Test Results of the First US ITER TF Conductor in SULTAN

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***Abstract*—The US Domestic Agency is one of six parties supplying TF cable-in-conduit conductors (CICCs) for ITER. Previous tests have shown that measured performance of the TF CICCs can be much lower than expected from the strand properties at the projected uniaxial strain and that the cabling pattern may also be an important factor. Worst of all, voltage signals well below the expected critical surface could not be reliably interpreted or canceled, making test results very suspect. The TFUS1 sample was prepared to achieve multiple goals: 1) to ensure uniform current distribution and to eliminate parasitic voltage signals by improving joints, 2) to explore the potential benefits of a different cabling pattern for better support of strain-sensitive strands, and 3) to explore the source of voltage development in the cable through the use of innovative penetrating diagnostics. Test results of the first US-made samples are presented and discussed.**

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

I. INTRODUCTION

FOR economic considerations, the temperature margin for ITER TF conductors has been set relatively low, but to ensure reliable operation of the ITER TF magnets, all TF conductors supplied to ITER must first be qualified in SULTAN facility at CRPP, Switzerland [1]. Also, qualifying of full scale conductor is necessary because, to date, there is no reliable correlation between performance of individual strands and the performance of the full CICC. The qualification requirement is Tcs $(\mathrm{E} = 10\ \mu\mathrm{V/m}) > 5.7$ K at 68 kA in the background field of 10.86 T.

Previous tests of the developmental TF CICCs have revealed that CICC properties are often much lower than that of the sum of the strands and that voltage signals appear substantially earlier than the onset of current sharing, making a reliable assessment of the test results difficult or impossible. It has been assumed [2], [3] that the most probable reason for the "early voltage" is a nonuniform current distribution in the cable and it has been shown that there is no reliable way to cancel this effect by post-processing [3]. This leaves only one possibility—eliminating this "early" voltage by a proper preparation of the sample. It is necessary to reduce substantially the inter-strand resistance in the cable—where we can—in the joint regions. Since a previous attempt with solder-filled terminations [4] did not lead to an improvement of the "early" voltage signals, the US team made a more deliberate effort wherein the subcable wraps were first removed, then the chrome plating on the strands was chemically etched away prior to termination, compaction, and heat treatment (HT), and finally the terminals were chemically cleaned and solder-filled after heat treatment.

At the beginning of the TFUS1 sample fabrication, most of the TF relevant samples tested in SULTAN did not meet ITER requirements. The reason was uncertain and innovative ideas were solicited. Based on successful experience with the 45 T hybrid magnet superconducting outset, one of the authors (John Miller) proposed an alternative cable design, based on the stiff "six-around one" pattern rather than the traditional soft "triplet" configuration used so far in most CICCs for fusion applications, including ITER. Thus, the US team built two legs, one with the cabling specified by ITER Option I and another leg with an alternative cabling [5] with practically the same amount of copper and superconductor in these cables.

Another goal we tried to accomplish was to measure the origin of the voltage. This question has a long history. There is a strong gradient (about 1–1.6 T) of the magnetic field across the ITER CICC. The question is: which part of the cable starts generating resistance first—the one in high field, or the one in low field? In the high field area the strands experience only forces generated in these strands themselves. In the low field, forces are accumulated from the whole cable and generate very high pressure on the strands. In order to study this, we used specially designed penetrating sensors that take voltage signals from individual strands.

II. SAMPLE DESIGN

The TFUS1 sample contained two legs, made of two different cables, containing different strands made by Luvata. The left leg, which we refer to as the "ITER" or "baseline" leg, had a cable specified by ITER as Option I. The right leg with the cable designed by J. Miller on the basis of six-around-one subcables is referred to as the "Alt".

The terminations were designed to provide minimal transverse resistance between the strands, and because of that were

