Proposals for Cold Testing of the ITER TF Coils

P. Libeyre, D. Ciazynski, N. Dolgetta, J.L. Duchateau, F. Kircher, C. Lyraud, T. Schild, W.H. Fietz and G. Zahn

Abstract— **The ITER Toroidal Field (TF) magnet system will be made of 18 coils using Nb_3Sn as superconducting material. These coils will operate at a maximum field of 11.8 T for a nominal current of 68 kA carried by a dual channel cable-in-conduit conductor cooled by a forced flow of supercritical helium at 4.5 K. In each coil, seven 760 m conductor lengths wound in double pancakes will be connected to each other by low resistance joints. As a final step of the reception tests, it is proposed to perform cold tests of these coils at liquid helium temperature after completion of their manufacture. The testing shall include high voltage tests to check the quality of the insulation, leak tests and pressure drop measurements of the hydraulic circuits as well as measurement of the joint resistances. Testing the coils up to nominal current is a discussed option, addressing on one hand measurement of the electrical performances in self field and on the other hand the mechanical behaviour of the coils. To perform these tests, a dedicated test facility has to be built, allowing possible simultaneous testing of two coils, assembled together in a twin coil configuration, similarly to their assembly in the torus.**

Index Terms—**ITER, coils, cold testing**

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P. Libeyre is with the Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 Saint Paul Lez Durance Cedex, France (phone: +33 4 42 25 46 03; fax: +33 4 42 25 26 61; e-mail: paul.libeyre@cea.fr).

D. Ciazynski is with the Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 Saint Paul Lez Durance Cedex, France (phone: +33 4 42 25 42 18; fax: +33 4 42 25 26 61; e-mail: daniel.ciazynski@cea.fr).

N. Dolgetta is with the Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 Saint Paul Lez Durance Cedex, France (phone: +33 4 42 25 29 13; fax: +33 4 42 25 26 61; e-mail: nello.dolgetta@cea.fr).

J.L. Duchateau is with the Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 Saint Paul Lez Durance Cedex, France (phone: +33 4 42 25 49 67; fax: +33 4 42 25 26 61; e-mail: jean-luc.duchateau@cea.fr).

F. Kircher is with CEA/DSM/DAPNIA, CEA/Saclay, F-91191 Gif-sur-Yvette Cedex, France (phone: +33 1 69 08 25 88; fax: +33 1 69 08; e-mail: francois.kircher@cea.fr).

T. Schild is with CEA/DSM/DAPNIA, CEA/Saclay, F-91191 Gif-sur-Yvette Cedex, France (phone: +33 1 69 08 37 75; fax: +33 1 69 08; e-mail: thierry.schild@cea.fr).

C. Lyraud is with the Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 Saint Paul Lez Durance Cedex, France (phone: +33 4 42 25 61 15; fax: +33 4 42 25 63 75; e-mail: charles.lyraud@cea.fr).

W. H. Fietz is with Association Euratom-Forschungszentrum Karlsruhe, P.O.Box 3640, D-76021 Karlsruhe, Germany(phone: +49 7247 82 41 97; fax: +49 7247 82 28 49; e-mail: walter.fietz@itp.fzk.de).

G. Zahn is with Association Euratom-Forschungszentrum Karlsruhe, P.O.Box 3640, D-76021 Karlsruhe, Germany(phone: +49 7247 82 41 77; fax: +49 7247 82 28 49; e-mail: gernot.zahn@itp.fzk.de).

I. Introduction

THE Toroidal Field (TF) coils (Fig. 1) of the International Thermonuclear Experimental Reactor (ITER) will use a 68 kA cable-in-conduit Nb_3Sn conductor inserted in stainless steel radial plates, operating at a design temperature of 5.0 K up to a maximum magnetic induction of 11.8 T [1]. The manufacturing techniques to be used in the construction of these coils have been applied at a reduced scale to manufacture the Toroidal Field Model Coil (TFMC) [2], [3] and the results of the tests of this coil have been already reported [4]. In the framework of the preparation of the construction of the full-size coils, a debate was initiated to tackle the question which final tests should be made on these coils [5]. In this paper, proposals are made to perform cold tests of the coils at liquid helium temperature after completion of their manufacture. The tests to be performed are discussed and a testing sequence is proposed. Finally an outline design of the testing facility is presented.

