T_{CS} Tests and Performance Assessment of the ITER Toroidal Field Model Coil (Phase II)

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***Abstract*—The tests of the Toroidal Field Model Coil (TFMC) were completed in 2002 in the TOSKA facility of Forschungszentrum Karlsruhe, Germany. Operation reached a combined 80 kA in the TFMC and 16 kA in the LCT coil, resulting in a peak electromechanical load very close to that expected in the full-size ITER TF coils (800 kN/m). Here we concentrate on the measurements of the current sharing temperature (T_{cs}) of the TFMC conductor, possibly the highlight of the whole test campaign. These tests were performed by increasing in steps the helium inlet temperature T_{in} in double pancake DP1, resulting in an increasing normal voltage V across the DP1.1 and DP1.2 conductors, and were repeated for several combinations of currents in the TFMC and in the LCT coil. The analysis of the $V - T_{in}$ characteristic by means of the M&M code allows to self-consistently deriving an estimate of T_{cs}, as well as an indirect assessment of the "average" strain state in the conductor. The TFMC isolated strand has also been very recently characterized at different applied uniaxial strain, and preliminary results indicate a stronger reduction of carrying capacity compared to the extrapolation from Summers scaling used in the analysis so far. As a consequence, the performance of the TFMC conductor, as preliminarily re-evaluated here, appears more in line with the strand performance than in previous analysis, although a BI-dependent "degradation" is still present.**

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

I. INTRODUCTION

THE Toroidal Field Model Coil (TFMC) [1] is a Nb_3Sn superconducting coil developed in the EU for the International Thermonuclear Experimental Reactor (ITER), to demonstrate the manufacture feasibility and the design principles of the ITER TF coils [2]. This big $(\sim 3\,\mathrm{m}\times 4\,\mathrm{m}\times 1\,\mathrm{m})$ racetrack coil is wound in double pancakes in the grooves of stainless steel radial plates using dual-channel cable-in-conduit conductors (CICC) [3]. The conductors, connected through shaking-hands joints, are made of 1080 twisted strands jacketed by a circular thin SS conduit and they are cooled by supercritical helium at nominal operating temperature $T_{op} \sim 4.5$ K and pressure $p_{op} \sim 0.5$ MPa. The coil was designed for DC operation, and it carries a transport current of up to 80 kA giving a peak field of ~7.8 T in stand-alone operation, and of 9.97 T when the background field of the EURATOM LCT coil at 16 kA is added.

The TFMC was tested in the TOSKA facility of Forschungszentrum Karlsruhe, Germany: in Phase I, completed in 2001, the coil was tested in its self-field, while in Phase II, completed in 2002, it was tested in the additional background field of the LCT coil. In both cases, the operation was satisfactory and successful: the nominal Phase II conditions of $I_{TFMC} = 70$ kA and $I_{LCT} = 16$ kA, corresponding to a stored energy of 0.337 GJ, were reached without problems, and even an extended operation up to $I_{TFMC} = 80$ kA and $I_{LCT} = 16$ kA was obtained.

One of the main issues in the test program was the investigation of the operation limits of the TFMC conductor through the measurement of the conductor current sharing temperature (T_{cs}) for several combinations of I_{TFMC} and I_{LCT}. This paper focuses on the description and experimental results of the T_{cs} tests in Phase II, as well as on their interpretation by means of the M&M code [4]. The assessment of the TFMC performance is then made by comparing the behavior of the coil to that measured on the isolated single strand. The results and analysis of the T_{cs} tests of Phase I were presented in [5]–[8].

