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Abstract— The US Domestic Agency (USDA) is one of the six suppliers of the TF conductor for ITER. In order to qualify conductors according to ITER requirements we prepared several lengths of the CICC and short samples for testing in the SULTAN facility in CRPP, Switzerland. We also fully characterized the strands that were used in these SULTAN samples. Fabrication experience and test results are presented and discussed.

***Index Terms*—Superconducting device testing, Superconducting cables, Superconducting materials measurements**

I. INTRODUCTION

THE ITER TF conductor is one of the most critical parts of the magnet system. Due to limited fabrication capacities in industry and risk mitigation the USDA will use two strand suppliers. The strands from different suppliers are not allowed to be mixed in the same cable. Before production of the TF conductor and its components begins it must pass the SULTAN test. The US DA selected Luvata Waterbury (called Luvata in this paper) and Oxford Superconducting Technology in Carteret, NJ (OST) to be suppliers of the US batch of the TF CICC (Cable-in-Conduit Conductors). In the beginning of the 2008 we prepared and tested the first US made conductor, nominated TFUS1 with Luvata strand [1]. This sample preparation was done in the US and details are given in [2]. Main features of the sample were special preparation of the terminations and an intrusive instrumentation. In order to improve the uniformity of current distribution the chromium was removed from the strands and the subcable wraps were removed from the cable in terminations before heat treatment. After heat treatment the terminations were filled with solder. Such preparation of the terminations resulted in very low parasitic signals from the voltage taps; a big problem at the time. This noise was making interpretation of the tests results difficult or impossible. Intrusive voltage taps provided new information about location of the electrical field origination in the cable, which was unknown at the time [2].

TFUS1 met ITER performance requirements and showed low degradation to the load cycles. These results made it possible to start preparations for full production activity of the TF CICC in the US with the Luvata strand.

In this paper we give results of the three other SULTAN tests with US made TF CICC and present our conclusions.

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II. TFUS2

A. CICC fabrication

The second test sample, TFUS2, was prepared out of the CICC built by the US DA using the OST strand. As in the TFUS1, it had different cabling patterns in each of two legs comprising the SULTAN test sample. The cabling pattern of the TFUS2 ITER Option II leg is given in Table I. The cabling pattern of the Alt leg was based on six-around-one strands and is described in [2].

TABLE I CABLING PATTERNS OF THE TFUS2 OPT 2 LEG

Margin	ITER Opt II
1st stage(2sc+1 Cu strand)	80 mm
2nd stage (3 cables from 1st stage)	140 mm
3rd stage (5 cables from 2nd stage)	190 mm
4th stage (5 subcables from 3rd stage around 12 Cu strands core)	300 mm
5th stage (6 subcables from 4th stage around central spiral)	420 mm

The Option II cabling was introduced by ITER International Organization Magnet Team (ITER IO) after some encouraging results obtained on a long twist pitch cable [3] tested after TFUS1 was fabricated. We were requested to change the cabling pattern in the TFUS2 sample, in the ITER leg, which was still in fabrication. The new cabling pattern of Opt II turned out to be more difficult for fabrication than Opt I and with a very limited amount of material and practice our Opt II cable had several broken strands per meter of the cable.

The Alternate (Alt) cable was even more difficult to make defect free. Due to a much higher stiffness, the number of broken strands was measured by tens of broken strands per defect and there were typically several of them per meter of the cable. By no means is the Alt cable acceptable for production of the TF conductor, but we still decided to test it in order to obtain qualitative information about Tcs in the TF CICC with defects.

Compaction of the TFUS2 samples and all other US made CICC in the jacket took place on a specialized 8-stations compaction mill with cold work in the jacket of about 5%.

The test samples were prepared from the US CICC by the CRPP SULTAN group [4]. The joints were made by a method that did not remove the subcable wraps and the strands were soldered to each other by dipping into a melted 5%Ag-Sn solder as opposed to complete impregnation of the termination with a solder like in the TFUS1.

B. *TFUS2 test results*

The scatter of the voltage signals taken from six pairs of voltage taps equally spread around CICC circumference in the TFUS2 was significantly larger than that in TFUS1 over the 45 cm base embracing the high field zone. The Opt II leg had a scatter from -4 μV to + 4 μV in the background 10.9 T field and 68 kA and the Alt leg had the scatter +2 to +8 μ, which suggested that the uniformity of current in the conductor was not as good as in TFUS1, where the scatter was on the level of +/- 0.5 μV.

