Influence of Cable Layout on the Performance of ITER-type Nb₃Sn Conductors

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Abstract. In 2005-2006, the European Union tested in the SULTAN facility (CRPP Villigen, Switzerland) four ITER-type conductors assembled in two samples. Each conductor made use of an advanced Nb₃Sn strand specially developed by European companies for the ITER Toroidal Field (TF) coil conductor. The cable layout of these conductors was the one of the ITER TF Model Coil conductor. In 2007, the European Union tested in SULTAN four other conductors within two other samples as prototypes of the updated ITER TF conductor. These conductors differed mainly from the former by their cable layout whereas identical or similar Nb₃Sn strands were used. The paper reports on the current sharing temperature measurements of the second samples under ITER relevant operating conditions. The effect of cycling (1000 cycles) in current under full magnetic field was also investigated. The analysis of the test results is performed with respect to the strand properties using the usual smeared models of the cable. These test results were found to be significantly better than those obtained on the first conductors. The paper discusses the possible causes as well as the consequences of such a performance scattering.

1. Introduction
After the test analyses of the ITER model coils in 2001-2002, the ITER conductors were redesigned using Nb₃Sn strands with higher performance (i.e. higher $J_c$) called ‘advanced’ strands [1]. Four European companies succeeded in producing these strands in 2004, European Advanced Superconductors (EAS) using the bronze route, Oxford Superconducting Technology (OST), Luvata Pori (OKSC) and Luvata Italy (OCSI) using internal tin.

In a first step, the EU fabricated and tested two full-size conductor samples with advanced Nb₃Sn strands but based on the Toroidal Field Model Coil (TFMC) conductor design. Four conductor lengths

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6 This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
were manufactured, each using a different EU strand, and coupled into two hair-pin samples (TFAS1 and TFAS2) [2]. These samples were tested in the SULTAN facility (Villigen, Switzerland) in 2005-2006. The results of these tests were not satisfactory as no conductor could reach at the end of its test the current sharing temperature specification (5.7 K) of the ITER TF conductor [1, 2].

In a second step, new conductors were fabricated using the remaining lengths of advanced strands and based on the new ITER TF conductor design, with some variations regarding (lower) cable void fraction and (longer) cabling twist pitches, in order to improve their DC performance thanks to a better mechanical support of the strands in the cable [3]. Two new samples (TFPRO1 and TFPRO2) were fabricated and tested in 2007 in SULTAN.

2. Description of the samples

2.1. The conductors

The tested conductors are cable-in-conduit conductors composed of twisted Nb$_3$Sn and copper strands compacted in a thin (1.6 mm thick) stainless steel jacket (see table 1 and figures 1 and 2). The main subcables are called petals. The name of each conductor refers to the name of its strand. All EAS strands are identical, OST0 and OST2 strands are identical but slightly different from OST1 strand.

| Sample  | TFAS1 | TFPRO1 | TFPRO2 |
|---------|-------|--------|--------|
| Conductor| EAS0  | OST0   | EAS1   | EAS2   | OST1 | OST2 |
| Strand diameter [mm] | 0.81  | 0.91   | 0.91   | 1.0    |      |      |
| Cu: non-Cu in strand |      | 1.0    | 1.0    |        |      |      |
| Strand manufacture | bronze | internal tin | bronze | internal tin |      |      |
| Jc @4.2 K,12 T [A/mm$^2$]$^a$ | 710  | 1020   | 710    | 1150   | 1020 |      |
| Cable layout | $3^b \times 3 \times 5 \times 4 \times 6$ | $((2s/c+1Cu) \times 3 \times 5 \times 5 + 3 \times 4Cu) \times 6$ |       |       |      |      |
| Nr. of s/s strands | 1080 | 720    | 900    |        |      |      |
| Nr. of Cu strands | 0    | 360    |        | 522    |      |      |
| Twist pitch sequence [mm] | 45 - 87 - 126 - 166 - 415 | 45 - 87.5 - 126.5 - 245 - 460 | 116 – 182 - 245 – 415 - 440 |       |      |      |
| Petal void fraction [%] | 34.0 | 33.3   | 33.8   | 29.3   | 29.1 | 27.7 |
| Central spiral id \times od [mm] | 10 \times 12 | 7 \times 9 |       |       |      |      |
| Outer diameter [mm] | 40.4 | 43.45 | 42.05 | 42.05 | 41.45 |      |

$^a$ As measured by CRPP.
$^b$ (2 s/c + 1 Cu) in OST0, 3 s/c in EAS0.

