Estimation of performance of Nb$_3$Sn CICC with thermal strain distribution

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Abstract. In the last few years, the critical temperature ($T_c$) of several ITER cable-in-conduit conductors (CICC) was determined by magnetization measurements at zero current. The distribution of the critical temperatures ($T_c$), caused by variation of strain in the Nb$_3$Sn strands, was found to vary with the number of load cycles. A comparison with mechanical modelling requires the strain distribution, while the $T_c$ distribution is sufficient to determine the CICC performance. The current sharing temperature ($T_{cs}$) is calculated supposing that the measured distribution of $T_c$ is representative of its variation along a single strand and that the current is uniformly distributed among the strands. The $T_{cs}$ values, found for background and peak magnetic field, are compared with the results of the DC test in the SULTAN facility. The presented estimation techniques lead to an overestimation of $T_{cs}$. The differences of the estimated and measured $T_{cs}$ values are discussed including the effect of different current-voltage characteristics of single strands and CIC conductors.

1. Introduction

For the design of cable-in-conduit conductors (CICCs), it would be desirable to know the relation between the strand and the cable properties. The uncertainty in the prediction of the performance of large Nb$_3$Sn CICCs made it necessary to qualify each of the ITER (International Experimental Thermonuclear Reactor) conductors by tests in the SULTAN (SUPraLeiterTestANlage German acronym for superconductor test facility) facility. In contrast to Nb-Ti, the critical current density of Nb$_3$Sn depends not only on field and temperature but also on the intrinsic strain experienced by the superconducting filaments. Furthermore, Nb$_3$Sn is a brittle material susceptible to filament breakages, when the tensile strain exceeds a certain limit ($\epsilon_{irr}$).

It is always possible to explain the measured initial cable performance by a supposed value of the thermal strain and a load dependent extra strain. However, the test of large Nb$_3$Sn CICCs indicated that cyclic loading, performed by ramping up and down the conductor current in the high background field of the SULTAN facility, led in some of the conductors to a decrease of the current sharing temperature ($T_{cs}$). The conductor performance was also found to depend on the number of warm-up and cool-down (wucd) cycles. Furthermore, the width of the transition in Nb$_3$Sn cables, described by the power law $E = E_c (I/I_c)^n$ ($E$ electric field, $E_c = 0.1 \mu V/cm$, $I$ operation current, $I_c$ critical current) defining the $n$ factor, was found to be broadened (i.e. reduced $n$ factor) in comparison with the behavior of single strands. It should be noted that the $n$ factor of Nb-Ti CICC is comparable to that of the strands [1]. The prediction of the CICC performance suffers from the not exactly known thermal
strain, strain distribution and the difficulty to distinguish between reversible strain effects and an irreversible degradation.

Mechanical modelling provided first evidence that there exists a distribution of thermal strains in CICCs [2]. Measurements of the cable critical temperature \( T_c \), performed at the Swiss Plasma Center (SPC) [3], [4], [5], [6], are in line with the existence of a \( T_c \) distribution caused by a distribution of the thermal strain. Details of the susceptibility measurements and the procedure to find the \( T_c \) distribution are described in [3], [4]. The determination of the thermal strain distribution requires the knowledge of the scaling of the critical current density of the Nb₃Sn strands with temperature, field and strain.

2. Scaling relation for the critical current of Nb₃Sn

The critical current density of Nb₃Sn strands depends on temperature, magnetic field and the intrinsic strain experienced by the superconducting filaments. One of the most important results is the fact that the dependence of the normalized pinning force \( F_p = j_c \times B = C \ g(\varepsilon) \ h(t) \ f_0(b) \) can be represented in a form in which the dependencies on temperature, field and strain are separable [7]. Here, \( j_c \) is the critical current density, \( B \) the magnetic field and \( C \) a constant. The function \( g \) depends only on the intrinsic strain \( \varepsilon \), \( h \) only on the reduced temperature \( t \) and \( f_0 \) only on the reduced field \( b \).

