -strands mixed with 360 pure copper strands in the 1st stage triplett cables. The conductor is a multistage cable in conduit with a central spiral. The jacket used for the TFMC is a SS 316LN seamless tube, while in the ITER reference design Incoloy 908 is foreseen.

The conductor shall carry 70 kA at 8.77 T at nominal operation together with the LCT as shown in Fig. 3. In this condition the Lorentz force on the conductor reaches 616 kN/m, which is 82 % of the Lorentz force acting in the ITER TF coils; during the test phase it will be decided if the TFMC can be energised up to 80 kA in order to reach 100 % of the ITER TF Lorentz force.

3. ANALYSIS

The magnetic field and the magnetic forces have been computed independently with two different computer programmes with quite good agreement. The results are shown in Table II. By energising the TFMC with 80 kA the field reaches 7.78T and could reach 9.73 T with the LCT background field.

TABLE II. Operating data	ITER TF	TFMC	TFMC+LCT
Operating current (LCT) [kA]	60	80	70 (16)
Ampere turns (LCT) [MA]	11.5	7.8	6.7 (9.40)
Bmax in ITER TF / TFMC [T]	12.5	7.78	8.77
Stored energy TFMC + LCT [MJ]	5000/coil	79.4	339
Max. Compressive load on insulation [MPa]	-130	-	-180
Max. shear stress between DP modules [MPa]	30	-	50
Max. Tresca stress in SS case [MPa]	527	-	470
Max. Lorentz force on conductor [kN/m]	750	622	614

The mechanical analysis of the TFMC has been performed in a first step with a simplified model in order to understand the basic behaviour of the coil under the electromagnetic loads [8]. The final stress analysis has been carried out by the AGAN consortium with a more detailed mesh (Fig. 4), in particular in the joints area. The TFMC is modelled by parabolic 27-node solid elements and the intercoil structure by shell elements. The compressive loads on the coil insulation have their maximum of -180 MPa at the location of the four wedges. The analysis confirms that the mechanical loads on the TFMC are representative for ITER as shown in Table 2. In case an extended performance at 80 kA could be reached at the end of the test period the ITER design loads would even be exceeded.

4. MANUFACTURE

All the superconductor for the TFMC has been manufacured sucessfully by Europa Metalli. The TFMC itself is manufactured by the European consortium AGAN consisting of the companies Ansaldo (Italy), Alstom (France), Preussag Noell and Accel (both Germany). The double pancake (DP) module manufacture at Ansaldo is in an advanced state with one of 5 modules being completed and tested and the others near completion. The sequence of operations is outlined in section 1 and is descibed in detail in [9]. Figure 5 shows two pancakes just before the reaction heat treatment. The completed DP modules are being shiped to Alstom where they will be stacked, insulated, electrically connected by electron beam welding, impregnated and finally potted into the case made of SS 316LN. After mounting all manifolds and instrumentation and the assembly with the bus bars the coil will be transported to FZK, Karlsruhe in summer 1999. At that time the ICS manufacured at Noell will also be ready for the assembly of the TFMC/ICS/LCT test rig.

In order to demonstrate the feasibility of the thick walled ITER TF case some full size models are in fabrication by forging, casting, machining and welding 316LN full austenitic material. One will be a forged hollow bent square section of 40 tons with 200 mm thickness.

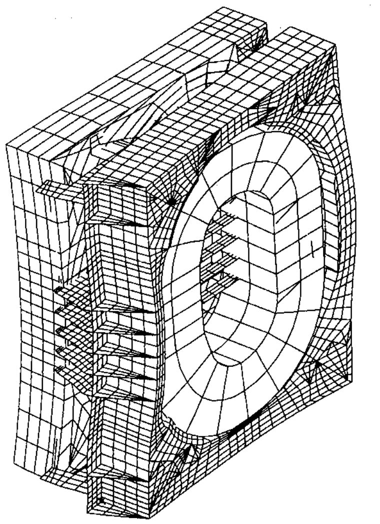

FIG. 4. The TFMC/ICS/LCT mesh is deformed under the magnetic loads

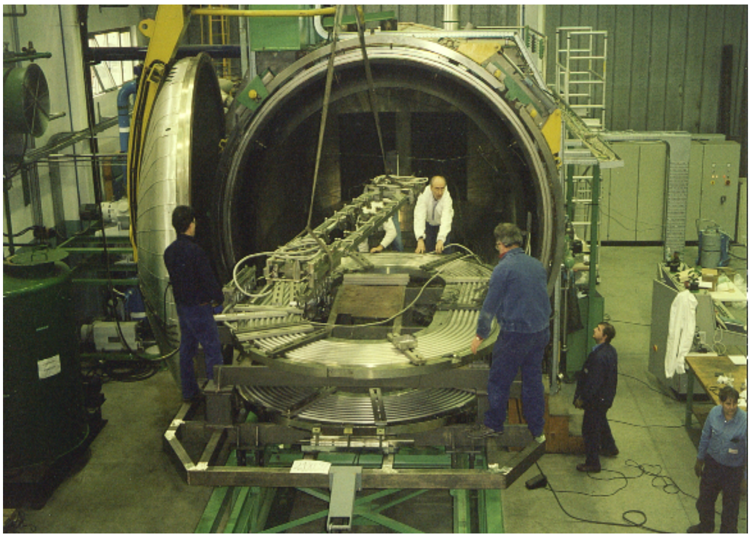

FIG. 5. Two pancakes in the moulds and one full size joint sample in front of the reaction oven at Ansaldo.

5. TEST OF THE TFMC

The upgrading of the TOSKA facility for the testing of the TFMC will be completed till the arrival of the TFMC at FZK [10]. The test of the coil in the TOSKA facility is specified in details in the test program. The test program contains the procedure to measure the properties of the coil, namely the electromagnetic, thermohydraulical, mechanical and dielectric insulation properties. The high voltage testing is an important part to gain experience for the ITER full-scale testing and reliable operation. The performance of the test program requires a cryogenic and electrical supply system designed for the operation parameter and the control of fault conditions without damage for the coil and facility. At the beginning the TFMC shall be tested alone, than together with the LCT at nominal current and, if possible, energised up to 80 kA at the end.

CONCLUSIONS

The manufacture of the TFMC is in an advanced state and the coil shall be delivered to FZK in summer 1999. Most of the technical problems are solved or already tested in mock-ups. The preparation of the TOSKA test facility and the test program is going on at FZK, Karlsruhe.

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