The TFAS2 conductor is not considered in this paper as using different s/c strands [1]. EAS1 is the closest to the reference ITER TF conductor layout. More detailed information on TFAS and TFPRO conductors can be found in [2] and [4], respectively.

2.2. The samples

Each sample is composed of two conductor legs connected at one end through an electric joint and having at the other end a termination for connecting the sample to the facility transformer. The sample is tested in vertical position. The two legs are fed independently with helium flow, with helium inlets either at top (TFAS1, except 4$^{th}$ campaign) or at bottom through the joint (TFPRO samples and TFAS1 4$^{th}$ campaign). The TFAS and TFPRO samples differ mainly by their joints. The TFAS joints make use of the so-called twin-box concept developed for the TFMC [5] which consists in pressing the
cable in a copper-steel box machined in a bi-metallic plate bonded by explosion, the electrical connection being made between the outer copper parts of the joint boxes. The TFPRO joints are fabricated by soldering the cable peripheries onto connecting copper pieces after the reaction heat treatment, this method ensures a lower joint electrical resistance (below 1 n\(\Omega\)). In addition, TFPRO samples make use of crimping rings at both leg ends to avoid any strain relaxation during the joint fabrication, and the central spiral was plugged during tests. More detailed information on TFAS and TFPRO samples can be found in [2] and [4], respectively.

Figure 1. Cross-section of TFAS1-EAS0 conductor.

Figure 2. Cross-section of TFPRO1-EAS1 conductor.

Once in the facility, a length of about 450 mm on each conductor is submitted to the SULTAN transverse background field. The voltage drop over 450 mm (\(V_{450}\)) is measured by voltage taps welded onto the jacket, and the temperature is measured upstream and downstream by sensors glued onto the jacket [2, 4]. The current sharing temperature \(T_{cs}\) is defined at a voltage drop of 4.5 \(\mu\)V, considered equivalent to an average electric field of 10 \(\mu\)V/m.

3. Description of the tests
The DC tests consisted in measuring \(T_{cs}\) by increasing slowly the inlet helium temperature (1-2 mK/s) at constant magnetic field and current.

TFAS1 was first tested under magnetic fields from 11 T to 8 T (1 T steps), and with current within the 10 – 80 kA range (test1). Then 1000 current cycles between 0 and 60 kA were applied under an 11 T field to create a mechanical cycling. After cycling, the sample was retested (test2), then warmed-up and retested again (test3). Last, the sample was retested end of 2006 (test4) [6].

Because the TFPRO conductors are identical or so to the ITER TF conductor they were tested in a reduced way, mainly under the nominal TF conductor operation, with a current of 68 kA under a background field of 10.78 T. Practically, 1000 current cycles between 0 and 68 kA were applied under a 10.78 T field, and \(T_{cs}\) was checked on both legs at cycles N° 1, 3, 10, and then every 200 cycles. After 1000 cycles, \(T_{cs}\) was measured at lower currents and lower field then the sample was warmed-up and retested at nominal operation and under an 11 T field with a mechanical overload produced by a current of 80 kA, and finally rechecked.

4. Results of the tests
The evolution of the \(T_{cs}\) under ITER TF nominal operation is given in figure 3 for the TFAS1, TFPRO1 and TFPRO2 conductors. Whereas the values come directly from the measurements for the TFPRO conductors[^7], they must be computed from experimental data for the TFAS1 conductors since

[^7]: Rigorously, the TFPRO1 and TFPRO2 non-copper areas are respectively 2.9% above and 1.2% below the ITER TF specification. This should lead to decrease the EAS1 and EAS2 \(T_{cs}\) by 0.1 K, and to increase the OST1 \(T_{cs}\) by 0.05 K and the OST2 \(T_{cs}\) by 0.03 K, using the smeared models depicted in sec. 5.
the non-copper areas are not equal to the one of the ITER TF conductor. Considering equal non-copper current density leads to consider operation at different currents (53.6 kA for OST0 and 83.7 kA for EAS0) which means different magnetic field and electromagnetic load. Rescaling has been made using the usual smeared models (see sec. 5) but results depend on the model, which has been translated in the figure by larger error bars. The ITER TF specification \(T_{cs} = 5.7 \text{ K}\) is also plotted in the figure. Note that there is not a full correspondence between TFAS1 and TFPRO tests, particularly regarding the overload. Note also that, for the sake of consistency, the method used for TFPRO data reduction is the same method as the one used for TFAS1 [2], although other methods have been also used producing slightly different results [4].

