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Application of calorimetry to the assessment of the performance of ITER Nb$_3$Sn TF conductor samples in SULTAN tests

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Abstract

In the frame of the International Thermonuclear Experimental Reactor (ITER), several short full-size Nb$_3$Sn samples of candidate toroidal field (TF) conductors were tested in 2007 at the SULTAN facility, PSI Villigen, Switzerland, in conditions relevant to the ITER TF (background magnetic field of 10.78 T and transport current of 68 kA). The performance of a SULTAN sample is determined by the current sharing temperature $T_{CS}$. This can be obtained in principle from voltage measurements along the conductor sample, but the procedure is not free of issues and ambiguities. Here a complementary approach, based on the calorimetric assessment of the Joule heating due to current sharing, is critically discussed. Suitable algorithms are defined and the respective error bars are estimated, also based on numerical thermal–hydraulic modeling. The calorimetric approach is then applied to assess the performance of the samples tested in 2007 and compared with the results of the standard (electrical) approach.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Toroidal field (TF) conductor samples have been tested in the SULTAN facility (Villigen, Switzerland) for the last 10 years or so within the framework of the ITER R&D program. In particular, Nb$_3$Sn conductor samples of the ITER TF model coil were tested as early as 1999 (Ciazynski et al 2000); after testing the model coil (Savoldi et al 2002, Zanino and Richard 2003, Heller et al 2003, Ulbricht et al 2005) an attempt to compare the performance of short samples and model coils was also made (Zanino et al 2005).

In view of the performance degradation observed during these tests, compared with single strand measurements (Taylor and Hampshire 2005), a new R&D effort was launched using advanced (higher performance) strands in the similar conductor layout (Bruzzone et al 2008a), but this did not give the expected improvement in conductor performance (Ciazynski 2007). Since strand bending and pinching had meanwhile been identified as critical issues (Mitchell 2005, Nijhuis et al 2005), an improved conductor layout based on a lower void fraction and/or longer cabling twist pitches (see figure 1) was proposed (Nijhuis and Ilyin 2006) as a means of increasing the support for the strands thereby reducing the bending and the contact pressure.

During 2007 several short samples of ITER TF conductors were tested in SULTAN (Bruzzone et al 2008a, 2008b). The detailed geometrical and material data for all conductors discussed in this paper can be found in Bruzzone et al (2008b) and will not be repeated here. The main purpose of these tests, included in the so-called R&D ‘crash program’, was to see if the new cable layout could indeed improve conductor performance with respect to previously tested samples. Reference ITER-relevant conditions for the performance assessment were transport current $I_{\text{sample}} = I_{\text{ref}} = 68$ kA and external field $B_{\text{SULTAN}} = B_{\text{ref}} = 10.78$ T. Typically, the current was ramped up to $I_{\text{sample}}$ at $B_{\text{SULTAN}}$ inlet temperature $T_{\text{in}} = 4.5$ K, pressure $\sim10$ MPa and mass flow rate from 2 to 4 g s$^{-1}$; then $T_{\text{in}}$ was increased until quenching.
In view of the difficulties in the interpretation of voltage signals that often present a non-zero offset at the end of the current ramp (Bruzzone et al 2008a), as already noted in previous sample tests (Bruzzone et al 2007), a complementary calorimetric approach was proposed for the assessment of $T_{CS}$ (Bruzzone et al 2008b, Bessette and Mitchell 2008). This approach relies in principle on accurate and sufficiently detailed thermometry, as well as on steady-state operation—not always verified in practice (see table 1) although improved from test to test.

The two key measurements for calorimetry are obviously those of temperature and of mass flow rate. The mass flow rate is measured separately on each leg at the conductor outlet. The reference thermometer set-up, adopted for all samples tested in 2007 up to August, is shown in figure 2(a). Except for the inlet thermometers T1 and T2, all other thermometers were mounted on the conductor jacket. Since testing of all samples except JATF1 (Bessette and Mitchell 2008) was carried out with the central channel plugged in the high-field region, i.e. up to 1.5 m from the joint inlet (Bruzzone et al 2008b), this temperature should be to some extent representative of the temperature in the annular region occupied by the strands, in view also of the long timescales (quasi-steady-state) involved in most of these transients. In a couple of samples, additional thermometers (T7, T8) were mounted on the same cross section but opposite T5, T6, respectively. A re-test of the TFPRO2 and JATF2 samples was also performed, with the sample equipped with extended diagnostics (see figure 2(b)).