Different parametrizations, proposed by Ekin [8], Durham University [9] and Twente University [10], [11], are compared in [12]. In the ITER project, a modified version of the Twente scaling is used to describe \( j_c(T,B,\varepsilon) \) [12]. The scaling relations for the critical surface are

\[
I_c(T, B, \varepsilon) = \frac{C_1}{B} \cdot s(\varepsilon) \cdot (1-t^{1.52}) \cdot (1-\varepsilon^2) \cdot b^p \cdot (1-b)^q \tag{1}
\]

where \( t = T/T_c(\varepsilon) \) is the reduced temperature, \( b = B/B_{c2}(T,\varepsilon) \) the reduced magnetic field, \( s(\varepsilon) \) the strain function, \( C_1 \) a constant and \( p \) and \( q \) the low and high field exponent of the pinning force. Equation (2) provides the dependence of the upper critical field \((B_{c2})\) on strain and temperature while equation (3) indicates the strain dependence of \( T_c \).

\[
B_{c2}(T, \varepsilon) \approx B_{c2m}(0,0) \cdot s(\varepsilon) \cdot (1-t^{1.52}) \tag{2}
\]

\[
T_c(\varepsilon) = T_{cm}(0) \cdot s(\varepsilon)^{1/2} \tag{3}
\]

where \( B_{c2m}(0,0) \) is the maximum value of \( B_{c2} \) at \( T = 0 \) and \( \varepsilon = 0 \), while \( T_{cm}(0) \) is the maximum value of \( T_c \) at zero strain and the strain function can be expressed as

\[
s(\varepsilon) = 1 + \frac{C_{a1} \left( \sqrt{\varepsilon_s^2 + \varepsilon_{0a}^2} - \sqrt{(\varepsilon - \varepsilon_s)^2 + \varepsilon_{0a}^2} \right) - C_{a2} \cdot \varepsilon}{1 - C_{a1} \cdot \varepsilon_{0a}} \tag{4}
\]

with

\[
\varepsilon_s = \frac{C_{a2} \cdot \varepsilon_{0a}}{\sqrt{C_{a1}^2 - C_{a2}^2}} \tag{5}
\]

Here, \( C_{a1} \) and \( C_{a2} \) are strain fitting constants, \( \varepsilon_{0a} \) is the residual strain component and \( \varepsilon_{in} \) the tensile strain at which the maximum critical current is reached.

Susceptibility measurements of several cable-in-conduit conductors provided the critical temperature and the broadening of the transition caused by a distribution of the thermal strain. The
measurement of the $T_c$ of free standing filaments is used as an estimation of $T_{cm}(\varepsilon = 0)$. For each value of $T_c(\varepsilon)$, the strain function $s(\varepsilon)$ can be written as

$$s(\varepsilon) = \left( \frac{T_c(\varepsilon)}{T_{cm}(0)} \right)^3$$

(6)

The strain dependencies of the upper critical field and the critical current can be expressed implicitly using the ratio of $T_c(\varepsilon)$ to $T_{cm}(0)$.

$$B_{c2}(T,\varepsilon) = B_{c2m}(0,0) \left( \frac{T_c(\varepsilon)}{T_{cm}(0)} \right)^3 (1-t^{1.52})$$

(7)

$$I_c(B,T,T_c(\varepsilon)) = C_1 \left( \frac{T_c(\varepsilon)}{T_{cm}(0)} \right)^3 (1-t^{1.52})(1-t^2)b^p(1-b)^q$$

(8)

The strand scaling parameters of all studied CICCs are listed in table 1. The value of the constant $C_1$ has been adapted to the witness strand results assuming an intrinsic strain of -0.15% for the measurements on ITER barrels. The left leg of CSJA5 L is made of Hitachi strands, while the right leg CSJA5 R uses Furukawa strands. The strands of TFCN4, TFKO4 and TFRF4 were manufactured by Western Superconducting Technologies (WST), Korea Advanced Technology (KAT) and Bochvar, respectively. In the nomenclature, CS indicates a conductor for the central solenoid, while TF represents a conductor for the toroidal field coil. The conductors were supplied by the Chinese (CN), Japanese (JA), Korean (KO) and Russian (RF) Domestic Agencies.