![Figure 3](image)

**Figure 3.** Evolution of \(T_{cs}\) during the tests of TFAS1 and TFPRO conductors.

It can be seen in figure 3 the continuous degradation of OST0 from test to test and its very low \(T_{cs}\) at the end. EAS0 shows degradation of \(T_{cs}\) mainly after the first test (which included the overload) but ended mid 2006 well below the ITER line, whereas the last increase of performance in the 4th campaign has not been explained.

The TFPRO conductors end all above the ITER line and even higher or equal to 6.0 K but their behaviours are different. EAS1 and EAS2 are very stable though there was a slight decrease of \(T_{cs}\) (about 0.25 K) after cycling in EAS2 which ends only slightly above EAS1 but the difference becomes almost within the error bars. OST1 does show a first degradation with cycling (drop of about 0.6 K) similarly to OST0 but then \(T_{cs}\) stabilizes at variance with the latter, it ends at the lowest \(T_{cs}\) among the TFPRO conductors though its strand has the best performance (see table 1). OST2 is very stable with a very high \(T_{cs}\) at about 7.3 K.

### 5. Smeared models

The smeared models consist in considering an average strand in the cable with respect to \(\text{Nb}_3\text{Sn}\) strain state, effective superconducting area and \(n\) index. The average electric field along the conductor is then computed by averaging the electric field in a conductor cross-section \(E_{ave}\), taking into account the background magnetic field as well as the self-field produced by the two legs. The current distribution among the strands is assumed uniform.

There are two usual smeared models used to fit the experimental data, both came from the need to understand and model the degradation of performance measured on the ITER-type conductors [1]. The extra strain model (m1) consists in computing the effective strain \(\varepsilon_{ef}\) by adding an extra compressive strain, proportional to the average Lorentz force \((\gamma \times B_{ave})\) to the so-called thermal strain \(\varepsilon_{th}\) (due to
cooling down from heat treatment temperature to operating temperature). The effective Nb$_3$Sn area model (m2) consists in considering a reduced non-copper area in every strand characterized by a coefficient $\alpha_{\text{eff}} \leq 1$ associated with $\epsilon_{\text{eff}} = \epsilon_{\text{th}}$ (and $\gamma = 0$).

$E_{\text{ave}}$ is usually computed at peak field (along the conductor) and the $T_{cs}$ is then defined by $E_{\text{ave-peak}} = 10 \ \mu$V/m. However, the SULTAN field is not uniform along the 450 mm length between the voltage taps (see figure 4) and it is more accurate to compute the voltage drop $V_{450}$ by integrating the average electric field along the 450 mm between taps. The effective length (i.e. $V_{450}/E_{\text{ave-peak}}$) has then turned out to be lower than 450 mm and to decrease with the n value, but the negative correction for a $T_{cs}$ computed with $V_{450} = 4.5 \ \mu$V is low and decreases with n: it is 0.08 K on OST0 and EAS0, 0.06 K on EAS1, EAS2 and OST1, and 0.04 K on OST2 (not included in figure 3).

**Figure 4.** SULTAN field profile along conductor (normalized to peak value).

**Figure 5.** Best fit (model m1) of OST1 $T_{cs}$ after cycling.

The model parameters have been computed by best fits of the experimental $T_{cs}$ points after cycling, for background fields $B_3$ within the 10-11 T range (see figure 5). For consistency, the 4$^{th}$ TFAS test campaign was not considered here. The n values used in the models are average (within current range) measured values: 6 for OST0 and EAS0, 7.5 for EAS1 and EAS2, 7 for OST1 and 17 for OST2. The values of the model parameters are given in table 2. The interest of these parameters is that they rescale the $T_{cs}$ values with respect to the intrinsic strand properties.