While scattered results of calorimetric analyses of single samples have been presented recently (Bruzzone et al 2008b, Kim et al 2008, Takahashi et al 2008) this paper represents, to the best of our knowledge, the first systematic attempt at a calorimetric analysis of the whole set of ITER TF samples tested in SULTAN during 2007.

2. The use of calorimetry for $T_{CS}$ assessment

The calorimetric estimate of the voltage across a reference length of conductor (control volume, CV) in the high-field region is given by

$$V_{\text{cal}} = \Phi/I_{\text{sample}}$$

where $\Phi$ is the Joule power generated inside the CV. When evaluating $T_{CS}$ by calorimetry, $\Phi$ has to be computed from measured temperatures, pressures and mass flow rates.

In SULTAN, the voltage threshold to be retained for the calorimetric definition of $T_{CS}$ is slightly higher than that used for the electrical one, since the distance $\Delta L_T = 500$ mm between the high-field thermometers (e.g. T3 and T5) is larger than the distance $\Delta L_V = 450$ mm between the reference voltage taps (e.g. V3 and V9). For an average electric field between the taps equal to the critical value $E_C = 10 \mu V \text{ m}^{-1}$, the voltage threshold for the electrical measurement ($=E_C \times \Delta L_V$) is $4.5 \mu V$. The Mithrandir code (Zanino et al 1995) was used to simulate a $T_{CS}$ measurement using for the cable n-index the ITER reference value of 7 (ITER 2004). A voltage $V_{\text{thres}} = 4.8 \mu V$ between the high-field thermometers was computed corresponding to the $4.5 \mu V$ between voltage taps. The non-negligible difference between these two voltages is due to the

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1. Another pair of voltage taps was present in the standard instrumentation but not shown in figure 2; they are also located across the high-field region, albeit only 350 mm apart (i.e. at a distance significantly shorter than the petal twist pitch).
Figure 2. SULTAN sample thermometry and reference voltage taps: (a) standard set-up, (b) enhanced diagnostics. The distribution of thermometers along the conductors/legs is shown in the left part of the figure, together with the He flow direction. The location of the thermometer on the conductor cross section is shown in the right part of the figure, together with transport current and external (SULTAN) magnetic field direction. Odd sensor numbers correspond to the left leg, even numbers to the right leg.

Figure 3. Spatial profile of the background magnetic field BSULTAN (thin solid line) and electric field (dashed line) computed along the conductor (left axis), and spatial profile of the computed strand temperature, for an average electric field of $10 \, \mu V/\text{m}^2$ between the voltage taps (right axis), in the case of transient inlet heating. The vertical solid and dashed lines indicate the position of the high-field voltage taps and thermometers, respectively. The zero abscissa is located at the joint inlet.

Profile of the background magnetic field along the conductor axis (see figure 3), still significantly high in the restricted space between voltage and temperature taps. The vertical solid and dashed lines indicate the position of the high-field voltage taps and thermometers, respectively. The zero abscissa is located at the joint inlet.

For the sake of simplicity, the specific enthalpy may be computed everywhere using the measured inlet pressure $\sim 1 \, \text{MPa}$, the dependence of enthalpy on pressure being very weak in the test conditions.
The main assumption behind (2) is that the CICC surface is adiabatic. For the limited purpose of improving the accuracy of the assessment of $T_{CS}$, the heat loss $W_{\text{cond}}$ was computed in a specific case using the Mithrandir code at the different plateau levels of a quasi-steady $T_{CS}$ scenario (see below); the interpolation of the results was then used to estimate $W_{\text{cond}}$ in all cases, at the different temperature levels. $W_{\text{cond}}$ increases with the increase of the inlet helium temperature, and at $T_{CS}$ it turns out to be $\leq 10\%$ of the Joule power. It should be noted that other authors (Bessette and Mitchell 2008, Kim et al. 2008, Bruzzone et al. 2008b, Takahashi et al. 2008) did not consider $W_{\text{cond}}$ in their assessment of $V_{\text{cal}}$, implicitly assuming it to be negligible.