**Table 1.** Strand scaling parameters of the studied CICCs.

| Parameter          | CSJA5 L | CSJA5 R | TFCN4 | TFKO4 | TFRF4 |
|--------------------|---------|---------|-------|-------|-------|
| $C_1$ (A T)        | 39971   | 40435   | 20571 | 36621 | 14126 |
| $C_{a1}$           | 35.12   | 51.30   | 47.52 | 70.28 | 49.62 |
| $C_{a2}$           | 0.254   | 14.90   | 0.00  | 32.91 | 9.51  |
| $\varepsilon_0$    | 0.00218 | 0.00163 | 0.00218 | 0.0034 | 0.00259 |
| $\varepsilon_0$    | 0.00383 | 0.00163 | -0.00067 | 0.0044 | -0.00110 |
| $B_{c2m}(0,0)$ (T) | 31.49   | 28.88   | 34.22 | 31.58 | 29.52 |
| $T_{cm}(0)$ (K)    | 16.28   | 16.24   | 16.26 | 15.95 | 16.62 |
| $p$                | 0.99    | 0.856   | 0.578 | 0.827 | 0.519 |
| $q$                | 2.57    | 2.146   | 2.211 | 2.488 | 1.662 |

3. **Estimation of CICC critical current**

3.1. Measured $T_c$ distributions

For the CSJA5 SULTAN sample, the critical temperature was measured for the initial state and after 3950 load cycles, 5970 load cycles plus one warm-up and cool-down (wucd) and finally after 7920
load cycles and two wucds. The $T_c$ distributions for the two conductor legs, made of different strands, which have been extracted from the measurements [3] are shown in figure 1. The mean values of $T_c$, defined as $T_{c,\text{mean}} = \Sigma f(T_c)T_c$ (here $f(T_c)$ is the probability to find $T_c$ in the measured cable cross-section), are listed in table 2. In both conductor legs, cyclic loading leads to an increased mean value of $T_c$, while the width of the distribution is only weakly affected.

The $T_c$ distributions found for the two legs of TFCN4 are presented in figure 2. For the left leg, the $T_c$ distribution after 1000 load cycles and an additional warm-up and cool-down is significantly broadened, while the effect is much less pronounced for the right leg. In the left leg the mean $T_c$ is reduced from 17.28 to 17.14 K, while it is slightly enhanced from 17.14 K to 17.19 K in TFCN4 R.

The $T_c$ distributions found for the right legs of TFKO4 and TFRF4 are shown in figures 3 and 4, respectively. For TFKO4, the $T_c$ distribution is shifted to lower values and slightly more broadened after 1000 load cycles. The mean $T_c$ values found before and after cyclic loading are 17.30 and 17.19 K, respectively. The wucd leads to a pronounced further broadening of the $T_c$ distribution, while $T_{c,\text{mean}}$ of 17.22 K is not much changed. The initial $T_c$ distribution of TFRF4 is narrower than that after 1000 load cycles and an additional wucd. However, the mean $T_c$ increases from 17.21 to 17.45 K due to the load and thermal cycles.

![Figure 1](attachment:image1.png)

**Figure 1.** Distributions of $T_c$ of CSJA5 sample before and after cyclic loading (adapted from [3]).

![Figure 2](attachment:image2.png)

**Figure 2.** Distributions of $T_c$ of TFCN4 sample before and after cyclic loading (adapted from [3]).
Figure 3. Distributions of $T_c$ of TFKO4 sample before and after cyclic loading (adapted from [3]).

Figure 4. Distributions of $T_c$ of TFRF4 sample before and after cyclic loading (adapted from [3]).

Table 2. Mean values of $T_c$ found from the $T_c$ distribution, the full width at half maximum (FWHM) of the distribution and the $T_c$ values of free-standing filaments.

| Conductor       | Cycle | Mean $T_c$ (K) | FWHM (K) | $T_c$ (filaments) (K) |
|-----------------|-------|----------------|----------|-----------------------|
| CSJA5 L Hitachi| 1     | 17.08          | 0.65     | 17.80                 |
|                 | 3950  | 17.27          | 0.50     |                       |
|                 | 5870 + wucd | 17.26      | 0.60     |                       |
|                 | 7920 + 2 wucd | 17.27      | 0.58     |                       |
| CSJA5 R Furukawa| 1     | 17.44          | 0.54     | 18.05                 |
|                 | 3950  | 17.55          | 0.51     |                       |
|                 | 5870 + wucd | 17.55      | 0.62     |                       |
|                 | 7920 + 2 wucd | 17.55     | 0.62     |                       |
| TFCN4 L         | 1     | 17.28          | 0.52     | 17.75                 |
|                 | 1000 + wucd | 17.12      | 1.20     |                       |
| TFCN4 R         | 1     | 17.14          | 0.79     | 17.75                 |
|                 | 1000 + wucd | 17.19     | 0.80     |                       |
| TFKO4 R         | 1     | 17.30          | 0.61     | 17.69                 |
|                 | 1000  | 17.19          | 0.66     |                       |
|                 | 1000 + wucd | 17.22    | 0.82     |                       |
| TFRF4 R         | 1     | 17.21          | 0.71     | 17.81                 |
|                 | 1000 + wucd | 17.45    | 0.83     |                       |

