Assembly in the Test Facility, Acceptance and First Test Results of the ITER TF Model Coil

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***Abstract*—As a joint European effort an ITER Toroidal Field Model Coil (TFMC) was manufactured in industry and has been assembled in the TOSKA test facility of the Forschungszentrum Karlsruhe. After cool down and acceptance tests of the racetrack shaped coil made of a Nb_3Sn cable in conduit conductor the first test campaign started in July 2001 reaching the design current of 80 kA within one week.**

This paper describes the assembly in the test facility, summarizes the acceptance tests before and after cool down, and reports on the first test results.

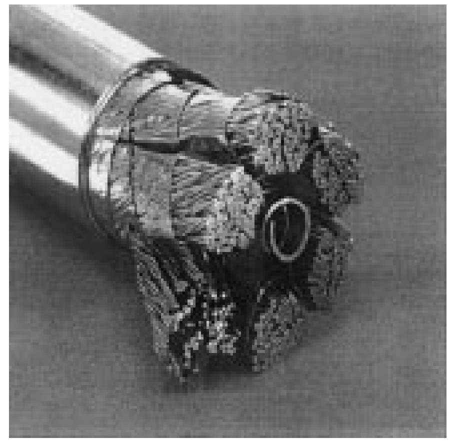
***Index Terms*—Cable in conduit, (CIC), Nb_3Sn, nuclear fusion, toroidal field coil.**

I. Introduction

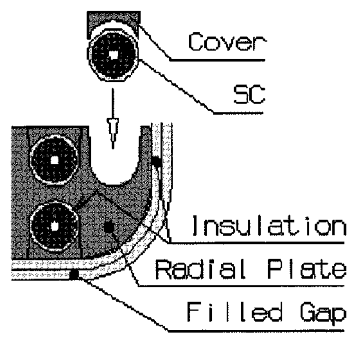
In the scope of the ITER Engineering Design Activities (EDA) a Toroidal Field Model Coil (TFMC) was manufactured by the consortium AGAN (Accel, Ansaldo, Alstom, Noell) based on a conceptual design developed by the ITER European Home Team [1], [2]. The TFMC was completed end of 2000 and has been assembled in the test facility in the first half of the year 2001.

The racetrack shaped winding pack is built up of 5 double pancake modules made of an insulated Nb_3Sn cable in conduit conductor embedded and impregnated in 316LN stainless steel radial plates (Fig. 1) [3].

The winding pack is surrounded by an 80 mm thick steel case also of 316LN. For the cooling and monitoring of the TFMC the helium header systems including the insulating breaks and a large number of sensors were assembled on the coil. Two superconducting NbTi bus bars were mounted to the winding terminals and aligned for meeting the interfaces of the TOSKA facility. Electric and hydraulic acceptance tests were performed before the coil left the factory [4], [5].



(a)



(b)

Fig. 1. (a) TFMC Conductor: 720 Nb_3Sn and 360 Cu strands cabled around a center spiral and inserted in a 316LN jacket. (b) The conductor is insulated with glass/Kapton tapes and is placed inside the groove of the radial plate.

To assemble the coil into the TOSKA facility and to fit it to the EURATOM LCT coil a heavy Inter-Coil Structure (ICS) has been built. The TFMC is held in the ICS by four wedges shaped in a way that the maximum stresses in coil and case, when energized together with the LCT coil, will be comparable to the ones in the ITER TF coils (Fig. 2).

A detailed test program has been elaborated [6]. After cool down and acceptance tests, the electromagnetic, thermohydraulic, mechanical, and dielectric insulation properties are being explored in two phases. First, the TFMC is tested alone until October 2001 and subsequently it will be assembled and tested in 2002 together with the LCT coil.