II. EXPERIMENTAL SETUP AND RESULTS

During Phase II, the T_{cs} measurements were performed on the conductor DP1.2 following the same strategy adopted during Phase I [5], [6]. Two resistive heaters, wrapped around the helium pipes upstream of each conductor (DP1.1 and DP1.2) in double pancake DP1, were operated following a multi-step heating strategy, in order to heat the He at the conductor inlets as shown in Fig. 1, until a resistive voltage was detected across the conductor. Here we shall concentrate on DP1.2, where the peak field was located. The diagnostics directly relevant to the present paper consisted of (see [5] for details):

- Temperature sensors at the inlet of DP1.1 and DP1.2 (signals TI710 and TI712, respectively);
- Voltage drop measurement across DP1.1 and DP1.2 including the joints (signals EK711 and EK721, respectively).

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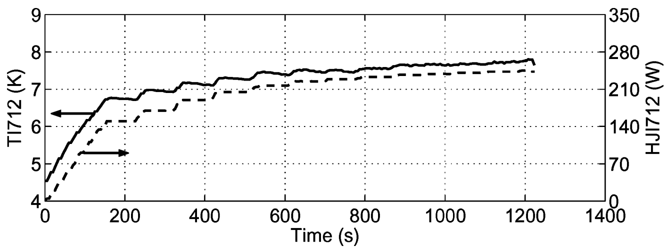

Fig. 1. Measured evolution of the heating power (dashed line) and inlet temperature (solid line) in DP1.2 for the T_{cs} test at 70/16 kA (Nov. 20, 2002).

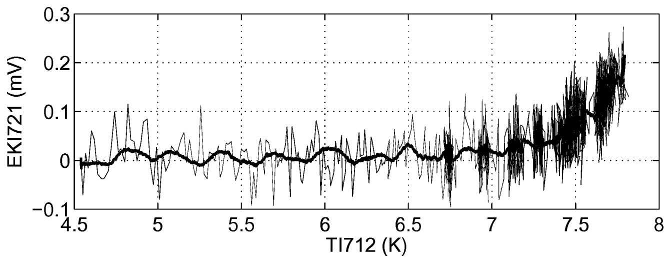

Fig. 2. Measured $V - T_{in}$ characteristic of DP1.2 in the T_{cs} test at 70/16 kA (Nov. 20, 2002): raw Spartan data (thin line) and smoothed data (thick line).

All the sensors above were located *outside* the coil, which means that a direct measurement of the T_{cs} is impossible and modeling is mandatory.

All signals were acquired with a sampling rate of 0.2 Hz (so-called "cyclic" data). However, in order to provide a more accurate description of the voltage take-off and a realistic reconstruction of the voltage-temperature $(V - T_{in})$ characteristic of the conductor, the temperature and voltage signals were also acquired with a sampling rate of 10 Hz and pre-amplified (so-called "Spartan" data). Smoothed Spartan data are used in the analysis below. An example of a measured $V - T_{in}$ is reported in Fig. 2. The raw data supplied by the Spartan system are still very noisy, therefore a moving average over 50 points was applied both on TI712 and on EK721. In some cases (e.g., at 80/16 kA, see below), a low-frequency noise $(\pm 10\ \mu V)$ is still present in the voltage after this smoothing.

In the first T_{cs} tests of Phase II, as well as in all those of Phase I, the heaters were operated until the coil quenched and a safety discharge was triggered. The recovery of the cryogenic system after a quench event was time-consuming, and in the particularly severe case of the first 70/16 kA test it was even necessary to release some He to the atmosphere [9]. After the 70/16 kA quench, EK721 was carefully monitored and the heating of DP1.2 was turned off as EK721 reached 200–300 μV, i.e., before a significant propagation of the quench occurred. The heated conductors could then be safely brought back to T_{op}.

Several T_{cs} tests were performed at different current combinations in the TFMC and LCT coil, as summarized in Table I. The tests without current in the LCT coil verified that no noticeable degradation had occurred, neither as a consequence of warm-up and cool-down between the two test phases, nor of (transport current) cycling on the conductors. While the nominal peak load conditions of the TFMC were at 70/16 kA, two tests were performed in an extended operation regime, and namely the 80/14 kA and the 80/16 kA, in order to achieve an electromechanical load more relevant for the TF coils.