3.2. Estimation of the critical current using mean value of $T_c$

The extracted mean $T_c$ can be used to estimate the critical current or the current sharing temperature of the conductor in question. The ratio of the mean value of $T_c$ to the measured $T_c$ of the free standing...
filaments, which is considered as an estimate of $T_{cs}(0)$, provides $s(\varepsilon) = (T_{\text{c,mean}}/T_{\text{cs}}(0))^3$. Using equations (7) and (8) and the scaling parameters $C_1$, $B_{2\text{cs}}(0,0)$ and $T_{\text{cs}}(0)$, provided in table 1, the critical current per strand can be estimated.

Variation of $T$ until $I_c$ equals the average strand current in the $T_{cs}$ measurement provides an estimation of the current sharing temperature of the cable. The results are presented in Section 4. This estimation ignores the effects of the broadness of the transition characterized by the $n$ factor in an $I_c$ measurement and the $m$ factor in a $T_{cs}$ measurement ($E = E_c (T/T_{cs})^{m}$).

3.3. Estimation of $T_{cs}$ using the measured $T_c$ distribution

Next, we take into account both, the $T_c$ distribution and the width of the transition. In an $I_c$ measurement the evolution of the electric field close to the transition is well described by the power law $E = E_c (I/I_c)^n$, where $E_c$ is the criterion used to define $I_c$. Empirically it was found that the $n$ factor is mainly a function of the critical current. This means that the $n$ factor is the same for different combinations of $T$, $B$ and $\varepsilon$ leading to the same value of $I_c$ [13]. Typically, the dependence of $n$ on $I_c$ can be well represented by the scaling relation $n = 1 + r I_c^2$. In figure 5, the relation between $n$ and $I_c$ is shown for the Hitachi witness strands of CSJA5 L. The values of $r$ and $k$ of the considered strands are provided in table 3. The measured $n$ factors of the CICC in question are also listed in table 3.

| Strand            | $r$  | $k$  | Number of strands | $n$ (cable) | $I_c$ (cable) (kA) |
|-------------------|------|------|-------------------|-------------|-------------------|
| CSJA5 L Hitachi   | 3.098| 0.466| 576               | 12.2        | 35.1              |
| CSJA5 R Furukawa  | 6.498| 0.376| 576               | 12.5        | 39.2              |
| TFCN4             | 3.291| 0.416| 900               | L 16.6 R 16.8| L 56.5 R 54.0    |
| TFKO4             | 3.436| 0.401| 900               | 16.9        | 57.8              |
| TFRF4             | 14.91| 0.154| 900               | 9.9         | 63.9              |

Table 3. Scaling parameters for the relation between the $n$ factor and $I_c$. The measured initial cable $n$ factors are also provided.

The measurement of $T_{cs}$ is used to characterize the performance of the SULTAN samples. In figure 6, the electric field versus temperature data of CSJA5 are presented. The measured data can be well described by the power law $E = E_c (T/T_{cs})^m$. In both conductor legs, the $m$ factor decreases with increasing number of load and thermal cycles. As an example the estimation of the initial performance of the left leg of CSJA5 is described. The estimation assumes insulated strands and a uniform current distribution among the strands. Furthermore, it is supposed that the probability to find a value of $T_c(\varepsilon)$ along the length of each strand is the same as the measured probability $f(T_c)$ measured in a single cross-section. In the estimation of the CICC performance, we are facing the problem that the parameters of the Twente scaling relation are found from transport measurements, whereas the $T_c$ distribution is obtained from magnetization measurements. The two different types of measurements may lead to systematic differences in the $T_c$, and hence $T_c$ values, obtained from different types of measurements, should not be used in one $T_c$ ratio. In our analysis, the magnetization measurements of $T_c$ of the cable and the free-standing strands are only used to determine the values of the strain function $s(\varepsilon) = (T_c(\varepsilon)/T_c(\text{filaments}))^3$, whereas the values of the reduced temperature in equations (7) and (8) are based on the scaling parameter $T_{cs}(0)$ quoted in table 1.