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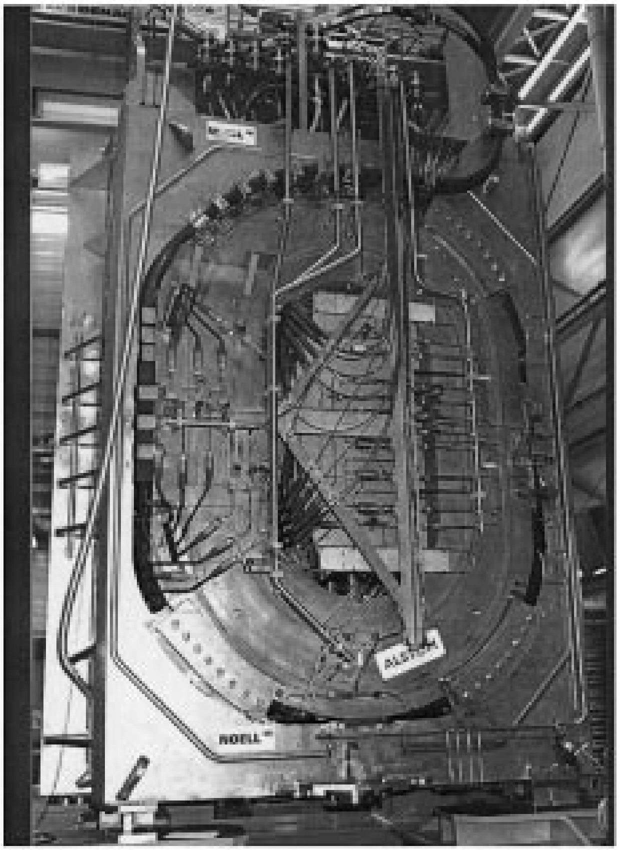


Fig. 2. The ITER TF model coil in the intercoil structure before lifting into the test facility of the Forschungszentrum Karlsruhe.

II. Assembly, Cooldown, and Acceptance Tests

A. Assembly of TFMC/ICS in the TOSKA Facility

After incoming tests to verify that the coil didn't suffer any damage during transport, the TFMC was assembled with the Inter-Coil Structure (ICS). Some minor interface mismatches were corrected without causing problems. Subsequently the TFMC/ICS assembly was put upright and assembled with the Auxiliary Structure and the gravitational support (Fig. 2).

Before lifting the assembly into TOSKA the first part of the so-called warm acceptance test was performed. This comprised various dc and ac high voltage tests between conductor and radial plates, between radial plates, between coil and ground, and the check of all sensors.

After lifting the assembly into TOSKA the hydraulic circuits were provisionally connected in order to be able to make a thorough leak test of the whole system under vacuum. The leak test showed a leak on one Gyrolock joint used for a temperature sensor, which had to be removed and sealed.

The 80 kA current leads were mounted to the facility and the SC busbars no. 1 (conductor end winding–intermediate joint) connected to the SC busbars no. 2 (intermediate joint–current lead) and insulated. The busbars no. 1 were preshaped in the suppliers works based on exact measurements by ENEA with a laser tracker system of the interfaces of the ICS, the busbar no. 2 terminations, the TOSKA vessel and the TFMC at the suppliers works [5]. Thanks to that only a small correction was necessary during final installation in TOSKA. All hydraulic pipes and low voltage and high voltage sensor cables were routed to the feedthrough boxes.

Before closing the lid the first part of the acceptance tests was performed. They were continued with high voltage (HV) and leak tests during and after evacuation. No leaks were found, but at pressure levels in the range of the Paschen minimum the dielectric strength of the insulation dropped down to 1.2 kV, indicating a weak point in the insulation.

B. Cool Down

The coil was cooled down at a rate of 1 K/h in 2 wk respecting the set temperature margins. Some temperature sensors of the ICS had to be excluded from the control loop to be able to keep the cooling rate. This was done based on the cool down analysis in agreement with AGAN.

C. Acceptance Tests

The function of the sensors and instrumentation were checked. The flow distribution through the channels was measured. As expected from the pressure drop measurements during fabrication, the two side DP modules show about 10% higher mass flows than the three inner ones. Scaling with pressure drop were found in good agreement with calculations [7]. A leak rate of 2×10^{-5} mbarl/s was measured at the operating temperature of 4.5 K, at 3.8 bar system pressure and 2×10^{-6} mbar vacuum vessel pressure.

The dc high voltage strength achieved 10 kV at 4.5 K and 2×10^{-6} mbar vacuum vessel pressure. The pulse voltage test showed a degradation to 5–7 kV. Up to 10 pulse tests at 4 kV for each polarity showed no breakdown. Therefore the safety discharge of the TFMC at voltage of 535 V has sufficient margin.