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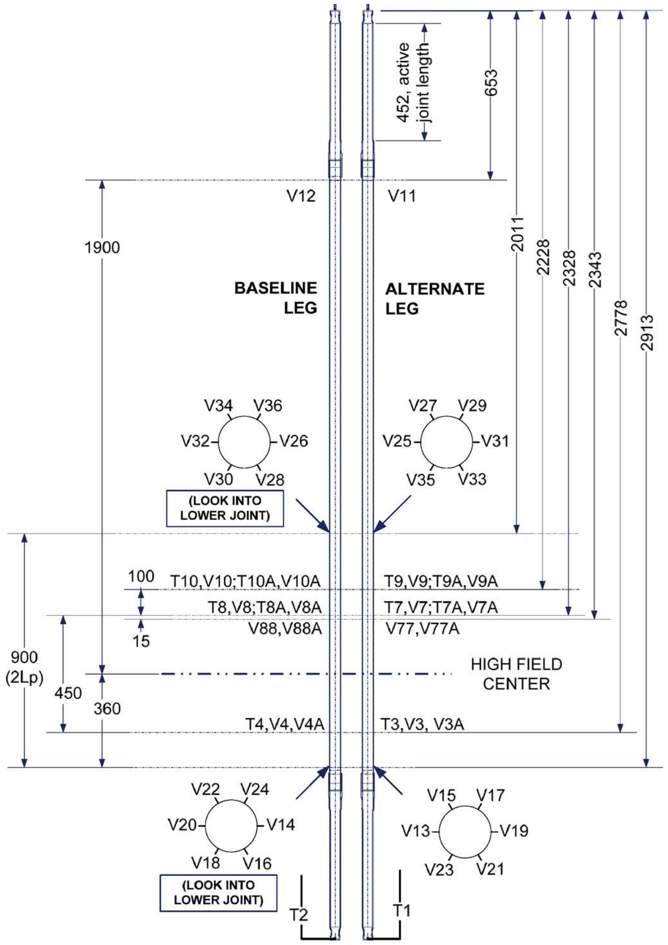

Fig. 1. TFUS1 instrumentation map. "T" denotes temperature sensors, "V" denotes voltage taps.

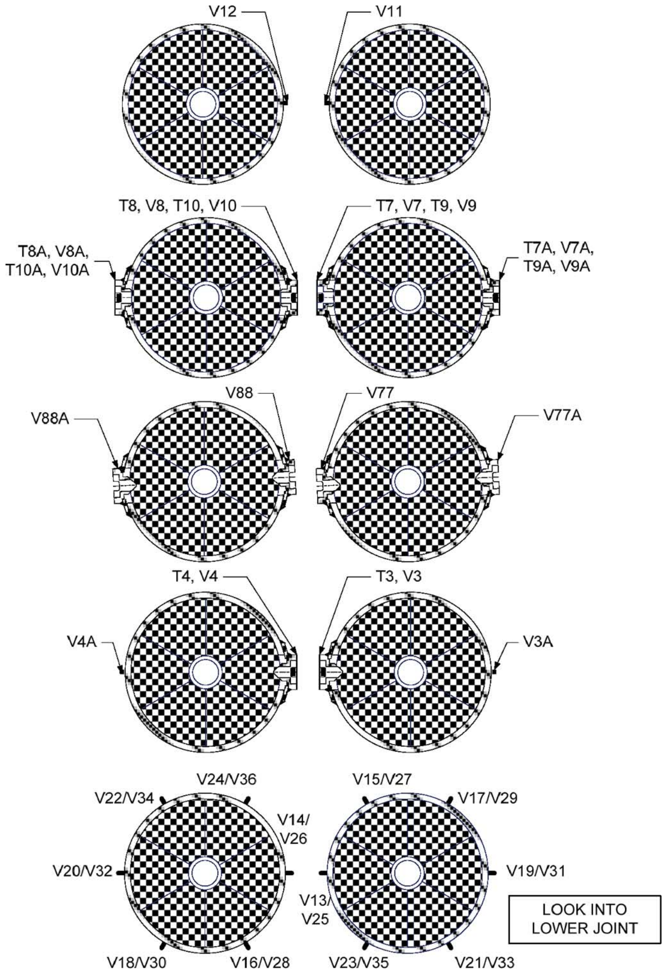

Fig. 2. Position of the sensors in the cross section of the conductors.

sintered during HT and solder filled afterwards. The parameters of the conductors and fabrication details are given in [5].

III. Instrumentation

Figs. 1 and 2 show the location of the voltage taps and temperature sensors.

The voltage taps were of two types—penetrating and conventional. The penetrating samples had a copper tip in contact with the strands. The conventional type taps were attached to the conduit surface. The temperature sensors were mounted in a slot in the copper insert for better thermal contact.

IV. Test Results

All the data given in this section refer to 68 kA and 10.86 T SULTAN background field conditions.

