First Measurement of the Current Sharing Temperature at 80 kA in the ITER Toroidal Field Model Coil (TFMC)

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***Abstract*—The first measurement of the T_{cs} at 80 kA was successfully performed in the ITER TFMC. Two resistive heaters are available on the inlet piping of the P1.1 and P1.2 pancakes, and can be independently operated. An "optimum" heating scenario, based on the multi-step (staircase) strategy developed before the tests, was determined and used for T_{cs} measurement. The test ended with the quench of the coil, followed by the dump. A normal zone was originated first in the P1.2 conductor, with the inlet helium temperature in P1.2 of about 8.7 to 8.9 K just before the quench, as expected from previous analysis. The results of the test are presented and analysis is performed for an accurate assessment of T_{cs}, evaluating the effects of Joule heating in the joint, heat exchange through the joint between P1.2 and the slightly colder P1.1, and helium propagation from the heater to the peak field region in the conductor.**

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

I. Introduction

THE TOROIDAL Field Model Coil (TFMC) [1], a racetrack coil pancake-wound on radial plates using ten Nb_3Sn two-channel cable-in-conduit conductors (CICC), is being tested in the TOSKA Facility in Karlsruhe [2] in the frame of the International Thermonuclear Experimental Reactor (ITER) [3]. A first test phase of the TFMC is being performed without the LCT coil, while in a second test phase the TFMC will be tested in the background field of the LCT. The TFMC 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, designed for DC operation, carries a transport current of 80 kA giving a maximum field of ~7.8 T, with a total stored energy of 86.4 MJ.

One of the main issues in the test program [4] was the investigation of the operation limits through the measurement of the conductor current sharing temperature (T_{cs}). Two resistive heaters (HJI710 and HJI712, respectively, see Fig. 1) were installed on the piping upstream the inlet of conductors P1.1 and P1.2. (In the test with LCT the maximum field is located in the first double pancake, DP1, while here it is in DP3 [5].) The T_{cs} measurement was then foreseen on DP1, by convecting the heated helium downstream to the peak field region, where a normal zone should be initiated.

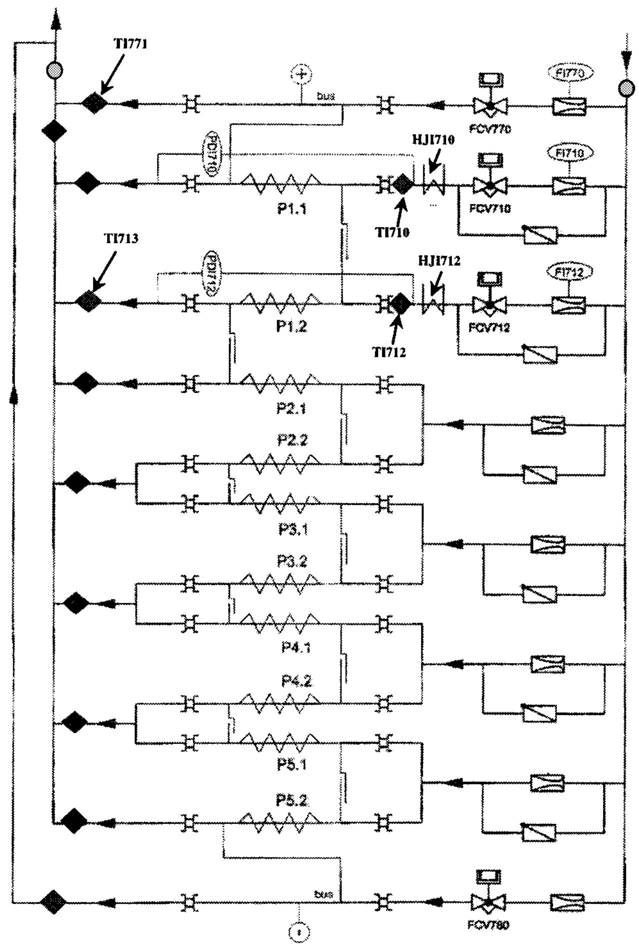

Fig. 1. Flow schematic of the TFMC winding (DP1-5 + busbars) with available sensors. Helium temperature sensors (marked with ♦) are available at the outlet of each double pancake, flow meters at the inlet. Inlet temperature sensors and pressure drop measurement are available on the heated pancakes. Flux control valves are available on the heated pancakes and on the busbars. Pressure sensors (•) are available at the common inlet and outlet manifolds.