TABLE I
SUMMARY OF T_{cs} TESTS PERFORMED IN 2002 ON THE TFMC (PHASE II)

Date	I_{TFMC}(kA)	I_{LCT}(kA)	Comments
Oct. 14	80	0	Repetition after Phase I
Oct. 23	69.3	0	
Nov. 6	70	16	First combined test and nominal conditions
Nov. 8	60.6	13.9	Current scan
Nov. 11	49.1	11.3	Current scan
Nov. 18	80	14	
Nov. 19	80	0	Repetition after cycling
Nov. 20	70	16	Repetition after cycling
Nov. 21	80	16	Extended operation to peak mechanical load (~ 800 kN/m) comparable to ITER TF

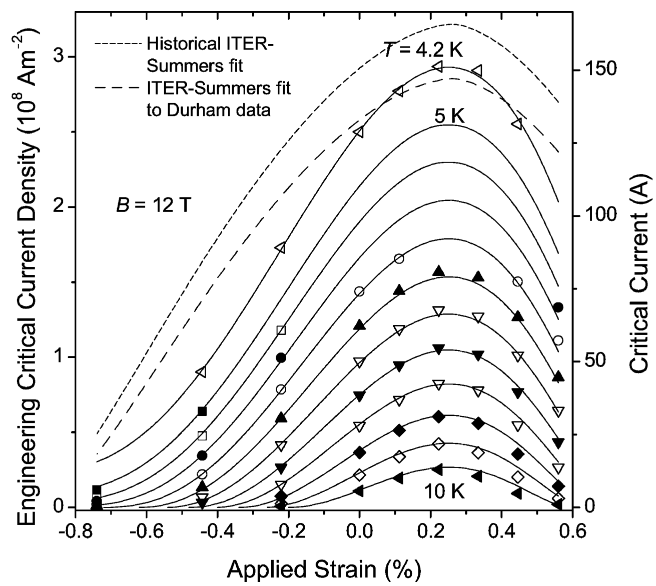

Fig. 3. Strand I_c from [15] and new proposed fit [17] (solid lines) as a function of mechanical applied strain, at 12 T and different temperatures. Electric field criterion at 10 $\mu V/m$.

III. EVALUATION OF THE COIL PERFORMANCE

A. *Critical Re-Assessment of the TFMC (LMI) Strand Database*

The TFMC conductor uses a strand produced by Europa Metalli-LMI in Italy.

Until very recently, the characterization of this strand was mainly performed without mechanically applied compressive strain [10]–[13]. So far, see, e.g., [6]–[8], [14], the Summers scaling [15] was then adopted to extrapolate to the strain conditions relevant for the TFMC, typically much more compressive than $\varepsilon_{th}^{strand}$ (the thermal strain due to the cool-down to cryogenic conditions of both strand and holder, which typically have a somewhat different elongation), using recommended values of the critical parameters [16].

During the last months, however, an extensive campaign of characterization of the LMI strand under applied strain has been performed at the University of Durham, UK [17], and the data have been preliminarily fitted using a different parameterization [18] than Summers, as it was not possible to reproduce them with sufficient accuracy using that functional form, see Fig. 3. Furthermore, the Summers extrapolation with the recommended parameter values [16] used so far in the TFMC analysis ("historical" fit in Fig. 3) significantly overestimates the measured I_c at large compressive strain, while (obviously) a very good agreement is obtained with the new proposed fit, at all temperatures. Finally, the Durham data are consistent with experimental I_c values from other laboratories at zero applied strain (including average cable data), all taken on the so-called ITER barrel [19].

Based on the above, the new proposed scaling [19] will be used in the following, although it is clear that an independent confirmation of the Durham data could be desirable.