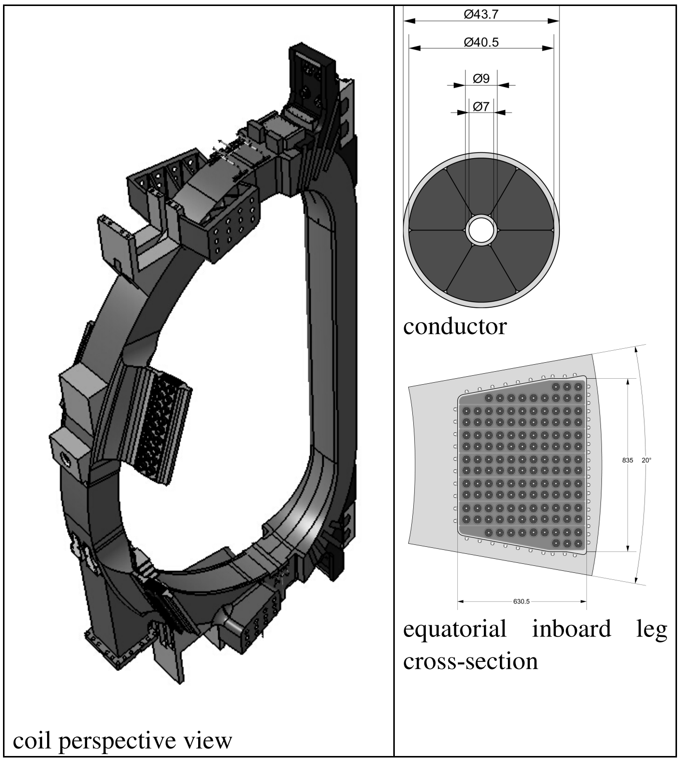

Fig. 1 : ITER TF coil design

II. Tests Objectives

The main aim of cold tests is the reception of the coils before their assembly to form the TF magnet. An extensive set of controls will be performed at different steps of the manufacturing process to check the quality of the manufacture. Nevertheless, the finally achieved properties of the coils can only be derived from tests performed in conditions relevant to operation at 4.5 K. A failure of a coil during operation would cause a major breakdown in the experimental programme and lead to costly repair resulting from a complicated disassembly and reassembly process. It is therefore of prime importance to carefully check all the properties which can be addressed in a component test.

A. *Leak check of hydraulic circuits*

It is obvious that any leak of helium should be avoided on the hydraulic circuits of the TF coils since it could induce electrical breakage in the coil insulation and would induce increased load on the cooling and pumping systems. It has been experienced in the tests of the ITER Central Solenoid model coil that, despite a leak test had been performed at room temperature prior to cool down, a leak occurred on a capillary pipe used for a sensor when the coil temperature was lowered to 4.5 K, which made compulsory to warm up the coil to repair. This shows that some leaks can arise from cooling down from room to liquid helium temperature. It can also be deduced from this experience that instrumentation tightness is a key point to check and that consequently the coil should be tested with its full equipment in its final status. In addition, to limit risks of leaks appearing at a further stage, a clearly identified interface should be designed minimizing modifications when performing the torus assembly. A leak test of all the hydraulic circuit is thus a major item of cold tests.