The measured temperatures needed in (2) are assumed to be (1) sufficiently accurate and (2) representative of the whole flow cross section (which would be contradicted in the case of significant transverse temperature gradients). The former issue is addressed here by a procedure which we call, for the sake of simplicity, thermometer ‘recalibration’: by this we mean the compensation of the offsets measured in dedicated ‘baseline’ runs (see table 1) where the inlet helium temperature is increased according to a given pattern at $I_{\text{sample}} = 0 \text{kA}$ and $B_{\text{SULTAN}}^{\text{ref}}$. The uniform temperature over the cross section requires (at least) plugging the central channel (see table 1), but even in this case temperature gradients can arise in the annular region, as discussed in the next section.

While the mass flow rate is measured only at the outlet, its signal turns out to be approximately constant over a transit time, for the tests considered here. Therefore, we may assume $W_{\text{cond}}$ in their assessment of $V_{\text{cal}}$, implicitly assuming it to be negligible.

The recalibration of the thermometer was performed in this case through a dedicated quasi-steady or staircase baseline run, performed in thermal–hydraulic conditions relevant for the respective $T_{CS}$ tests, where the temperature profile along the conductor was measured at increasing inlet temperatures (see figures 4(b)–(d)). The procedure is based on the assumption that all (longitudinal and transverse) temperature gradients measured in the conductor in the absence of Joule heating ($I_{\text{sample}} = 0 \text{kA}$) can be treated as an offset, which is consistent with the adiabatic assumption above. Different temperature readings at different locations could be related, for instance, to the magneto-resistance of the sensors, as suggested in Calvi (2007).

After correcting the temperatures at zero external heating ($T_{\text{in}} \sim 4.5 \text{ K}$), the results of the baseline run for all samples tested with quasi-steady heating are summarized in figure 5 (the TFPRO2 re-test is discussed in a dedicated section below). The temperature differences $T_{5} - T_{3}$ and $T_{6} - T_{4}$, are always within $\pm 0.01 \text{ K}$; this may be compared with the measurement accuracy of $\pm 2 \text{ mK}$ on temperature differences (Bruzzone et al. 2007), which was well confirmed by the polarity checks performed during the TFPRO2 re-tests (see below). On the contrary, $T_{7} - T_{3}$ and $T_{8} - T_{4}$ significantly increase in modulus with increasing $T_{\text{in}}$. Furthermore, basically the same drift is obtained for both KOTF and RFTF1, for which the sensors are physically the same (detached from KOTF and reattached on RFTF1), thus confirming the non-physical nature of these differences.

The temperature differences in figure 5 can be fitted by least squares with a second-degree polynomial, and the following fits will be used as corrections of the raw temperature signals for the evaluation of the enthalpies in (3a): for JATF2 (subscript $J$) we find

$$T_{5\text{corr}} = T_{5} + m_{5} I_{1} (T_{3} - T_{30}) + m_{5} I_{2} (T_{3} - T_{30})^{2}$$

and for KOTF/RFTF1 (subscript KR)

$$T_{5\text{corr}} = T_{5} + m_{5} \text{KR} I_{1} (T_{3} - T_{30}) + m_{5} \text{KR} I_{2} (T_{3} - T_{30})^{2}$$

where $T_{30}$ and $T_{3}$ are the values of $T_{3}$ and $T_{4}$, respectively, before the inlet heating is turned on, and the coefficients of the fits are reported in table 2.

In the calibration runs, the computed $V_{\text{cal}}$ after the signal correction is on average 0, as shown in figures 6(b)–(d), confirming the adopted procedure.

$$\Phi = W_{\text{cond}} + \left( \frac{dm}{dt} \right) (h_{\text{out}} - h_{\text{in}}).$$

The whole recalibration procedure could be equivalently justified even if the conductor was not adiabatic, provided the heat sources/sinks were constant and in particular unaffected by the transport current and temperature increase: if the temperature differences are small enough, which is always verified in our case, these sources/sinks are canceled out by the recalibration of the sensor. The independence of heat sources/sinks on the temperature increase is verified a posteriori by the fact that the same recalibration fits hold in the whole temperature range of the baseline runs, thus confirming the absence of other temperature-dependent effects.
Figure 4. Evolution of the temperature (recalibrated signals) at the different sensor locations in the baseline runs (no transport current, reference background magnetic field) for the different samples: (a) TFPRO2 (transient), (b) JATF2, (c) KOTF and (d) RFTF1. A moving average on 50 points has been applied to the raw T signals.