B. M&M Fit of $V - T_{in}$ *Characteristics*

The strategy for the M&M analysis of the T_{cs} tests has been already established in previous work [7], so that it will only be briefly reviewed here. An "average" strand is considered representative of the conductor performance (uniform current distribution is assumed in the model). The strain on the average strand is assumed given by $\varepsilon = \varepsilon_{th} + \varepsilon_{op} + \varepsilon_{extra}$. We assume $\varepsilon_{th} = -0.61\%$ [16] as the thermal strain, while ε_{op} is the uniaxial (hoop) strain computed by finite element methods and ε_{extra} is a fitting parameter. M&M computes the strand temperature profile $T_{st}(x)$ along the conductor, for a given measured inlet temperature evolution of the helium $T_{in}(t)$. Using the computed profile B(x) of the average and maximum magnetic field along DP1.2, an average electric field $\langle E\rangle(x)$ on the conductor cross section is computed by M&M, assuming a critical value of the electric field $E_c = 10\ \mu V/m$ and a value for the second fitting parameter, the exponent or index "n", in the power law relating $\langle E\rangle$ to the critical current density $j_c(T_{st}, B)$ [7]. The resistive voltage V along the conductor is then computed integrating $\langle E\rangle(x)$ along DP1.2, and one attempts to fit the measured $V - T_{in}$ characteristic with the computed one, using the two fitting parameters (ε_{extra}, n). From this fit one deduces: a) the possible "degradation" ε_{extra} of the conductor performance with respect to the strand; b) the *conductor* n; c) the "measured" T_{cs}, defined here as the value of T_{st} *computed* at the first time and location when $\langle E\rangle = E_c$. Except for the two fitting parameters, the rest of the input is the same for all simulations.

In Fig. 4 we show a selected comparison between measured and computed $V - T_{in}$ characteristics, for the cases 80/0 kA (Nov. 19) and 80/16 kA. A very good agreement is obtained for suitable values of the fitting parameters (ε_{extra}, n).

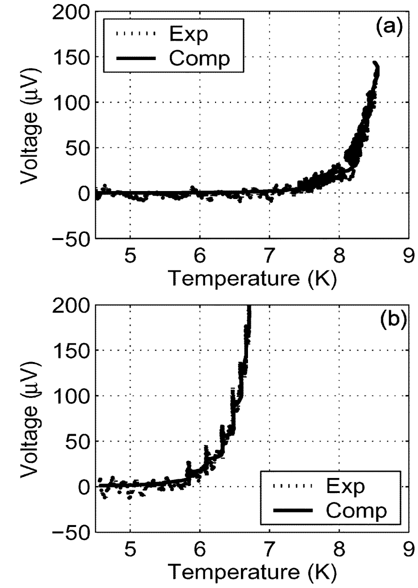

Fig. 4. Comparison between measured (dots) and computed (solid lines) $V - T_{in}$ characteristics of DP1.2. (a) 80/0 kA (Nov. 19); (b) 80/16 kA.

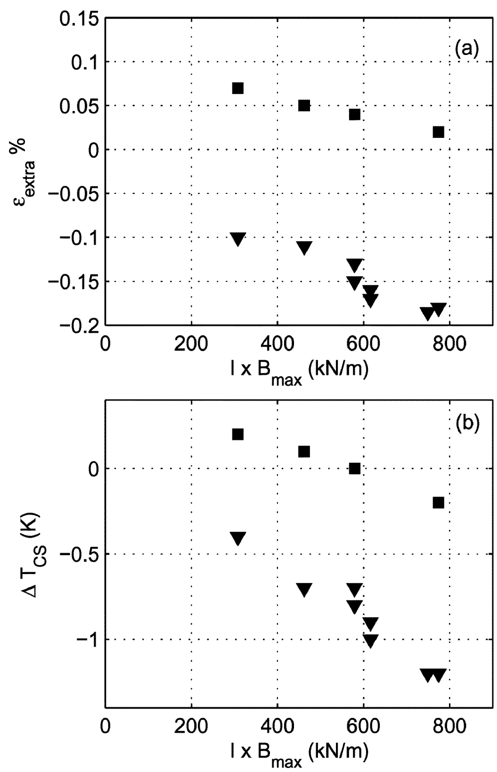

Fig. 5. Summary of M&M performance assessment of the TFMC in Phase II. New scaling [19] results (squares), old Summers scaling results (triangles). See text for details.