A. *Early Voltage Signals*

The TFUS1 sample gave very low voltage signals (typically less than 0.7 $\mu\mathrm{V}$) on all pairs of voltage taps as long as operating parameters were far away from the critical surface at all currents. That proves that all distribution of current takes place in the terminations because resistance between the strands is low. With such terminations there is no ambiguity in determination of the real performance of the CICC. This result shows that solder filling of the termination can provide a uniform distribution in the CICC at the specified voltage of 4.5 $\mu\mathrm{V}$. This is in contradiction to the previously reported experience [4] where solder filling after HT did not reduce the early voltage.

B. *Joints Resistance*

The joint resistance at the lower joint was measured to be 1.5 nOhm and the resistances to the facility flags were 0.6 nOhm and 0.7 nOhm, correspondingly. These resistances are very low, but not record low among similar conductors tested at SULTAN. That shows that the overall low resistance of the joint does not guarantee a uniform current distribution.

C. *Thermometry*

Temperature sensors show disagreement with the facility inlet and outlet sensors that are known to be reliable. The deviation varied from several tens to 1 K. We had to recalibrate the sensors on the sample every day when we measured Tcs or Ic against facility sensors due to a slight but non-negligible drift between shots on different days.

D. *Tcs Measurements*

To measure Tcs, we used voltage taps over the 450 mm base of the high magnetic field area. For the ITER baseline leg the

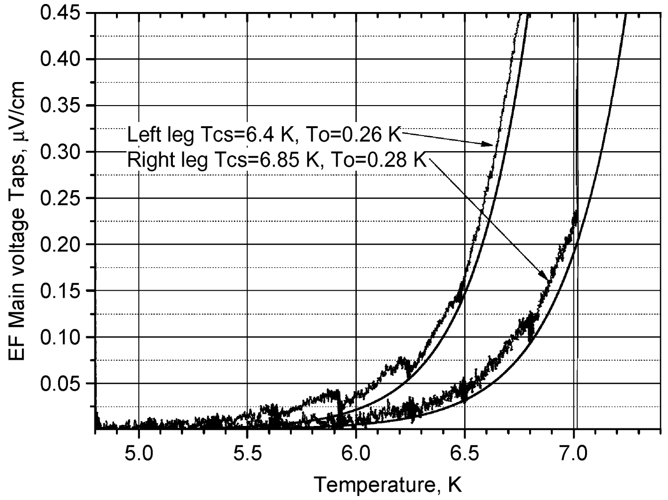

Fig. 3. Volt-temperature characteristics of the TFUS1 conductors and fitting curves from 450 mm base (main voltage taps).

sensors were V8-V4 on the high field side and V8A-V4A on the low field side. For the Alt leg, the pairs were V7-V3 and V7A-V3A, respectively. To determine the Tcs we chose the highest voltage value (lowest Tcs value), which happened to be V4A-V8A and V3-V7. The difference in Tcs between the opposite sides of the same leg in CICC was 0.2–0.3 K.

The "effective average temperature" $\mathrm{T}_{\mathrm{ave}}$ was averaged between the T4, T8 and T8A for the ITER leg and T3, T7 and T7A for the Alt leg.

Fig. 3 shows transitions of the both legs of the TFUS1 before cycles and approximating curves. In order to process the data, we used our observation that the transition in CICC is exponential versus current, temperature and magnetic field, just like in the strands [6]. We used as an approximation the following relation:

$$E = 0.1 \exp\left(\left[T - T_{cs}(B)\right]/T_0\right) \qquad (1)$$

where E is expressed in $\mu\mathrm{V/cm}$, Tcs is the current sharing temperature, and T_0 is the temperature increment. The conventional criterion of the Tcs is 0.1 $\mu\mathrm{V/cm}$. The approximating curve must hit only the lowest points on the V-T curves, since those are the equilibrium points, and other points are transients. Both legs comfortably meet the ITER requirement of 5.7 K.

It is known that the deviation of the parameter To (or related to that, N-value) in CICC from the To (N-value) in the strand at the same conditions is a very sensitive parameter showing degradation or problems with current uniformity [7]. The N-value is the exponent in the approximation:

$$E = 0.1(I/I_c)^N \qquad (2)$$

Measurement of the N-value in the Volt-Ampere characteristic is difficult in SULTAN because of significant noise and varying temperature in the sample due to Ohmic heat in the joints and self heating in the conductor when the current is changing. The strand N-value at such currents in the strand is about 15. Calculation of the N-value from the measured To parameter and derivatives dI/dT gives the N-value of about 10, which shows low degradation and low current nonuniformity. This reduction in N is consistent with our observation of voltage appearance in the high pressure area with broad transition (discussed below). In the recent measurements of strongly degraded CICC samples, the N-value was much lower [8].