The definition of the heating strategy for T_{cs} measurement *in the conductor* without quench propagation out of the joint region required a detailed predictive study [6]. In fact, the heated helium flows through the inlet joint and travels from there to the peak-field region (~1.5 m downstream of the joint outlet). According to the magnetic field maps [7] (computed on the in-

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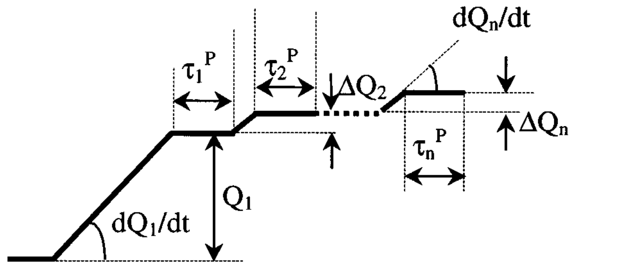

Fig. 2. Multi-step strategy: schematic view of the heating power wave-form. For the generic (nth) step, the free parameters, which need to be defined are the slope (dQ_n/dt), and the duration (τ_n^P) and height $(Q_n = Q_1 + \Sigma\Delta Q_k)$ of the plateau.

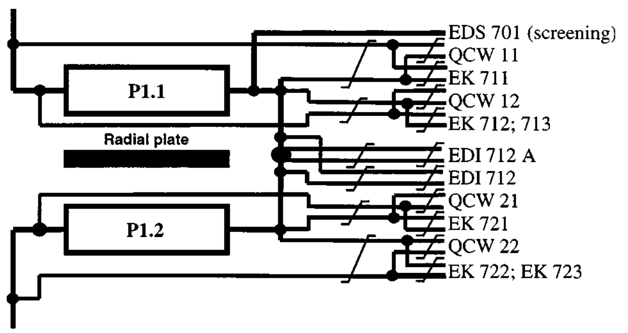

Fig. 3. Arrangement scheme of the voltage taps relevant for T_{cs} measurement in P1.2.

nermost line with respect to the center of the racetrack), the peak field in the joint is only ~6.2 T at 80 kA, while in the conductor (P1.2) it reaches ~7.2 T. Despite that, in view of the local degradation of the critical properties in the joint (longitudinal strain −0.6%, vs. −0.5% in the conductor, deduced from the analysis of the Full Size Joint Sample [8]), the minimum expected value of T_{cs} in conductor P1.2 is $T_{cs,\min}^{conductor} \sim 8.6$ K, while in the joint $T_{cs,\min}^{joint} \sim 9.1$ K. Therefore, it was thought it could be difficult, in principle, to avoid quench propagation out of the joint during the T_{cs} measurement.

The paper is organized as follows: after the description of the heating strategy and the definition of a proper scenario, the results of T_{cs} measurement at 80 kA will be presented and discussed.

II. Heating Strategy

Predictive computational analysis performed with the M&M code [6], [9] showed that it was indeed possible to raise the temperature $T_{in}^{\mathrm{P1.2}}$ at the inlet of P1.2 up to a value above $T_{cs,\min}^{conductor}$ but still below $T_{cs,\min}^{joint}$ as desired, heating both P1.1 and P1.2 by means of a sequence of steps with increasing power (multi-step strategy, see Fig. 2).

In order to perform the T_{cs} measurement using this strategy, proper software was developed and installed to independently control the power waveform in the two heaters.