Table 2. Coefficients of temperature calibration fits (4)–(9) for the samples JATF2, KOTF and RFTF1.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>JATF2</th>
<th>KOTF</th>
<th>RFTF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{51}$</td>
<td>0.0002</td>
<td>0.0037</td>
<td>0.0003</td>
</tr>
<tr>
<td>$m_{61}$</td>
<td>-0.0022</td>
<td>0.0235</td>
<td>-0.0018</td>
</tr>
<tr>
<td>$m_{71}$</td>
<td>NA</td>
<td>0.0192</td>
<td>-0.0008</td>
</tr>
<tr>
<td>$m_{81}$</td>
<td>NA</td>
<td>-0.0009</td>
<td>-0.0026</td>
</tr>
<tr>
<td>$m_{52}$</td>
<td>0.001</td>
<td>-0.0009</td>
<td>-0.0026</td>
</tr>
<tr>
<td>$m_{62}$</td>
<td>NA</td>
<td>NA</td>
<td>-0.0008</td>
</tr>
<tr>
<td>$m_{72}$</td>
<td>NA</td>
<td>NA</td>
<td>-0.0008</td>
</tr>
<tr>
<td>$m_{82}$</td>
<td>NA</td>
<td>NA</td>
<td>-0.0008</td>
</tr>
</tbody>
</table>

2.2. Transient heating

In this case, $dU/dt$ in (3a) cannot be neglected. Indeed, for the phases of the transient when $\Phi$ (and therefore $W_{\text{cond}}$) is negligible we get from (3a):

$$
\left( \frac{dU}{dt} \right)_{\text{CV}} \approx \left( \frac{dm}{dr} \right) (h_{\text{in}} - h_{\text{out}}) \approx \left( \frac{dm}{dr} \right) (h_{\text{in}} (t) - h_{\text{in}} (t - \Delta t)).
$$

(10)

The second approximation in (10) assumes the pure advection of the temperature along the conductor, where $\Delta t$ is the transport time between the two thermometers.

We now further assume that $dU/dt$ does not vary significantly when $\Phi$ (and $W_{\text{cond}}$) is $\neq 0$, i.e. that Joule heating (and conduction) contributes only to the enthalpy variation across the CV. Then we can use (10) as a rough estimate of $dU/dt$ for the whole transient and substitute into (3a) to obtain

$$
\Phi \approx W_{\text{cond}} + \left( \frac{dm}{dr} \right) (h_{\text{out}} (t) - h_{\text{in}} (t - \Delta t)).
$$

(11)

The error introduced by the assumptions leading to (11) from (3a) was estimated as $\sim 0.1$ K on $T_{\text{CS}}$ by means of a Mithrandir simulation of a transient $T_{\text{CS}}$ measurement with comparable $dT_{\text{in}}/dt$ as in the tests; the simulation results were then post-processed comparing the $T_{\text{CS}}$ computed by evaluation of the average voltage across the high-field region and by calorimetry.

Also in the transient case a thermometer recalibration is needed, and it can be performed using a transient baseline run, where the temperature gradients $T_5 - T_3$ and $T_6 - T_4$ are
monitored for continuously increasing inlet temperatures, at $I_{\text{sample}} = 0$ kA and $B_{\text{SULTAN}}$.

Among the samples for which a transient strategy had been applied for the $T_{\text{CS}}$ measurements, a dedicated (transient) baseline run was performed only in TFPRO2 (see figure 4(a)). The correction to be applied to T5, T6 has been computed in this case imposing $\Phi$, $W_{\text{cond}} = 0$ in (11). We get:

$$T_{\text{0corr}} = T_6 + m_6 \times (T_4 - T_4)$$

(12)

with $m_6 = 0.0055$, whereas no correction is needed for T5. This correction was validated in the first part of a $T_{\text{CS}}$ measurement at 40 kA ($T_4 < 6.5$ K), where $\Phi = 0$ on average was obtained (not shown), as expected.

No recalibration was possible on TFPRO1, since no dedicated baseline run was performed; the calorimetric analysis in that case therefore suffers from large uncertainties (Savoldi Richard and Zanino 2007).