**Table 2.** Values of model parameters after cycling

| Model | Conductor | TFAS1 | TFPRO1 | TFPRO2 |
|-------|-----------|-------|--------|--------|
|       |           | EAS0  | OST0  | EAS1  | EAS2  | OST1 | OST2 |
| m1    | $\epsilon_{\text{th}}$ (%) | -0.605 | -0.505 | -0.592 | -0.595 | -0.540 | -0.477 |
|       | $\gamma$ (%.kA$^{-1}$T$^{-1}$) | $2.4\times10^4$ | $4.4\times10^4$ | $9.5\times10^5$ | $7.5\times10^5$ | $3.1\times10^4$ | 0 |
| m2    | $\epsilon_{\text{th}}$ (%) | -0.558 | -0.370 | -0.560 | -0.570 | -0.460 | -0.477 |
|       | $\alpha_{\text{eff}}$ | 0.614 | 0.400 | 0.800 | 0.840 | 0.470 | 1 |

6. **Discussion**

It can be clearly seen in table 2 that the thermal strains for all the EAS conductors are very similar and higher (absolute value) than in the OST conductors. However, EAS1 is much less sensitive to the electromagnetic load than EAS0 (see $\gamma$ or $\alpha_{\text{eff}}$), and this could be explained only by the cable structure. EAS1 has longer last stage twist pitches, a smaller spiral, larger contact areas between petals and more uniform strand distribution inside petals (see table 1 and compare figures 1 and 2). Although it is difficult to separate individual effects, it is clear that as a whole, all these slight differences have produced a significant improvement of the conductor performance (see figure 3). On the other hand, the over-compaction of the EAS2 cable has not been found to bring a significant improvement.
Since the OST1 strand is slightly better than the OST0 strand and is less sensitive to strain [7], one cannot conclude on the absolute $T_{cs}$ values. However, though OST1 has shown an overall cycling degradation similar to OST0, this degradation has been stabilized at variance with OST0 (see figure 3) which continuously degraded. Therefore, here again, the beneficial effect of the cable change seems to be confirmed. On the other hand, OST1 performance is slightly below EAS1 is spite of a better intrinsic strand performance (see table 1) which can be explained by a much higher sensitivity to the electromagnetic load (see $\gamma$ or $\alpha_{eff}$ in table 2) within an identical cable.

OST2 is by far the best conductor as well for the higher $T_{cs}$ as for the higher n value close to its strand value. Also no cycling degradation has been observed. This exceptional performance cannot be disconnected from its special cabling pattern with longer twist pitches, more especially as this improvement was predicted by the University of Twente using their TEMLOP code [3]. However, the thermal strain value (-0.477%) looks rather low since with such a compacted cable with almost parallel strands one could have expected to be close to the so-called fully bonded model with $\varepsilon_{th} = -0.68\%$. Even in the case of a 10% strain relaxation with $\varepsilon_{th} = -0.61\%$, the $T_{cs}$ would have been of 6.4 K, i.e. much lower than the measured 7.3 K. Therefore the exceptional performance of OST2 has not yet been fully understood.

The drastic decrease of the AC losses (about one order of magnitude) observed on all TFPRO conductors after cycling [4] shows that on EAS1, EAS2 and OST2 the value of $T_{cs}$ is not affected by a drastic change of the interstrand contacts and by the associated increase of the interstrand resistances.

7. Conclusions

The new four European TF conductors for ITER tested in 2007 have shown much better performance than the previous conductors tested in 2005-2006, particularly with a current sharing temperature $T_{cs}$ above the ITER specification. Since the same Nb$_3$Sn strands were used in the old and the new conductors this improvement has to be related only to the change in the cable structure. However, for all but one conductors the reasons for this improvement have not been clearly identified and could lie in the sum of slight improvements leading to a better mechanical support of the strands inside the cable, such as better shaped subcables, smaller spiral, longer last cabling twist pitches. For one conductor, the improvement can be associated with the increase of the first cabling twist pitches, as predicted by the TEMLOP code developed at the University of Twente. However, even for this conductor, the exceptionally high measured $T_{cs}$ cannot be explained without considering a low thermal strain in the Nb$_3$Sn filaments which a priori is not related to the change of the cable structure.

Whereas the general performance of the new conductors can be considered as a good result, the lack of full explanation for the improvement compared to the first TFMC-type conductors calls for further studies in order to optimize the conductor design.

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