The $T_c$ distributions, presented in figures 1 to 4, do not include a possible contribution of the Lorentz force to the strain distribution, and hence to the $T_c$ distribution. Moreover, the entanglement of field and strain distributions is not known, which may be different at the low-field, high-load side and the high-field, low-load side. For simplicity, $T_{cs}$ is estimated supposing a constant magnetic field in the
cross-section. Estimations have been performed for the SULTAN background field \( B_b \) and the peak magnetic field \( B_p \) including the contributions of the self-field and the return conductor (see e.g. [1]).

The electric field along each strand is \( E = \sum f(T_c) E_c \left( \frac{I_{	ext{strand}}}{I_c(T_c)} \right)^m \), where \( E_c = 0.1 \mu \text{V/cm} \). In case of CSJA5, \( B_b = 10.85 \text{T} \), \( B_p = 11.656 \text{T} \) and \( I_{	ext{strand}} = 78.3 \text{A} \). The \( E-T \) characteristic has been calculated for different ratios of \( n_{	ext{cable}}/n_{	ext{strand}} \). A fit to the calculated \( E-T \) characteristic provides the \( m \) factor. The \( m \) factors obtained for the initial performance of CSJA5 L are presented in figure 7. The blue line indicates the \( m \) factor found in the SULTAN test. Using \( n \) factors of 0.34 \( n_{	ext{strand}} \) for \( B_b \) and 0.4 \( n_{	ext{strand}} \) for \( B_p \) the \( m \) factor, found from the simulation, equals the measured value.

**Figure 5.** Index of resistive transition \( n \) versus \( I_c \) of the Hitachi witness strands used for the left leg of CSJA5.

**Figure 6.** Measured electric field versus temperature curves of left and right leg of CSJA5 sample. The fit lines are based on a power law dependence \( E = E_c \left( \frac{T}{T_{cs}} \right)^m \).

**Figure 7.** Dependence of the \( m \) factor, found from the simulation, on the ratio \( n_{	ext{cable}}/n_{	ext{strand}} \).

**Figure 8.** Dependence of the \( T_{cs} \), found from the simulation, on the ratio \( n_{	ext{cable}}/n_{	ext{strand}} \).
Figure 9. Comparison of the initial electric field versus temperature characteristics of CSJA5 found from a simulation with $n_{\text{cable}} = 0.4$, $n_{\text{strand}}(I_c)$ and a calculation using $n_{\text{cable}} = 12.2$ independent of $I_c$.

The $T_{cs}$ values estimated for the initial performance of CSJA5 L are shown in figure 8. The presented data indicate that the value of the estimated $T_{cs}$ depends weakly on the ratio $n_{\text{cable}}/n_{\text{strand}}$. The estimated $T_{cs}$ values for $B_b$ and $B_p$ are 7.87 and 7.24 K, respectively, as compared to 6.87 K (blue line) obtained from the SULTAN test.

In a second estimation, the $n$ factor of 12.2, found from the SULTAN test, is used to estimate $T_{cs}$. For simplicity, the $I_c$ dependence of $n$ is omitted, i.e. $n = 12.2$ independent of $I_c(T_c)$. The results of the two different estimations for $B_p$ are compared in figure 9. The use of the measured cable $n$ factor leads to a slightly lower $T_{cs}$ of 7.16 K than the use of 0.4 $n_{\text{strands}}$. The $m$ factor of 51.8, obtained from an estimation using the measured cable $n$ factor, is significantly larger than the measured $m$ factor of 34.7.