Dedicated tests were first performed without current to define a heating scenario in the frame of the multi-step strategy, which could allow the temperature at the inlet of P1.2 to get into the window between $T_{cs,\min}^{conductor}$ and $T_{cs,\min}^{joint}$. The following constraints were taken into account:

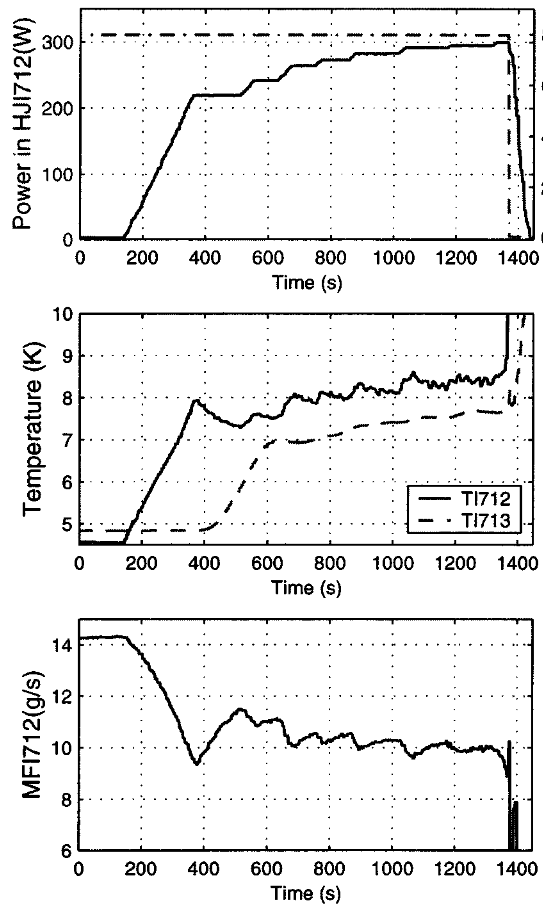

Fig. 4. (a) Top: Heating power evolution in HJI712 (solid), in HJI710 (dash-dotted) and evolution of the current (dashed) up to the quench. (b) Middle: Temperature evolution at the inlet (solid) and outlet (dashed) of P1.2, and in the inlet (dash-dotted) of P1.1. (c) Bottom: Evolution of the mass flow rate upstream of the heater in P1.2 (solid) and P1.1 (dash-dotted).

1) The temperature increase should be as gradual as possible, in order to have a quasisteady-state evolution of the transient, which helps in the analysis of the results. In quasisteady state the temperature variation along the first meters of conductor should be small, being influenced in principle only by some heat generation and heat exchange in the joint, and by heat exchange through the radial plate. Quasi steady state requires having long plateaus ($\tau^P \sim$ 100 to 200 s), small slope of the power ($dQ/dt \sim 0.5$ W/s) and small steps ($\Delta Q \sim 4$ W), see Fig. 2, especially when $T_{in}^{\mathrm{P1.2}}$ approaches the expected value of T_{cs}. Also, using the same heating scenario in both P1.1 and P1.2 minimizes the heat transfer in the joint. It was also observed that, by increasing the operating pressure from, e.g., 0.5 MPa to 0.6 MPa, the small oscillations, which arise during the heating, are slightly damped as expected [9].
2) The total load by the resistive heaters must be tolerated by the refrigeration system, forcing the total power from the heaters to stay below ~600 to 650 W for such long heating (~600 s). Together with the required temperature this forces the mass-flow rate in the heated conductors to stay below ~14 g/s while, on the other hand, the mass

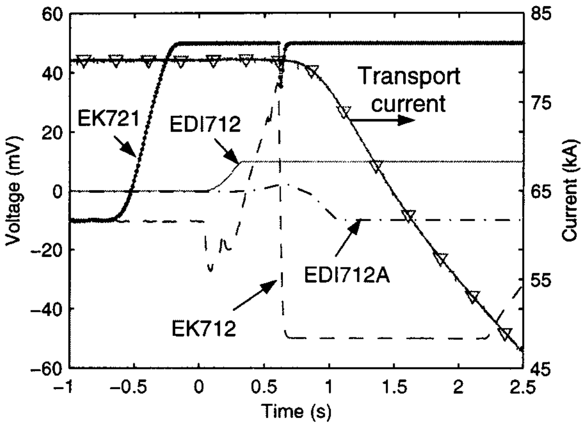

Fig. 5. Evolution of the voltage drop EK712 along P1.1 (dashed), EK721 along P1.2 (solid with dots), and across the joint between the P1.1 and P1.2: EDI712 (solid) including ~0.6 m of conductor on each side and EDI712A (dashed) including the joint only (see also Fig. 3). The transport current evolution is also reported (solid with triangles).

flow rate measurement in the heated pancakes was reliable[1] only above ~8 g/s.