Averaged voltages on the Opt II leg had a low slope, see Fig. 1 (lower curve), since the scatter was about symmetrical around zero signal. Some of us think that this good compensation of the signals is somewhat artificial and that averaging sometimes is hiding the nonuniformity of the current distribution. The basis for this speculation is that sometimes the signals from the longer base may look accidentally cleaner (lower slope) after averaging, which contradicts common sense.

Fig. 1 shows the averaged signals from both legs before cycles. From 4.5 K to about 4.9 K the current is charged in the sample and heat generation in the lower joint raises the temperature. Normally, without nonuniform distribution in the sample, there should be no slope, like in TFUS1 [1]. In the TFUS2 at 68 kA and no external heating we see a significant voltage in Alt leg that is about Tcs criteria. In other words, a nonuniform distribution is obvious and assessment is impossible without corrections, which is based on difficult to verify assumptions with large uncertainty.

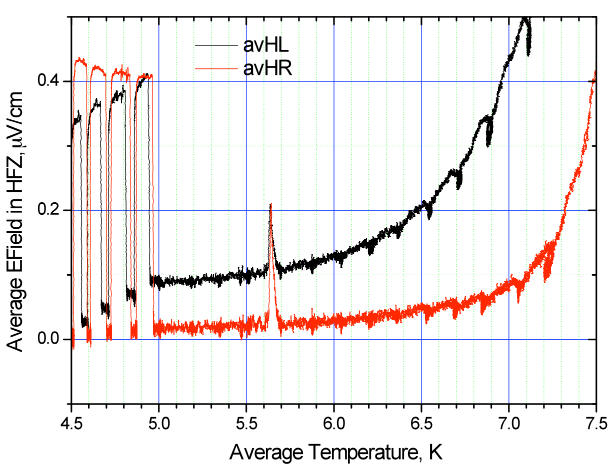

Fig. 1. Filtered voltage signals from TFUS2. The upper curve is from Alt leg, lower curve is from Opt II leg

Our method of the Tcs assessment was based on the extrapolation of the electrical field from a high level, say 40-100 μV/m, (where the effect of nonuniformity is suppressed) to the level of 10 μV/m. This method is explained in [5] in details.

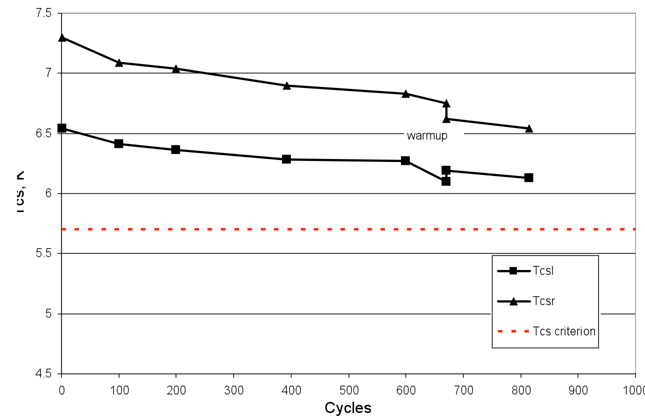

Fig.2. Tcs evolution in the TFUS2

The current sharing temperature Tcs evolution versus load cycles is shown in Fig.2. As one can see the process of apparent degradation with cycles is not saturated even after 850 cycles. After 700 cycles the sample was warmed up and then cooled down. The effect of warm up and cool down is also very noticeable, especially in Opt II leg (upper curve). The ITER requirement to survive 50 warm up cycles leads to a need to verify that the performance of the TF conductor remains acceptable after so many warm up cycles.

It is remarkable that the Alt leg of TFUS2 showed so good performance despite so many defects.

III. USTF3

The USTF3 sample was made out of the same cable as the TFUS1. The only difference between the TFUS1 and USTF3 CICC was the conduit material – 316LN for TFUS1 and 304L for USTF3. The purpose of the test was to see if joint preparation with solder dipping and not removing the subcable wraps could be as good as solder filled terminations with the wraps removed. Also, it was the first opportunity to check the performance reproducibility of seemingly identical conductors.

A. *USTF3 fabrication*

The USTF3 sample was prepared by CRPP in the same fashion as TFUS2.

B. *USTF3 test results*

USTF3 scatter of the signals from 450 mm base embracing high field zone was about 2.5 μV on Opt I leg and 1.5 μV on the Alt leg to compare with 1 μV in TFUS1. This shows that preparation of the sample with the dipped method could also achieve a low current nonuniformity.

Fig. 3 shows evolution of the current sharing temperature in TFUS1 and USTF3 samples. As one can see, the performance is quite different, especially for the ITER Opt I leg (two lower curves). Moreover, it grew in USTF3 after the first cycles. The cables are identical; there is a slight difference in the conduit material, which is not considered a reason for the difference.