4. Results and discussion

In figure 10, the results of different estimations of $T_{cs}$ using the peak field are presented for the two legs of CSJA5. In both legs, strain relaxation leads to an increase of the measured $T_{cs}$ for increasing number of load cycles. All estimations suggest that the $T_{cs}$ after cyclic loading is increased, which is in line with the trend found from the SULTAN test. However, even for the peak magnetic field the estimated $T_{cs}$ values are higher than the measured values. The highest values are provided by an estimation based on the mean $T_c$ value. For the left leg, the $T_{cs}$ measured after 7920 cycles and two wucds is 7.06 K, while an estimation based on the mean $T_{cs}$ leads to a value of 7.92 K. The lowest $T_{cs}$ value of 7.55 K is obtained from the use of the $T_c$ distribution and the measured cable $n$ factor. The estimated $T_{cs}$ exceeds the measured one by around 0.5 K. An estimation based on the background field and the measured cable $n$ factor provides a $T_{cs}$ of 8.12 K, more than 1 K higher than the measured value (see table 4). For the right leg, the measured $T_{cs}$ after cyclic loading is 7.4 K, while the estimation using $B_p$ and the measured cable $n$ factor leads to 7.96 K, which is 0.56 K higher than the measured value. For $B_b$ the estimation provides a $T_{cs}$ as high as 8.51 K (see table 4). The gap between measured and estimated $T_{cs}$ values is in both legs comparable.

In figure 11, the results for both legs of TFCN4 are presented. The initial $T_{cs}$ values of 6.55 K for the left and 6.58 K for the right leg are nearly identical. The estimation, based on $B_p$, the cable $n$ factor and the $T_c$ distribution, provides $T_{cs}$ values of 8.07 K (left leg) and 7.59 K (right leg). The difference of estimated and measured $T_{cs}$ is as large as 1.52 K for the left leg, while it is 1.01 K for the right leg. For the left leg, the estimated $T_{cs}$ after cyclic loading is reduced to 7.12 K, while the measured value is 6.35 K. In line with the experimental data, $T_{cs}$ decreases with cyclic loading, however, the effect is much more pronounced in the simulation. The measured $T_{cs}$ of the right leg decreases by 0.31 K, whereas the estimated value based on $B_p$ and the cable $n$ factor, increases by 0.1 K, i.e. the difference of the measured and estimated $T_{cs}$ after cyclic loading is 1.42 K.
Figure 10. Comparison of measured and estimated $T_{cs}$ values of CSJA5 before cyclic loading and after 3950 cycles, 5870 cycles plus warm-up and cool-down and 7920 cycles plus in total two warm-up and cool-down cycles. The left panel shows the data for the left leg, made of Hitachi strands, while the right panel provides the results for the right leg, made of Furukawa strands.

The results for the right leg of TFKO4 are shown in figure 12. The initial $T_{cs}$ of 6.89 K drops to 6.6 K after 1000 load cycles plus wucd. The estimation, based on $B_p$ and the cable $n$ factor provides 7.68 K before cyclic loading and 7.39 K after cycling. The corresponding differences of measured and estimated $T_{cs}$ values are 0.79 K for both, the initial and the final performance. This means that measured and simulated changes in $T_{cs}$ are identical.

The current sharing temperatures of the right leg of TFRF4 are provided by figure 13. Due to cycling the measured $T_{cs}$ increases from 5.92 K to 6 K, while the estimation, based on $B_p$ and the cable $n$ factor, provides an increase of $T_{cs}$ from 7.43 to 7.7 K. Again the estimated $T_{cs}$ value is significantly larger than the measured one, leading to a difference of 1.7 K after cycling. The estimated increase of $T_{cs}$ due to strain relaxation is 0.29 K larger than the measured one.

Figure 11. Comparison of measured and estimated $T_{cs}$ values of TFCN4 at 68 kA and 10.78 T before cyclic loading and after 1000 load cycles plus an additional warm-up and cool-down. The left panel shows the results for the left leg, while the right panel provides the data for the right leg.
The results of estimations using the background field are summarized in table 4. Besides the estimated current sharing temperature the values of the ratio of \( n_{\text{cable}}/n_{\text{strand}} \) or the measured cable \( n \) factor used in the estimations are listed.