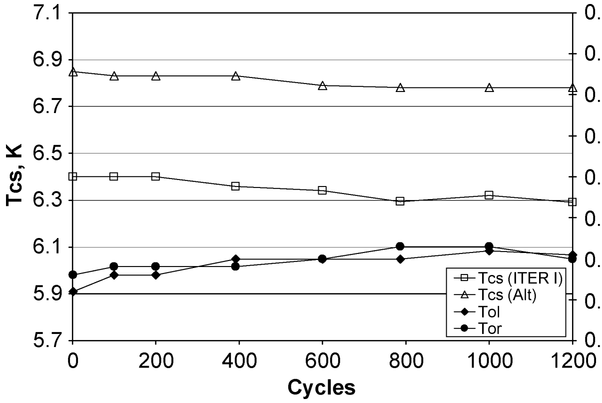

Fig. 4. Evolution of Tcs and To versus number of cycles. Tol is the To for the left leg (ITER) and Tor is for the right leg (Alt).

E. Degradation Due to Cyclic Load

One of the most important characteristics of the CICC is its ability to withstand cyclic loads. Fig. 4 shows evolution of the current sharing temperature Tcs and the parameter of transition broadness To as a result of cycling. Degradation of the Tcs in both legs is small, especially in the Alt leg. There is slight broadening of the transition, but it should not affect seriously the operating margins of the conductor.

F. Observations of the Voltage Origination

Our penetrating sensors allowed studying the place of the voltage signal origination in the CICC. The degradation of the Nb3Sn strands in the CICC is one of the top topics of discussion. At the moment the leading speculation is that the degradation is caused by bending the strands in the cable under electromagnetic (EM) forces. Others think that it is a pinching effect that causes the degradation. The forces are highest in the low field area. However, many researches think that the voltage is originated in the high field area. The strands in the high field do not experience forces on the strands other than their own, which are low. The strands in the low field area experience the force from the whole cable, containing about 1000 strands. Our penetrating voltage taps on the ITER leg allowed measurements of the voltage from the same strand, on the base of 15 mm. On the Alt leg we could attached the pins only to the same subcable, not the same strand due to a sharp twist pitch of the subcable.

Fig. 5 shows development of the voltage in the strands in high field and in high pressure (low field) areas at the first Tcs measurement in 11 T, at 68 kA. The voltage appears first in the high field area and then in 1 K or so it starts appearing in the high pressure area. After the cycling took place, the voltage in the strand in the high field area in the ITER leg decreases and increases in the high pressure area (Fig. 6); the latter voltage is still lower than in the high field area. It is observed also, that the transition is broader in the high pressure area, presumably, an indication of mechanical damage of the filaments by the

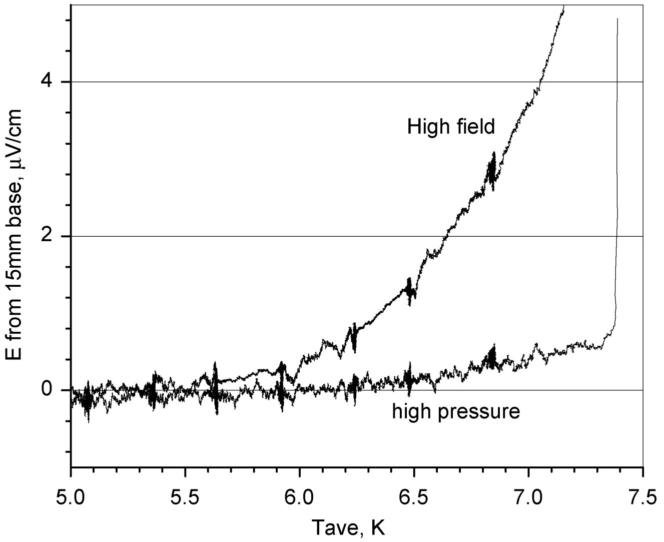

Fig. 5. Voltage signals from the ITER leg, same strand, in high field and high pressure areas at the first charge.