3. Evaluation of uncertainties in the calorimetric estimation of $T_{\text{CS}}$

The recalibration procedure described above allows the reproduction of a zero voltage with zero transport current (see figure 6), with an accuracy on average better than $\pm 0.5$ $\mu$V. We will then consider this accuracy on the voltage as an indication of the typical error in the calorimetric assessment of $T_{\text{CS}}$. The effect of this error on the $T_{\text{CS}}$ error bar depends, however, on the conductor $n$-index, a lower $n$-index giving broader uncertainty on $T_{\text{CS}}$ (see below).

Two other issues affect the calorimetry and are addressed below$^4$. They are related to possible inhomogeneities on the conductor cross section of either: (A) the temperature (related to non-uniform heat generation inside the cable bundle region or at the joint, for example), or (B) the mass flow rate (related to the opening of a ‘third channel’ or gap in the cable bundle space due to the cable displacement driven by Lorentz forces in the high-field region, for example). These two items have been investigated using the $M^3$ code (Savoldi Richard et al 2007), which allows an arbitrarily refined discretization in the CICC cross section with respect to the limited number of cable components included in the Mithradir model.

3.1. Impact of temperature inhomogeneity on the cross section

When we reach $T_{\text{CS}}$ during the SULTAN tests, a temperature increase $\Delta T_{\text{crit}} \sim 20$ mK across the high-field region is expected for a mass flow rate of, say, 3 g s$^{-1}$, due to Joule heating $E_C \times \Delta L \times I_{\text{sample}}$. Therefore, as a rule of thumb, a maximum temperature inhomogeneity of, say, $\Delta T_{\text{crit}}/10$ (i.e. lower than a few mK) is required on the conductor cross section and along the conductor, far from $T_{\text{CS}}$, in order to apply (2) with acceptable accuracy. Transverse gradients would imply the need for different thermometers on the same cross section to accurately assess the average inlet and outlet enthalpies. Longitudinal gradients have to be excluded in the absence of Joule heating, unless they result from the downstream propagation of upstream transverse gradients, combined with the mismatch between pitch length of the petals and distance between the thermometers.

As already mentioned above, when testing KOTF and RFTF1 it was possible to check the temperature homogeneity on the conductor cross section, thanks to the presence of two opposite sensors downstream of the high-field region. Very good temperature homogeneity was recorded for both samples in the left legs. On the contrary, a temperature difference $> 20$ mK was measured for both right legs, already at the end of the current ramp and still before turning on the inlet heater, both between T6 and T8 and between T6 and T4. The temperature gradient, measured both on a cross section downstream of the high-field region and across the high-field region itself (while, the measured difference between T8 and T4 was one order of magnitude lower), could be due for instance to measurement errors or to non-uniform heating in the joint. However, there is no way to positively assess the reliability of either option. In this condition, the calorimetric analysis can lead to ambiguous results depending on which (combinations of) temperatures are chosen to compute the enthalpy at the CV outlet (see figure 7), which is unacceptable.

Therefore, a calorimetric assessment cannot be performed on these two conductors.

3.2. Impact of inhomogeneity of the mass flow rate on the cross section

Since the central channel is blocked in the considered CV, the whole flow is in the petals (the mass flow rate in the so-
Figure 6. Computed $V_{\text{cal}}$ in the baseline runs ($I_{\text{sample}} = 0$ kA, $B_{\text{SULTAN}} = B_{\text{ref}}$) for the different samples: (a) TFPRO2 (transient), (b) JATF2, (c) KOTF and (d) RFTF1. Although $I_{\text{sample}} = 0$ kA for these runs, we computed $V_{\text{cal}}$ here using (1) and $I_{\text{sample}} = I_{\text{ref}}$, in order to translate the error in the estimated power $\Phi_1$ into an estimate relevant for the voltage error assessment under reference $T_{\text{CS}}$ test conditions.

called triangles should be negligible here, in view of the high conduction compaction).