3) The heat transfer through the joint at the outlet of P1.1 heats the helium in the NbTi bus bar (Fig. 1). The temperature at the outlet of the bus bar should remain below ~6 K, which is the maximum estimated value to avoid a quench in the bus bar at 80 kA [6]. (Also a heat load of unknown origin on the bus bar influences this temperature.) In order to meet the 6 K requirement, the mass flow rate in the bus bar must be at least ~20 g/s.

After the test of the heating scenario at zero current and the check of its reproducibility, the T_{cs} measurement at 80 kA has been performed in the same thermal-hydraulic initial conditions. The arrangement of the voltage taps relevant for the interpretation of the T_{cs} measurement is shown in Fig. 3. In case of a quench (which was *a priori* the most probable end of the T_{cs} test), the coil protection system initiates the safety discharge of the coil when the voltage threshold of 0.1 V is reached in the quench detector channels QCW11/12 or QCW21/22.

III. Results

This first test was performed on August 8, 2001. The P1.1 and P1.2 conductors were heated as shown in Fig. 4(a), and the resulting evolution of the temperature at the inlet of the pancakes is shown in Fig. 4(b), up to the point when a quench was detected and a safety discharge of the coil was initiated. The strong heat deposition also caused, as usual, a significant reduction of the mass flow rate in the heated pancakes [Fig. 4(c)]. All of these data were acquired with a sampling rate of ~0.2 Hz.

The analysis of the voltage signals (Fig. 5), sampled at 1 kHz, shows that the *T_{cs} is first reached in the conductor P1.2*, since the first voltage to take off is EK721 along P1.2. (In Fig. 5, time = 0 s represents the quench detection time, when 0.1 V are reached in QCW21/22, see Fig. 3.) Notice, however, that due to the small length (~1 m) of conductor in the high field region, the voltage that should meet the classical T_{cs} criterion of the order of 10 μV/m is too small to be detected, so that it is not easy to discriminate here between current-sharing and quench temperature. The quench propagates upstream reaching a point ~0.6 m ahead of the joint in ~0.6 s, as shown by the take-off of EDI712, and then the joint itself after about another 0.3 s, as shown by the take-off of EDI712A. The negative voltage shown by EK712 right after the quench detection is due to the switch of the power supply to the inverter mode. Its subsequent increase may be due to a normal zone being initiated in P1.1 by heat exchange with P1.2 through the radial plate, which appears to be the only available mechanism for this. Indeed, the temperature at the inlet of P1.1 [Fig. 4(b)] is lower than the estimated minimum T_{cs} (~9.0 K) in that conductor; the only alternative way for a quench to develop in P1.1 would be through the joint, but the almost simultaneous rise of EK712 and take-off of EDI712A seems to exclude also this possibility; finally, this is also in agreement with an estimate of the relevant conduction time scale through the radial plate (~1 s to increase by ~1 K the temperature in P1.1, with a temperature difference of ~10 K between P1.2 and P1.1). The later evolution of EK712 during the dump, which is just starting at t ~ 2.2 s in Fig. 5, clearly indicates the presence of a normal zone in P1.1 [11]. The delay in the current dump (~0.5 to 0.6 s) is due to the sequence of switching in the dump circuit [12].

The peak temperature and pressure reached during the quench were ~70 K (inlet of P1.2) and ~0.8 MPa, respectively.

[1]This was shown by calorimetric calibration of the resistive heaters and by pressure drop measurements, to be discussed elsewhere [10].

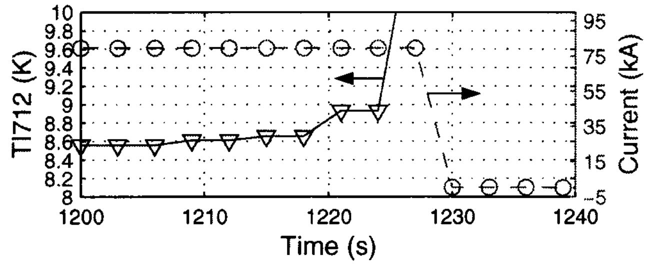

Fig. 6. Evolution of TI712 (triangles) and of the current (circles) in the final heating phase before the quench. (Notice that, for each couple of points the second is, in most cases, just a fictitious repetition of the first.)