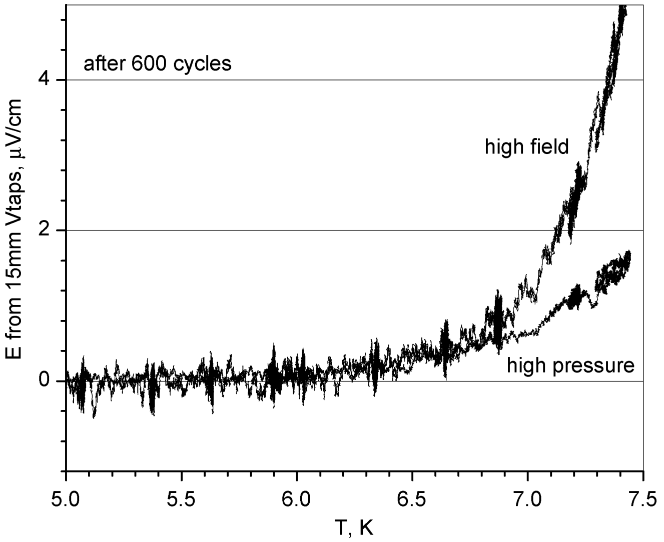

Fig. 6. Same voltage taps as in Fig. 5, after 600 cycles.

EM forces. Thus, some strands improve their characteristics, relieving stress after cooldown due to EM forces, and evidently some strands degrade. The Alt leg, showed similar performance as ITER leg, but the effect of cycles was much smaller.

These particular conductors did not show high degradation versus cyclic load, but some other ITER conductors did [8]. Although the high field area remained a “weak link” responsible for overall CICC performance, it seems possible that in high degrading conductors the weak link is in the low field area. That would require revision of our views on the Nb3Sn degradation in CICC, since at the moment all analyses on degradation assume that the voltage originates first in the high field area.

V. TEST ANALYSIS AND DISCUSSION

A. Comparison of the CICC Performance With the Strand Performance

The strands were characterized in four laboratories. In two laboratories (NIST and University of Geneva) the characterization took place on the Walter springs, while the other two laboratories measured Ic on the ITER barrels. Table I gives averaged results of the measurements. NIST and UG data are shown at the compressive strain of 0.1%. Note that the NIST data are taken at 4.0 K, not 4.2 K and no correction made for that in the Table I. The Luvata data are for 240 hr heat treatment at 650 C, the rest are for 200 hr at 650 C.

TABLE I
Ic(12 T, 4.2 K, −0.1%) OF LUVATA STRANDS USED IN TFUS1 LEGS

	Alt Ic, A	Alt jc, A/mm2	ITER Ic, A	ITER jc, A/mm2
Luvata	197	922	240	935
NIST	193	903	223	871
CRPP	181	847	208	812
U Geneva	190	889	230	898

As we can see, the scatter is significant. In the ITER community it is conventional to express the strand performance in the CICC in terms of “effective” uniaxial degradation, despite full realization that the stress conditions in the CICC are 3D. We used University of Geneva measurements, since these were the only ones performed at the elevated temperatures. Analysis showed that the effective strain was −0.52% for ITER specified strands and −0.51% for the Alt strands. The expected value was in the range of −0.6–0.7%, based on the previous experience. Post test measurements of the strain performed at the CRPP showed that the compression of the jacket was low. There are at least two possibilities. First, the cable slipped after heat treatment and following cooldown. This seems unlikely, since the ends are compacted to 20% void over 500 mm length. Second, the cable expands less than expected. We do not have data to verify this, but such low residual strain needs further investigation.

B. Comparison Between Performance of the Alt Cable and ITER Option I Cable Pattern

As we can see from Fig. 4, the Tcs of the Alt cable leg is higher than in the ITER leg by approximately 0.4 K and has lower sensitivity to the cycles. That is a very significant margin. In terms of critical current gain, it is equivalent to almost 17%, which shows that there is a reserve to boost the temperature margin of the ITER conductors by optimizing the cabling pattern.

VI. CONCLUSIONS

Both legs in the TFUS1 met ITER requirements with a comfortable margin. We proved that by proper preparation of the terminations it is possible to obtain a uniform current distribution and eliminate guesswork in the CICC performance assessment.

Using innovative penetrating voltage taps, we discovered that in our conductors voltage appears first in the high field area, but after cycles, voltage is generated also in the high pressure area of the cable, in the low field region. Transition in this area is much broader than in the high field region. That observation gives credence to the speculation that the broadening of the overall transition is explained by strand damage in the high pressure areas of the cable.

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