C. Comparison Between Coil and Strand Performance

The critical parameter influencing the T_{cs} assessment is ε_{extra}. As a matter of fact, the conductor at room temperature returns elongated by 0.05% from the heat treatment. Thus the cable is under axial compression, putting the jacket under axial tension. The strands therefore are exposed to additional stresses, e.g., bending stresses, on top of which the electromagnetic forces are applied. ε_{extra} is plotted in Fig. 5(a) as a function of BxI_{TFMC}, in view of the role, which the strand bending is expected to play on the current carrying capability of the strand [20]. For the sake of comparison, also the results based on the Summers scaling used so far [14] are given. The conductor performance is closer to expectations from strand measurements (i.e., ε_{extra} is closer to 0) than in previous analysis, although a BI dependence of ε_{extra} is still there (slope ~1/2 of that with Summers scaling). Notice, however, that the positive values of ε_{extra} are most likely related to a too large (compressive) ε_{th} assumed here. If a linear extrapolation would hold back to $BI = 0$, then $\varepsilon_{th} \sim -0.5\%$ would probably be a more consistent assumption, leading to larger "degradation" than shown in Fig. 5(a). The difference between the measured T_{cs} on the TFMC, and the strand T_{cs} evaluated at $\varepsilon - \varepsilon_{extra}$ and peak average magnetic field, is given in Fig. 5(b). Also for this representation similar considerations can be made as for Fig. 5(a) above. Finally, in

TABLE II
SUMMARY OF M&M RESULTS FOR THE CONDUCTOR N AND T_{cs} AT DIFFERENT COMBINATIONS I_{TFMC}/I_{LCT} IN PHASE II

I_{TFMC}(kA)	I_{LCT}(kA)	n	T_{cs}(K)
80	16	8.5	6.0
80	0	7	8.2
60.6	13.9	7	8.5
49.1	11.3	6	10.0

Table II we report both the T_{cs} measured on the coil and the value of the fitting parameter n. By comparison with previous analysis [14], it turns out that the T_{cs} does not depend on the strand scaling. The latter can be compared with $n_{strand} \sim$ 12–25 [17] (increasing with I_c), showing that the n of the average strand in the conductor is significantly smaller (by a factor of ~2) than that of the isolated strand, and that also n increases with I_c. Finally, from the comparison of Table II and Fig. 4 it may be noticed that the temperature margin is shifted in the resistive region of the conductor, i.e., stable DC operation of the TFMC was still possible at voltage above T_{cs}.

IV. CONCLUSIONS AND PERSPECTIVE

The Phase II T_{cs} tests of the TFMC DP1.2 conductor were successfully performed at several combinations of I_{TFMC} and I_{LCT}, including conditions very close to the peak electro-mechanical load, which will be encountered in the full-size coil.

Very recent preliminary data show that the dependence of the TFMC strand critical current on strain is stronger than expected from Summers scaling. Taking this into account, the analysis of the T_{cs} tests with the M&M code shows that the TFMC performed closer to strand performance than evaluated before. However, a BI dependent "degradation", possibly related to strand bending not presently included in the design criteria, is present, although weaker than in previous assessments, confirming the interest for a strand with improved performance. Also, the conductor n index is significantly smaller than n_{strand}, and appears to increase with the critical current.

An experimental confirmation of the strain dependence of the strand critical current will be needed, together with an assessment of the error bars of the performance evaluation with M&M, to make such conclusions on the TFMC performance assessment definitive.

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