IV. Discussion

We now want to use the information coming from the analysis of the experimental signals to estimate where along P1.2 the normal zone was initiated and, at the same time, to compute the corresponding value of T_{cs}.

From the take-off of the voltage signal, we can see that the 0.6 m of conductor which make the difference between EDI712 and EDI712A (see Fig. 3) are covered in ~0.37 s, leading to a quench speed of V_q ~ 1.6 m/s. Under the rough hypothesis of a constant quench speed, the initiation of the normal zone could be located ~1.6 m ($V_q * 0.6$ s + 0.6 m) after the joint outlet, i.e., near the peak field location.

On the other hand, the transit time of the helium from the temperature sensor TI712 to the peak field region is ~4.5 to 6.5 s. Therefore, we can trace back the inlet temperature to the approximate value, which was then transported downstream leading eventually to the normal zone initiation, see Fig. 6. This value can be estimated between 8.7 and 8.9 K. (Unluckily, we can only use the slow data acquisition system, because the fast acquisition of the temperature data had a lower accuracy.) This same test was repeated three times, confirming this range, with no apparent degradation so far within the available accuracy.

Starting from the range 8.7 to 8.9 K, the actual value of the temperature near the peak field region depends, as already noticed above, on several effects that may influence the temperature profile along the conductor:

1) *Heat generation in the joint*, which can be roughly estimated from the inlet and outlet temperature at 80 kA, before the heating starts [see Fig. 4(a) and (b)]. The total temperature increase due to joint heating (2 half-joints) in P1.2 is 0.25 K with a mass flow rate of ~14 g/s. With ~10 g/s [at the end of the heating, see Fig. 4(a) and (c)] this would correspond at 4.5 K to an increase of ~0.18 K after the joint, while this increase reduces to ~0.08 K at ~8.8 K.
2) *Heat transfer between P1.1 and P1.2 through the joint*. From analysis performed with the M&M code [13], the temperature reduction in P1.2 due to the heat transfer to the colder P1.1 [see Fig. 4(b)] is estimated to be ~0.05 K.
3) *Heat transfer to the radial plate*, which can be estimated from the total temperature decrease along the conductor in a shot without current (to exclude heat generation in the joint). This value, which includes the effect of heat transfer to the colder adjacent half-joint at the outlet of P2.1 (see Fig. 1), is ~1 K. The heat transfer in the outlet joint gives a temperature decrease of ~0.25 K (computed with M&M), so that the total decrease along the 82 m long P1.2, excluding the joint, is ~0.75 K. The temperature drop over the first few meters of conductor should thus be negligible.

Accounting for all these issues, the T_{cs} value, which can be estimated from experimental data only ($+$ a minimum of analysis mainly on heat exchange through the joints) is then between 8.7 and 8.9 K. This is very near to the expected $T_{cs,\min}^{conductor}$ as defined previously, and it is above the conservative estimate of the ITER design criteria (~8.2 K), where a longitudinal strain $\varepsilon = -0.61\%$ had been assumed for the conductor.

Finally, it may be noticed that the measured T_{cs} value is in good agreement with the prediction of a model [14] accounting for magnetic field nonuniformity on the cross section, when a uniform current distribution is present among the petals. This gives a first preliminary indication that in the TFMC the current distribution near current sharing in the peak filed region could be relatively uniform among the petals.

V. Conclusions

The T_{cs} at 80 kA has been successfully measured on the TFMC using a heating strategy (multi-step), which had been computationally studied before the tests. A quench was initiated in the P1.2 conductor as expected. The same strategy, as presented here, was successfully applied to the T_{cs} measurement at 69.3 kA (3/4 of the energy at peak current) and at 56.6 kA (1/2 of the energy at peak current), to be reported elsewhere.

Analysis indicates that the coil performed somewhat above the expectations of the design phase. This same test was repeated another three times at 80 kA, always ending with a quench of P1.2. The quench events did not cause any degradation of the T_{cs} of the coil conductor.

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