B. *Electrical insulation tests*

The TF coils will operate with nominal voltages below 1 kV and during a safety discharge a maximum voltage of 3.5 kV will arise between conductor and ground. However, fast excitations caused by some fault scenarii can cause much higher transient voltages by internal oscillations. In [6] a fault scenario was examined that demonstrates that radial plate and conductor insulation should withstand 11 kV and in case of the ground insulation even 34 kV. But the reference ITER fault scenario leads to a test voltage at 21kV. It seems then of great important to define clearly an ITER reference fault scenario and then define a test voltage. This value has to be defined cautiously taking into account the coil safety requirement for long term operation as it has a strong impact on the test facility and test duration.

Electrical insulation tests will be performed at the manufacturer site before coil delivery. Nevertheless, thermal stresses are applied to the insulation during cooling down and weak points could lead to leaks occurring only when the operating temperature is reached. The test of the electrical insulation is a second major item of cold tests and should be performed with enough safety margin.

C. *High voltage tests in Paschen minimum*

If a helium leak occurs during magnet operation, conditions of Paschen minimum could arise within the cryostat. It is therefore compulsory to perform high voltage tests in these conditions to check that they induce no damage of the coils. These tests are performed at room temperature in a vacuum vessel, e.g. the cryostat that is used for the cold test.

D. *Electrical resistance of joints*

It is only possible to measure the electrical resistance of the joints between double pancakes by injecting current (> 24 kA) in the coil when it is in superconducting state. Although relevant joint samples will have been tested during coil manufacture, the measurement of the resistance of the actual joints can only be performed on the completed coil at 4.5 K. The later discovery of a too high joint resistance could lead to difficulty or in the worst case impossibility to operate the coil. This check is therefore a key point to guaranty reliable coil operation.

E. *Operation of the safety system*

The operation of the safety system requires relevant conditions to be checked, which means that current should be injected in the coil at 4.5 K. This is again a major aim of the cold testing.

F. *Instrumentation behaviour*

Safe operation of the coils will rely on a correct behaviour of the instrumentation. The discovery of faulty sensors when performing the commissioning tests of the TF magnet could lead to complicated and difficult repairs. It appears then important that all sensors had been tested previously, equipped with their final wiring and connectors and at operating temperature. This calls clearly for cold tests of the completed coils, fully equipped with their instrumentation.

G. *Critical electrical performances of the conductor*

A main difficulty in addressing the critical electrical performances of the conductor of a TF coil is the magnetic field level, which in a single coil test at nominal current is much reduced than in the assembled TF magnet (maximum induction in the range of 6 T compared to 11.8 T). Consequently, measurement of the critical current implies operation of the coil at higher temperature. As shown in [5], current sharing regime can be reached above 9 K. Nevertheless, extrapolation to operation at higher magnetic field requires calibration which could only be performed by previous testing of a similar conductor length in variable field and temperature conditions. This should be achieved in testing a relevant TF Insert in the CSMC test facility. The precision of the extrapolation remains unknown, which makes this test a secondary goal of the cold tests.

H. *Pressure drop of the double pancakes*

The actual pressure drop in the double pancakes will have a direct impact on the effectively required power of the cryogenic system. Measurement on the actual coils can be performed at room temperature with nitrogen gas flow. However, extrapolation to operation with supercritical helium will require first calibration on actual geometry with measurements performed in both conditions. This item is also a secondary goal of the cold tests.

I. Mechanical behaviour

Investigation of the mechanical behaviour of the coil is of major interest to assess the reliability of the mechanical analyses carried out to evaluate the life time of the magnet. Although some information could be derived from mechanical tests performed at room temperature by applying an external load, for example by a hydraulic jack, this would not be completely relevant to operation of a coil in a TF magnet where the loads arise in the winding-pack. This can only be achieved by flowing current in the coil, which by interaction with the self field will give rise to electromagnetic forces. In a single coil test only in-plane loading can be achieved whereas in a two coil test both in-plane and out-of-plane loading can be obtained [7]. This calls for testing coils by pairs, which allows to address mechanical behaviour as well under in-plane loading when ramping the current in one coil only as under out-of-plane loading when ramping the current in both coils. Such tests will be helpful to fully characterize coil deformations and stresses during operation. If an anomalous behaviour was observed during the prototype coil tests, it might still be possible to implement some design changes, which will not be the case during the magnet commissioning tests.