In general, the estimations of \( T_{cs} \) presented in this work overestimate the performance of the considered CIC conductors. An estimation of \( T_{cs} \) based on the mean value of \( T_c \) leads to the highest overestimation of the current sharing temperature. The use of the measured cable \( n \) factor and the observed \( T_c \) distribution leads to the smallest difference of estimated and measured \( T_{cs} \) values. However, this procedure leads to an overestimation of the cable \( m \) factor. A simulation using a ratio of \( n_{\text{cable}} \) to \( n_{\text{strand}} \) including variation of \( n_{\text{strand}} \) with \( I_c \), which reproduces the measured \( m \) factor, leads to \( T_{cs} \) values between the two extremes.

A further piece of information is the variation of \( T_{cs} \) with cycling. Except for the right leg of TFCN4, the estimated \( T_{cs} \) shows the same trend (increase or decrease) as the measured \( T_{cs} \). A comparison of the changes of the measured initial and final \( T_{cs} \) with the estimation based on the cable \( n \) factor, the \( T_c \) distribution and the background field (see table 4) indicates that for CSJA5 L the measured value increases by 0.19 K, while the estimation provides an enhancement of 0.37 K. For CSJA5 R, the measured change in \( T_{cs} \) of 0.19 K is even closer to the \( \Delta T_{cs} \) of 0.25 K found from the estimation. In case of TFKO4 both, the measured and the estimated change in \( T_{cs} \), is -0.29 K. The estimated increase of the \( T_{cs} \) of TFRF4 due to strain relaxation is 0.25 K as compared to the measured change of 0.08 K. A considerable discrepancy of measured and estimated changes in \( T_{cs} \) has been found for TFCN4. The test provides a reduction of \( T_{cs} \) after cycling of -0.2 and -0.31 K for the left and right leg, respectively. The estimated change of \( T_{cs} \) is -0.9 K for the left leg and +0.1 K for the right leg.

A possible explanation for the overestimated performance could be an additional strain contribution caused by the Lorentz force, which is always present in the SULTAN \( T_{cs} \) measurement and absent in the measurement of \( T_c \) distribution used in the \( T_{cs} \) estimation. The variation of the magnetic field within the conductor cross-section has a significant impact on the estimated \( T_{cs} \) values as can be seen from the differences found for calculations using the background or the peak field. In addition, the \( T_c \) distribution may vary along the length of the conductor in the high field zone. A main problem in the estimation of the current sharing temperature is the broadened transition in the cable, i.e. reduced \( n \)
and $m$ factors. The reduction of the cable $n$ factor can be caused by redistribution of current among the strands and/or irreversible degradation of the strands accompanied by reduced $n$ factors. For CSJA5, showing an improvement of $T_{cs}$ with cyclic loading, the probability for strand degradation is expected to be much smaller than in conductors showing cyclic load degradation. The difference of estimated and measured $T_{cs}$ is smallest for this conductor. For all TF conductors, the difference of estimated and measured $T_{cs}$ is significantly larger than for CSJA5 (see figure 14). A strand degradation cannot be excluded for the TF conductors.

**Table 4.** Results of the estimations using the background field of 10.85 T for CS conductors and 10.78 T for TF conductors.