If a gap opens on the less loaded side of the conductor (Hamada et al 2004), where the magnetic field has its peak, the mass flow rate fraction in the petals decreases because of the reduced flow area. If the cable deforms elliptically, the re-partition of the total (imposed) mass flow rate between the gap and the petals can be computed analytically, relying, for example, on the Katheder correlation for the petal region and on the smooth tube correlation for the gap. The opening of a gap of $\sim 0.5$ mm (which would already be large, in view of the already high conductor compaction) may lead to a reduction of mass flow in the petals $< 10\%$ for a total mass flow rate $\sim 3$ g s$^{-1}$. The main effect on calorimetry is that only a (gap-dependent) fraction of the total mass flow rate is Joule heated, assuming that the gap flow channel is approximately adiabatic. The effect on the calorimetric assessment of $T_{\text{CS}}$ would be a maximum overestimation of $V_{\text{cal}}$ by $\sim 10\%$, i.e. less than 0.5 $\mu$V in the worst case, and the $T_{\text{CS}}$ computed neglecting this effect is in any case a conservative estimate.

However, the gap opening would affect the calorimetry only when the sensors located just downstream of the high-field region are used, while during the re-test of TFPRO2 the calorimetric exercise on the right leg shows that the $T_{\text{CS}}$ computed using the far-downstream sensors gives essentially the same results as that computed using the sensors closer to the high-field region (see below). This indicates that the error introduced by the opening of a third channel is de facto negligible, at least in the TFPRO2 case.

4. Results

The calorimetric approach is applied here systematically to the $T_{\text{CS}}$ assessment of the TF samples. Comparison between calorimetric and electrical characteristics is discussed. As for the latter, both raw data and ‘corrected’ characteristics in the form of the power law $V = V_0(T/T_{\text{CS}})^m$ (Bruzzone et al 2008b) are considered. For all cases of quasi-steady (staircase) heating, the calorimetric estimate of $T_{\text{CS}}$ is determined as the temperature at which the similar power law fit of the $V_{\text{cal}}$ data (plateau values) reaches the value $V_{\text{thres}}^{\text{cal}}$. In the case of transient heating, the whole calorimetric characteristic is directly computed.
Figure 7. VT characteristic of the $T_{CS}$ test at 1000 cycles, for (a) the KOTF sample, right leg and (b) the RFTF1 sample, right leg, respectively, from voltage taps (open circles) and reconstructed from calorimetry using T6 (open diamonds) and T8 (open squares) in the computation of the downstream enthalpy, respectively. The temperature in the abscissa is $T_{ave} = \frac{(T6 + T8)}{2}$ for the electrical characteristic, and T6 and T8, respectively, for the points reconstructed from calorimetry. The voltage corrected according to the recipe in Bruzzone et al (2008b) is also reported (thick dashed line), together with the fit of the (steady-state) calorimetry results (thin dashed-dotted line for calorimetry with T6 and thin dashed line for calorimetry with T8, respectively). The horizontal line corresponds to $V_{thres}$. The $T_{CS}$ value obtained by Bruzzone et al (2008b) is also reported (solid circle).

The $T_{CS}$ values obtained by the different methods and authors are summarized in table 3 at the end of this section. The comparison between electrical and calorimetric assessments can be used to estimate the uncertainty of the measurement (Bessette and Mitchell 2008).

The tests with the reference instrumentation are considered first. The calorimetric assessment of the TFPRO2 re-test with extended diagnostics is then briefly discussed, confirming the calorimetric analysis performed on the test with standard diagnostics. The JATF2 re-test is not considered here, since on this sample, as we shall see below, there is already a good agreement between our calorimetric assessment and (most of the) other authors, based on standard instrumentation only.

Figure 8. TFPRO2 OSTII (left) leg. VT characteristic of the $T_{CS}$ test at 1000 cycles, from voltage taps without corrections (thick solid line, obtained with a moving average on 50 points on raw $V$ and $T$ signals), from voltage corrected according to the recipe in Bruzzone et al (2008b) (thick dashed line) and reconstructed from calorimetry (thin solid line, obtained with a moving average on 50 points on raw $T$, $p$, $dm/dt$ signals and an additional moving average on 100 points on the resulting enthalpy differences). The $T_{CS}$ value obtained from calorimetry is indicated (solid diamond), together with its error bar, as well as the $T_{CS}$ value from Bruzzone et al (2008b) (solid circle). While the $T_{CS}$ values obtained from calorimetry and from electrical measurements are directly comparable, the electrical and calorimetric characteristics are not directly comparable because they refer to different conductor lengths.