III. First Test Results

A. Summary of Achievements

Within one week from the acceptance tests, the TFMC reached 80 kA, which is the largest current ever put in such a large coil. It demonstrated that the design principles and technology chosen are suitable to be applied for the ITER TF coils. No instabilities of the conductor were observed during the whole operation under current. The conductor joints showed the expected resistance between 1 to 2 nΩ.

The TOSKA facility was operated very reliably. All operation conditions of the TFMC (cool down, current tests, safety discharge, current sharing tests with heat loads far above the capacity of the refrigerator, and quench) were mastered successfully by the cryogenic, control and DAS system during the test time. During safety discharges or quenches no Helium gas was released to the atmosphere and the recooling time was only around 2 h. During all tests the vacuum remained stable at a pressure of 2×10^{-6} mbar.

The 80 kA current was well handled by the current leads, by the superconducting and water cooled bus bar systems as well as by the power supply system and the safety discharge circuit.

B. Current Tests

The TFMC was ramped up in steps to 10, 20, 30, 40, 56.6, 69.3, 75.9, and 80 kA. Each step consisted of three ramping-up's

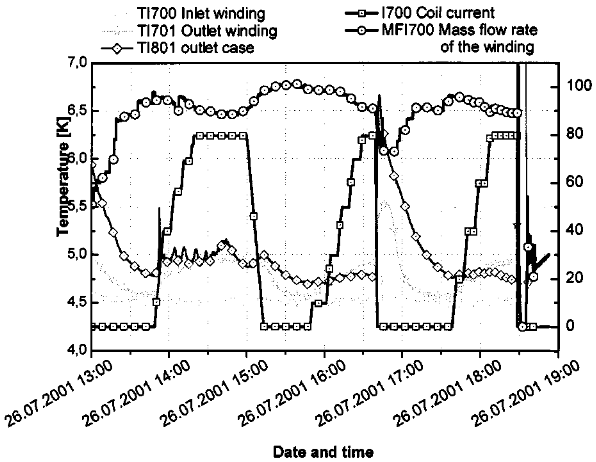


Fig. 3. Current tests up to 80 kA with different discharge modes (slow discharge, inverter mode discharge, safety discharge).

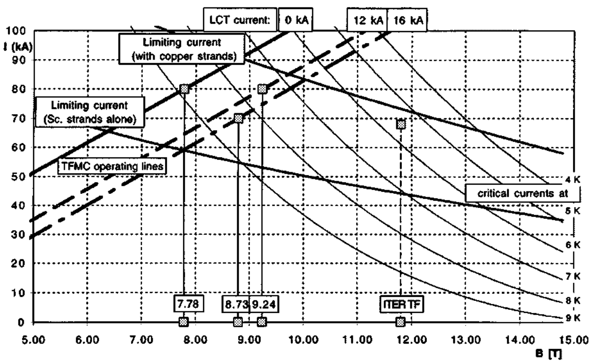
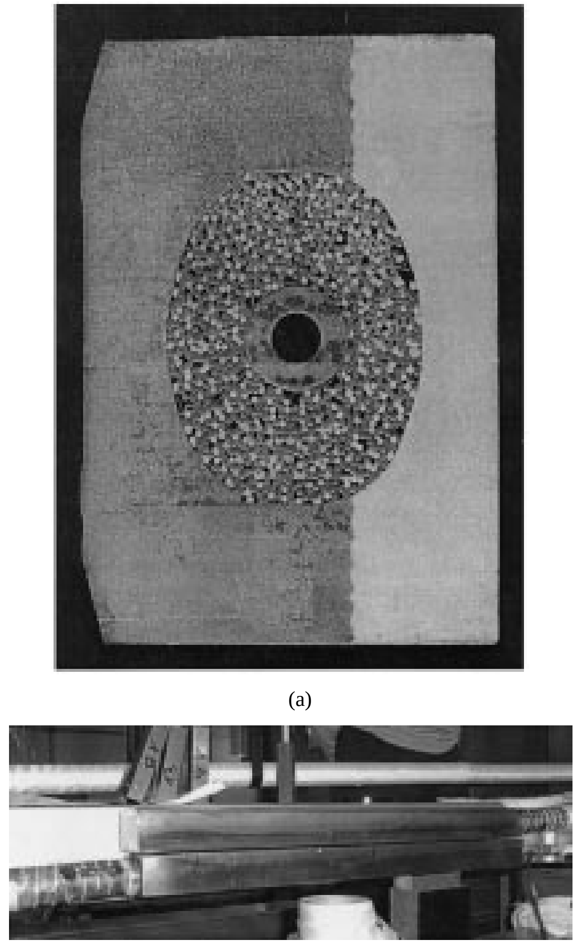