| Conductor | Cycle | $T_{cs}$ (K) (test) | $n$ (test) | $T_{cs}$ (K) (mean $T_{c}$) | $T_{cs}$ (K) ($n$ test) | $T_{cs}$ (K) | $n_{cable}/n_{strand}$ |
|-----------|-------|---------------------|------------|-----------------------------|-------------------------|-------------|-------------------------|
| CSJA5 L   | 1     | 6.87                | 12.2       | 8.13                        | 7.75                    | 7.87        | 0.34                    |
| 3950      |       | 7.00                | 11.1       | 8.47                        | 8.22                    | 8.30        | 0.30                    |
| 5870 + wucd |     | 7.05                | 10.8       | 8.46                        | 8.07                    | 8.19        | 0.30                    |
| 7920 + 2wucd |    | 7.06                | 10.8       | 8.47                        | 8.12                    | 8.24        | 0.29                    |
| CSJA5 R   | 1     | 7.21                | 12.5       | 8.62                        | 8.26                    | 8.37        | 0.20                    |
| 3950      |       | 7.35                | 10.3       | 8.81                        | 8.56                    | 8.65        | 0.18                    |
| 5870 + wucd |     | 7.40                | 9.8        | 8.81                        | 8.51                    | 8.60        | 0.18                    |
| 7920 + 2wucd |    | 7.40                | 10.0       | 8.81                        | 8.51                    | 8.60        | 0.175                   |
| TFCN4 L   | 1     | 6.55                | 16.8       | 8.85                        | 8.57                    | 8.72        | 0.27                    |
| 1000 + wucd |       | 6.35                | 10.2       | 8.54                        | 7.67                    | 8.08        | 0.22                    |
| TFCN4 R   | 1     | 6.58                | 16.6       | 8.57                        | 8.11                    | 8.36        | 0.35                    |
| 1000 + wucd |       | 6.27                | 9.7        | 8.65                        | 8.21                    | 8.46        | 0.22                    |
| TFKO4 R   | 1     | 6.89                | 16.9       | 8.71                        | 8.21                    | 8.47        | 0.33                    |
| 1000      |       | 6.59                | 12.3       | 8.52                        | 8.00                    | 8.33        | 0.22                    |
| 1000 + wucd |       | 6.60                | 12.2       | 8.57                        | 7.92                    | 8.28        | 0.22                    |
| TFRF4 R   | 1     | 5.92                | 9.9        | 8.37                        | 8.01                    | 8.20        | 0.16                    |
| 1000 + wucd |       | 6.00                | 8.7        | 8.80                        | 8.26                    | 8.64        | 0.085                   |

**Figure 14.** Estimated $T_{cs}$ versus measured $T_{cs}$. Current sharing temperatures of TF conductors (squares) are much more overestimated than those of CSJA5 (triangles). The estimation is based on peak field and the measured cable $n$ factor.
5. Conclusion

The presented estimations overestimate the performance of the considered CIC conductors. The trends for the changes in $T_{cs}$ are typically in line with the measured data. However, the estimated changes in $T_{cs}$ are typically larger than the measured ones. The results suggest that the knowledge of the $T_c$ distribution, caused by thermal strain distribution, provides only an incomplete characterization of Nb$_3$Sn cable-in-conduit conductors. The overestimation of the conductor performance may be partly caused by the unknown contribution of the Lorentz force to the strain experienced by the Nb$_3$Sn strands during the $T_{cs}$ measurement. Moreover, the transition in cable-in-conduit conductors is broadened, reflected by a reduced $n$ or $m$ factor, which needs to be taken into consideration in an estimate of the cable performance. Finally, the $T_c$ of the Nb$_3$Sn strands is not only broadened because of the strain distribution but also susceptible to variations of the Sn concentration in the Nb$_3$Sn filaments [14] possibly affecting the estimation of the strain function.

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References

[1] Wesche R, Anghel A, Stepanov B, Vogel M and Bruzzone P, 2005 Cryogenics 45 755
[2] Bajas H, Durville D and Devred A, 2012 Supercond Sci. Technol. 25 054019
[3] Calzolaio C, 2013 Irreversible degradation of Nb$_3$Sn Cable in Conduit Conductors Thèse No. 5292 École Polytechnique Fédérale de Lausanne
[4] Calzolaio C, Bruzzone P, Uglietti D, Stepanov B, Bessette D and Jewell M, 2012 IEEE Trans. Appl. Supercond. 22 9002604
[5] Calzolaio C, Bruzzone P and Stepanov B, 2013 IEEE Trans. Appl. Supercond. 23 4200404
[6] Calzolaio C and Bruzzone P, 2014 IEEE Trans. Appl. Supercond. 24 4802204
[7] Ekin J W, 1980 Cryogenics 20 611
[8] Ekin J W, 2010 Supercond. Sci. Technol. 23 083001
[9] Taylor D M J and Hampshire D P, 2005 Supercond. Sci. Technol. 18 S241
[10] Godeke A, ten Haken B, ten Kate H J J and Larbalestier D C, 2006 Supercond. Sci. Technol. 19 R100
[11] Ten Haken B, Godeke A and ten Kate H J J, 1999 J. Appl. Phys. 85 3247
[12] Bottura L and Bordini B, 2009 IEEE Trans. Appl. Supercond. 19 1521
[13] Taylor D M J and Hampshire D P, 2005 Supercond. Sci. Technol. 18 S297
[14] Senatore C, Abächerli V, Canton M and Flükiger R, 2007 Supercond. Sci. Technol. 20 217