Table 3. Results of the performance assessment of ITER TF short samples tested in 2007 in SULTAN.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Leg</th>
<th>Calorimetric</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFPRO2</td>
<td>OSTII</td>
<td>7.27 ± 0.10</td>
<td>7.33–7.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.30</td>
<td>6.60–6.50</td>
</tr>
<tr>
<td></td>
<td>OSTI (1st test)</td>
<td>5.66 ± 0.17</td>
<td>6.16–6.50</td>
</tr>
<tr>
<td>JATF2</td>
<td>JAB2</td>
<td>6.33 ± 0.11</td>
<td>5.50–6.40</td>
</tr>
<tr>
<td></td>
<td>JAI2</td>
<td>5.95 ± 0.07</td>
<td>5.77–5.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.8–6.1</td>
<td></td>
</tr>
<tr>
<td>KOTF</td>
<td>L</td>
<td>5.44 ± 0.08</td>
<td>5.45–5.50</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>5.50</td>
<td>5.65–5.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.45</td>
<td></td>
</tr>
<tr>
<td>RFTF1</td>
<td>L</td>
<td>6.03 ± 0.05</td>
<td>5.90</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>5.90</td>
<td>6.25</td>
</tr>
</tbody>
</table>

$^a$Bruzzone et al (2008b) and Bessette and Mitchell (2008) from voltage taps across the high-field region ($V/3 V/9$ or $V/10 V/4$).


$^c$Calorimetric assessment is unreliable in this case, see text.

4.1. Samples tested with ‘standard’ instrumentation

The electric results for the TFPRO2 OSTII (left) leg (Bruzzone et al 2008a) are confirmed by the (transient) calorimetric approach (see figure 8).
Figure 9. JATF2 sample, $VT$ characteristic of the $T_{CS}$ test at 1000 cycles, from voltage taps without corrections (open circles) and reconstructed from calorimetry (open diamonds), for the JAB2 (left) leg (a) and JAI2 (right) leg (b), respectively. The voltage corrected according to the recipe in Bruzzone et al (2008b) is also reported (thick dashed line), together with the fit of the (steady-state) calorimetry results (thin dashed line). The $T_{CS}$ value obtained from calorimetry is indicated (solid diamond), together with its error bar, as well as the $T_{CS}$ value from Bruzzone et al (2008b) (solid circle).

The (transient) calorimetry on the TFPRO2 OSTI (right) leg gives, for the $T_{CS}$ measurement at 1000 cycles, a slightly higher value than that computed from the electrical signals without correction. In both cases (measured and calorimetric voltage) the signal at the end of the ramp already shows some current sharing (not shown). Different corrections of the voltage signals, however, give much higher $T_{CS}$ values—compare Bruzzone et al (2008b) with Bessette and Mitchell (2008). The $T_{CS}$ value determined here by transient calorimetry is slightly below the calorimetric estimate in Bessette and Mitchell (2008), possibly because the transient contribution (as well as $W_{cond}$) in equation (3a) was neglected by those authors.

For JATF2, the calorimetry on the JAB2 (bronze route, left) leg gives a completely different picture from the raw electric signals (see figure 9(a)), where a voltage close to the $T_{CS}$ threshold was measured already at the end of the current ramp, but the resulting $T_{CS}$ is in very good agreement with the estimate from the corrected electrical characteristic (Bruzzone et al 2008b), as well as with the calorimetric estimate in Takahashi et al (2008). In contrast, the $T_{CS}$ deduced from the voltage signals in Bessette and Mitchell (2008) is almost 1 K below our calorimetric estimate.

In the JATF2 JAI2 (internal tin, right) leg (figure 9(b)), the $T_{CS}$ assessed by calorimetry is again in good agreement with the analysis of Takahashi et al (2008), but the error bar is smaller ($\pm 0.07$ K) than that in JAB2 in view of the larger $n$-index of the cable (see above). In both JATF2 legs, the $VT$ characteristic reconstructed from calorimetry foresees a voltage $<0.5 \mu V$ (i.e. zero within the error bar) at the end of the ramp, as a consequence of a temperature difference across the high-field region within $\sim 5$ mK. The absence of a significant offset at the end of the ramp supports the fact that T5 and T6 are representative of the average temperature on the conductor cross section, and that no significant Joule heating is present in the high-field region.
In the case of the KOTF sample, left leg, the raw voltage signal showed a very large and negative voltage at the end of the current ramp (see figure 10(a)). The $T_{CS}$ found here is again in good agreement with the corrected electrical assessment from Bruzzone et al (2008b) (see figure 10(a)), and also with Bessette and Mitchell (2008) and Kim et al (2008).