J. Thermal behaviour

Due to the specific feature of the TF coil which is the surrounding of the conductor pancakes by thick stainless steel radial plates, during a fast discharge a significant part of the magnetic energy stored in the magnet will be released as heat deposited in the coils. The heat input induced by eddy current circulation in the plates and case will result in temperature increase in the conductor [8]. It is of major interest to confirm the ability of the cryogenic system to cope with this event. This issue can be addressed in relevant conditions by triggering a fast discharge from nominal current if achievable and measuring temperature excursion and recovery. It has already been observed on the TFMC that thermal behaviour of the coil was not exactly meeting expectations [9].

Actual measurement of coil behaviour is definitely a key point for adequate design of the cryogenic system.

III. TESTING PROGRAMME

As recommended in [5], the proposed testing strategy is to perform cold tests at 4.5 K of the prototype coil and of the 18 series coils to minimize the risks of discovery of a major defect when starting operation of the magnet.

A. Testing configuration

Two options can be considered: the test of each coil separately or the tests of coils by pairs. Except the prototype, which should be tested alone, the advantage of testing coils by pair is that it allows time saving on the overall tests and investigation of mechanical behaviour in out-of-plane loading. It is paid by the need of a slightly larger cryostat and of an additional current lead to allow separate coil charging.When testing coils by pair they would be connected adjacent to each other as assembled in the torus.

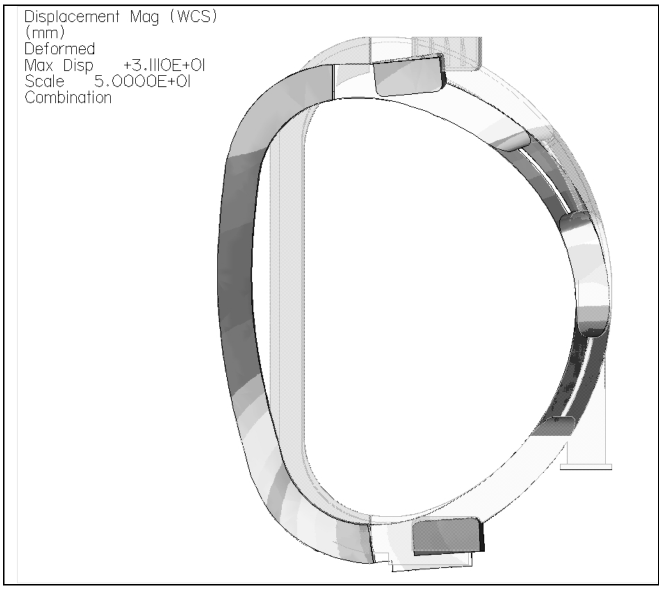

Fig. 2 : TF Coil deformation in a two-coil test at 34 kA

B. Test analysis

Several analyses have been performed to verify which testing conditions should be achieved to allow proper investigation of the coil behaviour without risking damage.

1) Tests of a single coil up to nominal current

A 3D mechanical FEM model of a TF coil was built with the Pro/Mechanica code to analyze the stresses and deformations arising in the coil when ramping up the current. The main goal of this analysis was to check whether it should be possible to test a single coil up to its nominal current. Owing to its D-shape, under its self field a TF coil tends to enlarge its size and to become circular, which induces high bending stresses in particular in the straight inner leg. Nevertheless, the reduced magnetic field leads to lower body forces than in the torus so that the operation at nominal current leads to large displacements, but with maximum stresses and strains remaining acceptable. This test is thus achievable.

2) Tests of two coils up to half nominal current

The model used for the analysis of a single coil test was modified by applying suitable boundary conditions and loading to analyze the possibility to load both coils up to half the nominal current. In this case loading up to nominal current would exceed allowables as far as stresses and deformations are concerned. The analysis of the results shows that simultaneous operation of both coils to half current remains possible with a maximum deformation of 31 mm (Fig. 2).