Fig. 4. TFMC Load lines and operating points without and with the LCT coil energized with 16 or 12 kA. The max. field reached in the TFMC is indicated in labels for each load case. The nominal parameters of the ITER TF coils are 68 kA at 11.8 T.



(a)

(b)

Fig. 5. (a) Termination cross section. (b) Two adjacent terminations of a DP Module inner joint before soldering them together.

with 100 A/s followed by a discharge with the same ramp rate, an inverter mode discharge (max. voltage of the power supply) and a fast safety discharge, as shown in Fig. 3. In the first test campaign the coil was repeatedly energized with 80 kA and withstood many safety discharges from currents larger than 50 kA. Several safety discharges were performed at 80 kA, some of them were initiated by quenches created by a heated helium flow.

In the second test phase further high current tests are foreseen together with the LCT coil. Fig. 4 shows the TFMC load lines and operating points without and with the LCT coil energized.

C. Joint Resistances

The good performance of the interpancake joints is of highest importance, particularly at high currents. The applied joint design was developed under the responsibility of CEA and proven with two full size joint samples manufactured in industry and being representative for the inner and outer TFMC joints. Tests in the SULTAN facility of CRPP in Switzerland showed resistances in the range of 1 to 2 nΩ [8]. The joints consist of two explosion bonded copper–stainless steel boxes in which the two conductor ends are pressed with a force of 200 tons, after having removed the petal wraps and the Cr-coating from the strands. The two boxes of the inner joints are soldered together with PbSn, while between the two boxes of the outer joints copper pins have been introduced, which were e-beam welded. Fig. 5 shows the cross section of a joint box and two adjacent inner joint boxes before soldering.

The TFMC joint resistances were determined by electrical and calorimetric measurement to be between 1 and 2 nΩ [9]. Electrical measurements were performed mainly for the five inner TFMC high field joints. Within the measuring accuracy of about ± 10 μV a time dependence of the resistance during long plateaus (30–100 min) was not seen.

The electrical measurements were confirmed by a calorimetric evaluation using the inlet temperature and the outlet temperature and the He mass flow of the pancakes. With this method, it is possible to estimate the sum of one half inner joint and one half outer joint of each pancake by plotting the steady power dissipated in the circuit as a function of the square of the coil current. The slope of this curve gives then the pancake joint resistances.

D. Thermo-Hydraulic Properties

The coil was operated first at 80 kA with a temperature of 4.52 K and a pressure of 5.0 bar at the inlet. The mass flow distribution and steady-state losses are given in Table I.

TABLE I

Mass flow and inlet data:		*Steady state losses:*	
Winding	70 g/s	Winding	12 W
NbTi busbars	2x10 g/s	Busbars	2 x 50 W
Case	10 g/s	Case	10 W
ICS	10 g/s	ICS	30 W
Aux. structure	10 g/s	Aux.	11 W

No systematic change of the pressure drop was observed across the winding during operation under current.

After a safety discharge from 80 kA the following maximum temperatures were measured: 18 K in the winding, 21 K in the case and 12 K in the ICS, the global maximum pressure was limited to 7 bar. During re-cooling, 3.6 MJ were removed from the winding and 1.7 MJ from the case.

E. Mass Flow and Pressure Drop Tests

Pressure drop tests were performed at zero current, at nominal 4.5 K and 5 bar. Both heater equipped pancakes P1.1 and P1.2 were tested. In each pancake the mass-flow rate was increased from ∼4 g/s to ∼16 g/s by increasing the pumps rpm. The regulation of the control valves allowed a further increase to ∼20 g/s.

At low mass-flow rates, P1.2, being about 10% longer, has at the same pressure drop a higher mass flow rate than P1.1, while the situation reverses at high mass flow rates. The crossover occurs around 10–12 g/s. This behavior is presently unexplained. For mass-flow rate above 8–10 g/s the experimental data in both pancakes can be well reproduced (within ±5%) [10].