In the case of the RFTF1 sample, left leg (Shikov et al, 2008), where only a marginal difference between $T_5$ and $T_7$ (on the same cross section) was present, the calorimetric estimate supports the corrected electrical estimate from Bruzzone et al (2008b) (see figure 10(b)).

4.2. TFPRO2 re-test with enhanced instrumentation

In view of the difficulties in the interpretation of the $T_{CS}$ measurements in many tested samples, a new set of diagnostics was implemented on the TFPRO2 sample (whose left leg had shown outstanding performance during the first test), including both additional stars of voltage taps (Bessette 2007) and additional pairs of thermometers, located along the conductor as shown in figure 2(b) and mounted on the jacket on the two opposite sides of the magnetic load neutral line.

The thermometers just downstream of the high-field region, T6/T6a and T8/T8a for instance, are located at a distance of $\sim 1/6$ of the petal twist pitch length ($\sim 500$ mm in this case, according to the measurement performed at CRPP) from each other, so that they can be considered representative of the temperature of about four different petals. The same rationale is behind the choice of the location of the thermometers further downstream on the conductor (e.g. T10/T10a, T12/T12a).

With the aim of clarifying the error bars in the calorimetric assessment of $T_{CS}$, a careful check of the sensor precision (i.e. the measurement repeatability in the same operating conditions) was performed, varying the polarity of the sensor current. The accuracy of the sensor measurements (i.e. the capability of the temperature sensor to indicate the actual temperature) was assessed by measuring the drift with respect to temperature and magnetic field. Under the assumption that, in the absence of external heat sources, the temperature must be homogeneous in the conductor, the temperature drift can be compensated and the signals can be recalibrated, as already done above for the samples with standard instrumentation, and across longer sample lengths. In both cases an average of the four signals located at one-sixth of the petal pitch is used to obtain the outlet enthalpy, whereas the average between T4 and $S T_4a$ is used to obtain the inlet enthalpy.

The analysis of the TFPRO2 re-test results is reported in figure 11. First, it can be noted that the agreement between the voltage reconstructed from the two different sets of downstream sensors (T6/6a/8/8a and T10/10a/12/12a) is excellent. This confirms that, as expected, no significant voltage is generated in the sample outside the high-field region. Also, the raw (uncorrected) electrical and calorimetric characteristics are in much better agreement than in most of the cases above. The resulting value of $T_{CS}$ is also in very good agreement with the calorimetric evaluation of $T_{CS}$ in the first campaign, performed using the transient strategy (see above), thus confirming the validity of that approach at least for the present sample. A preliminary evaluation of the results of the enhanced electrical diagnostics also supports this result (Van Lanen and Nijhuis 2007).

5. Conclusions

A new generation of ITER TF conductor samples was tested in the SULTAN facility during 2007.
A calorimetric approach to the assessment of conductor performance has been described here in order to allow comparison with and support of the standard but sometimes controversial electrical assessment. The Mithrandir and $M^3$ codes have been used to estimate the error bars resulting from the assumptions underlying the calorimetric analysis. Typically, the accuracy of the $T_{CS}$ estimate turns out to be of the order of $\pm 0.1$ K.

The results of the present paper are summarized in table 3 and it may be recalled that the ITER criteria for TF conductors require a $T_{CS}$ of at least 5.7 K.

The best performing conductor, OSTII of TFPRO2, shows excellent agreement between electrical and calorimetric assessments. The other TFPRO2 (right) leg, OSTI, showed a significant disagreement between calorimetry and electrical assessments in the first tests. However, while the calorimetric assessment was confirmed in the re-test, the electrical assessment of $T_{CS}$ in the re-test shows excellent agreement with the calorimetry.

For the JATF2/JAB2 conductor the calorimetric and electrical assessments are again in very good agreement. For JATF2/JAB2 the calorimetric estimate supports the more optimistic of the electrical interpretations.

For the KOTF left leg, the calorimetric estimate confirms the electrical interpretations. In the case of the KOTF right leg, the presence of temperature non-uniformities on the cross section makes the applicability of calorimetry questionable.

For the RFTF1 left leg the calorimetric and electrical assessments are in borderline agreement. For the RFTF1 right leg a similar comment applies as for the KOTF right leg above.

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