The jacket material for TFUS1 was 316LN with a low carbon content, the jacket material for the USTF3 was commercial 304L. Compaction of the jackets was the same.

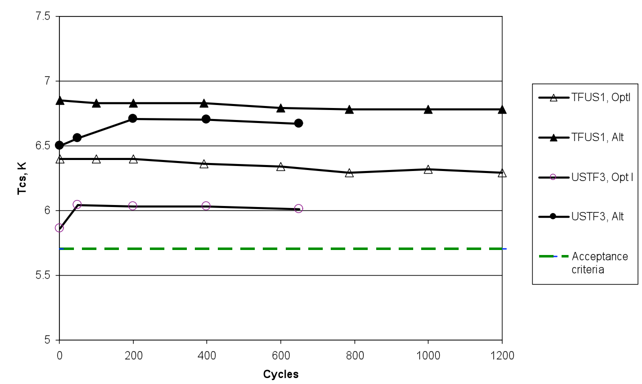

Fig. 3. Comparison of TFUS1 and USTF3 Tcs evolution with cycles

So far in most cases with few exceptions, the Tcs versus cycles monotonically decreased. This degradation is explained by breaking or degrading the Nb3Sn filaments in the strands. Since it is inconceivable to imagine "healing" of the filaments as a result of cycles, a new explanation of Tcs improvement is needed.

One of the possible explanations is that the initial strain of the cable in the jacket is not uniform along the length or in cross sections after the fabrication. Since only 45 cm of the conductor is in high field in SULTAN, that portion of the cable in the high field zone may be compressed more or less than average by the jacket that shrinks more than the cable during cooldown. As a result of the cyclic loading the cable may shake down to a uniform strain condition and stabilize its performance. In this case, we have two competing mechanisms – degradation and strain relaxation, which can give any combination of possibilities, but the most likely behavior, is a weak or strong degradation with cycles with or without saturation.

Even after saturation the difference in performance of TFUS1 and USTF3 is quite significant and unexpected. That is the first time that almost identical samples show noticeable differences in absence of indication of nonuniform current distribution. However surprising, from the project standpoint, the USTF3 sample still meets the Tcs acceptance requirements.

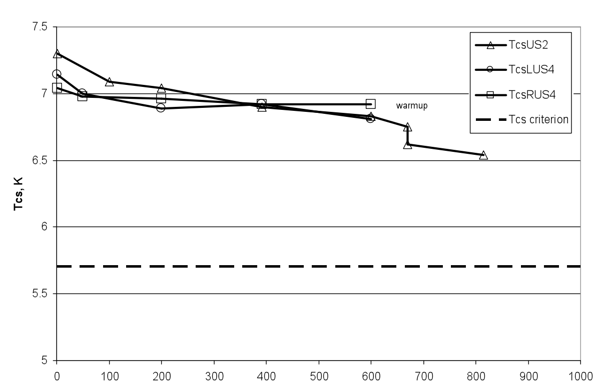

Fig. 4 Comparison of TFUS2 and USTF4 evolution with cycles

IV. USTF 4

The USTF4 sample was prepared and tested in order to verify performance of the TFUS2 sample. The USTF4 sample had identical legs as in TFUS2 containing Opt II cables. The same strand was used, same cabling pattern. The terminations of the both legs have solder filled terminations in a similar way as it was done for TFUS1, but it was done by CRPP [6].

The slopes in the both legs of the USTF4 sample were lower than in the TFUS2 and USTF3 samples, which suggests that the solder filled joints with removed wraps in the subcable provide better conditions for uniform current distribution.

Fig. 4 shows comparison of the USTF4 performance with TFUS2. The difference in the performance of the TFUS2 and USTF4 is small as expected. This assessment shows that despite significant slope scatter in the TFUS2 sample, the correction was applied in an appropriate manner. Due to a limited time allocated for the USTF4 testing, we did not proceed with cycling for a total of 1000 cycles, but even limited cycling gives all indications that the behavior of USTF4 is almost identical to TFUS2.

The USTF4 tests showed that the US made TF CICC with the OST strand and the Opt II cable pattern comfortably exceeds the acceptance criteria of 5.7 K. Close performances indicate a good behavior reproducibility of the TF CICC with the OST strand.

V. Broadness of the E(T) transition in the US made TF CICC

One of the important parameters of the superconducting transition is its broadness. For superconducting strands the broadness is often expressed in terms of so-called N-value (or N-index). This parameter is found from the best fit of the test data by an empirical approximation $E=Ec(I/Ic)^N$. The measurements are done at well controlled temperature.