C. Testing sequence

A detailed testing sequence has been established to meet the objectives defined in section II in both considered cases: tests of single coils or tests of pairs of coils. The times needed to perform the tests are respectively 58 days for a single coil, 77 days for two coils and less than 3 years for all coils.

IV. Test Facility

Owing to the large size of the ITER TF coils, it is not possible to use an existing test facility, which makes compulsory the building of a new dedicated test facility. The best location for this facility appears to be close to the ITER site, where area is available and which enables to minimize coil transportation, to take advantage of the site infrastructure and to train the team which will further operate the magnet.

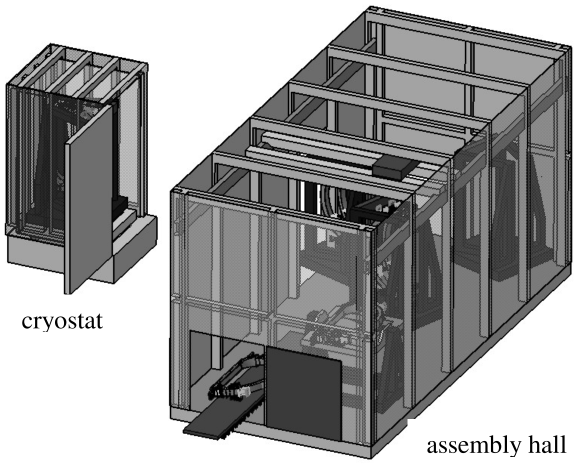

Fig. 3 : ITER TF Coil test facility outline design

A. Design

An outline design of this test facility has been sketched (Fig. 3) so as to evaluate the space required and the overall cost. The main components are detailed hereafter.

1) Cryostat

Housing two TF coils requires a large cryostat. In order to ease the handling of the assembled coils, the proposed design, derived from that of other large existing vessels in Europe, is a parallelepipedic cryostat with a sliding door. This allows installation of the coils on the supporting frame to be performed in an area close to the cryostat and translation of the two-coil assembly into the cryostat by sliding on rails. Easy accessibility to the coils is so provided for the major part of the test preparation and only the final connections to the electrical, hydraulic and instrumentation circuits have to be performed inside the cryostat. No vertical movement is necessary, which simplifies the handling equipment. To meet the working regulations, a maximum magnetic field of 50 mT should be reached in the personal working area, which calls for providing enough distance between the cryostat and the working area so as to limit the need for shielding.

2) Power supply and dump resistance

Operation at nominal current (68 kA) requires a bipolar 70 kA, ± 15 V power supply with a switching unit similar to the fast discharge unit developed for the ITER magnets operation. Discharge in 11 s is achieved by a dump resistor of 32 mΩ in a single coil test and 88 mΩ in a two-coil test at half current.

3) Cryogenic refrigerator

A supercritical He cooling circuit will be used for circulating the high mass flow rate with cold circulation pumps. Separate loops are planned for winding and case of the TF coil. A 3 kW (1.6 kW for single coil) refrigerator is needed [10].

B. Construction and cost

Starting in 2008, the construction would be completed in 2010. An estimation of the total construction cost of the test facility gives a capital cost about 25 M€. Operating costs are in the range of 22 M€ for testing all TF coils.

V. Conclusion

Cold testing of all the ITER TF coils is strongly recommended to check their actual behaviour and to minimize the risk of occurrence of defects at a later stage. It has been shown that test of single coils up to their nominal current or two adjacent coils to half nominal current is achievable. A testing sequence has been established assuming coil testing as single coils or by pairs. The tests of coils by pairs seems the best suited option, leading to testing all coils within 3 years. An outline design of a dedicated test facility to be built preferably on the ITER site has been drawn and its cost estimated. Its construction should be decided soon to fit within the TF magnet time schedule.

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