F. Heating Tests

A calorimetric calibration of the heaters was performed before the heating tests. For mass-flow rates above 8–10 g/s, the power received by the helium is in good agreement (difference ≤ 10%) with the electrical power input.

Heating tests were performed at zero current for optimizing the heating power strategy for quenching the conductor, aimed to explore the operational limits. A PC program generated the shape of the heater power pulses during ramp-up. A multistep strategy turned out to be a successful method [11]. Also other heater power pulses with ramped and trapezoidal heater power scenarios were tested [12].

The identified "optimum" scenario relevant for a T_{cs} test at 80 kA showed good reproducibility.

G. T_{cs} Test at 80 kA With Subsequent Quench [11]

Using the abovementioned optimum scenario based on the multistep strategy, the first measurement of the T_{cs} at 80 kA was successfully performed. Initial conditions were of ∼6.2 bar and ∼4.5 K at the conductor inlet, and ∼14 g/s in the heated channels. Just before the transition to normal, the power in each heater was ∼300 W. The test ended with a quench of the coil, followed by the safety discharge.

The normal zone was originated first in the P1.2 conductor, with an inlet helium temperature of about 8.6 K just before the quench, as expected from previous analysis [13]. After 8 quenches this value remained unchanged.

H. Mechanical Properties

The measured sensor values are compared to predicted values coming from the finite element model. All following calculated values assume a friction coefficient of 0.3 [14].

The general behavior of the displacement sensors corresponds well to the predicted values, but two of them do not work. The horizontal opening of the coil increases by about 1.5 mm (calculated: 1.7 mm) for 80 kA, while the vertical opening decreases by 0.8 mm (calculated: 0.65 mm). The joint region is elongated by 0.25 mm on the inner side (calculated: 0.25 mm) and 0.5 mm on the outer side (calculated: 0.5 mm).

The equivalent stresses measured with the rosettes are quite comparable with those predicted by the calculation. The maximum stress reached in the vertical plane is 130 MPa (calculated 130 MPa). The maximum stress reached in the equatorial plane is 100 MPa (calculated 80 MPa) on the outer side.

I. Behavior of the NbTi Busbars

The busbars were made of a cable in conduit conductor built up in a similar way than the TFMC conductor, but with 1152 NbTi strands having a Cu : NbTi ratio of 2.4 and an internal CuNi barrier [15]. This conductor having a square 316LN jacket is nearly representative for the ITER PF conductors. The two busbars are each divided in two pieces. The busbars 1 lead from the coil terminations to the ports of the TOSKA vessel, while the busbars 2 form the lower part of the current lead system. A de-mountable joint connects them to each other.

The busbar joints are made in a similar way as the TFMC joints. For the terminations the same boxes are used in which the conductor ends are pressed the strands being Silver coated and the Copper sole being Indium coated. The contact surfaces of all terminations are either silver or gold coated. As the busbars are divided there are three different joints: the joint to the coil terminations is soldered, while the joints to the current leads use a highly compressed indium foil to make the contact. The inter-busbar joints have to be de-mountable. Therefore Indium wires were compressed between the two terminations to connect them, as first used for the CS Model Coil Facility of JAERI, Naka, Japan [16].

The busbars were not specifically tested up to now, because the main interest was to explore the behavior of the coil. Nevertheless the busbars allowed the testing of the coil without problems and fulfilled in this respect the expectations. As the busbar voltage is only monitored as a whole the individual resistances of the three types of joints cannot be determined. The voltage measurement covers the busbar intermediate joint and the two half joints to the coil and the current leads. The total resistance derived amounts to 2.2 nΩ which is anyway less than expected. The methods of fabricating the terminations and to join them can therefore be taken as a valid design for the ITER PF coils.

IV. Conclusion

With the successful manufacture and first test campaign of the ITER TF Model Coil the main goals of the project have been achieved. The feasibility has been demonstrated and with the successful current tests up to 80 kA the design principles of the ITER TF Coils were confirmed. What remains in the further test program is to explore the operational limits of the conductor and the coil, namely also during the extended tests together with the LCT coil.

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