TABLE II. Parameters To for the US TF CICC

Margin	*To of the TF CICC, K*	*To of the strand, K*
TFUS1 Opt I	0.30	0.18
TFUS1 Alt	0.30	0.19
TFUS2 OptII	0.36	0.17
TFUS2 Alt	0.48	0.19
USTF3 Op I	0.37	0.18
USTF3 Alt	0.47	0.19
USTF4 Opt II, left	0.37	0.17
TFUS4 Opt II, right	0.35	0.17

This definition is convenient for individual strands, but for large CICC it is difficult to apply, since in the E(I) measurements the temperature is not constant due to heat generation in the joints and due to self-heating in the voltage generating portion of the conductor. Therefore, a temperature correction is necessary, which is tricky. The measurements of the E(T) characteristics represent a more convenient way of obtaining the information about broadness of the transition since only temperature changes, but the broadness is obtained in different terms.

Our assessment of the broadness of the transition was based on fitting the test data by the expression: E=Ec*exp[(T-Tcs)/To], where Tcs is the current sharing temperature, defined at constant current and Ec=10 μV/m. The To parameter is a temperature increment that raises electrical field by the factor of e=2.71..A relationship between the N parameter and To at the same strain, temperature and magnetic field can be expressed as:

$$N = \frac{I_c}{T_o(\partial I_c / \partial T)_{B,\varepsilon}}$$

Table II presents measurements of the To after cycling in all US made TF CICC so far. Also, the To parameters for the strands are given for comparison. The To in the CICC TFUS1 and TFUS2 is significantly higher than in the strand in similar conditions, but among the lowest observed so far in the SULTAN TF CICC tests on the samples prepared by all six ITER parties. Table II also shows that the TFUS2 results for To are abnormal and remain to be explained.

In terms of N, the To in the TFUS1 and TFUS2 correspond to N of about 10. The strands from Luvata and OST used in the TF CICC reported in this paper at 6.5 K, 12 T and 0.7% strain show the same N about 14. It is interesting to note that the N value for the OST strands used in TFUS2 and USTF4 showed N value about 30-35 at 12 T, 4.2 K and strain -0.2-0.3%. At the same conditions the Luvata strands used in the TFUS1 and USTF3 have N-value about 20.

VI. Strand characterization

In order to evaluate degradation of the CICC in comparison with the strand in similar conditions, we needed to characterize the strands and built a correlation Ic(T,B, eps) in accordance with the ITER recommended approach [7].

TABLE III. US Strand Characterization Parameters

Margin	*Luvata ITER*	*Luvata Alt*	*OST ITER*	*OST Alt*
Ca1	51.99	45.22	100.97	46.00
Ca2	5	0.10	71.05	5.00
eps_0a	0.26%	0.219%	0.407%	0.362%
eps_m	-0.26%	-0.190%	0.000%	0.000%
Bc2m(0)	27.4	26.70	28.22	29.95
Tcm	17.8	17.90	17.97	16.11
C	7478	9639	17288	19721
P	0.13	0.39	0.20	0.62
Q	1.05	1.36	2.00	2.04

Table III shows characterization parameters, which are defined in [7]. The Luvata strand was used in the TFUS1 and USTF3, the OST strand was used in TFUS2 and USTF4. Both legs of USTF4 contained ITER strands only, all the rest had one leg with the Alt strands, one leg with the ITER strands.

The characterization was carried out in the University of Geneva on the Walter spring rig in the parameters space: 4.2<T<7.5 K, 10<B<16 T, 0<I<300 K, -0.9%<ε<0.4%.

On the basis of the strand characterization, one can find that at the effective magnetic field of 11.3 T in the TFUS2 CICC and Tcs=6.5 K, the effective strain is -0.77%, which corresponds to a somewhat higher degradation than expected, but still with a lot of margin. For the TFUS1 ITER and Alt cables at Tcs=6.3 and 6.8 K, respectively, the effective strain of the cable is within expectations – 0.69%.

VII. Conclusion

All four samples and eight legs of the US made CICC for the ITER TF magnets exceeded ITER requirement on the Tcs>5.7 K. That gives the US DA a confidence to move towards production samples for the ITER TF system. We discovered that even almost identical samples TFUS1 and USTF3 could have significantly different performance, although TFUS2 and USTF4 results of identical legs were very similar. The US tests showed that solder filled terminations give the best chance to reduce the noise from nonuniform current distribution, although in some cases solder dipped terminations may achieve low noise conditions also.

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