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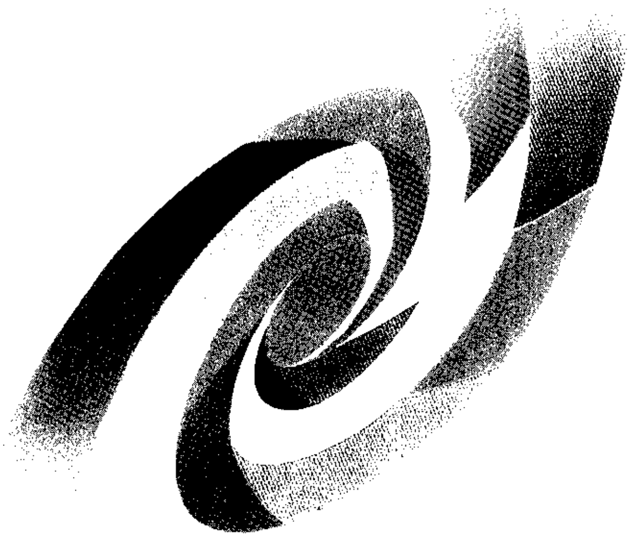

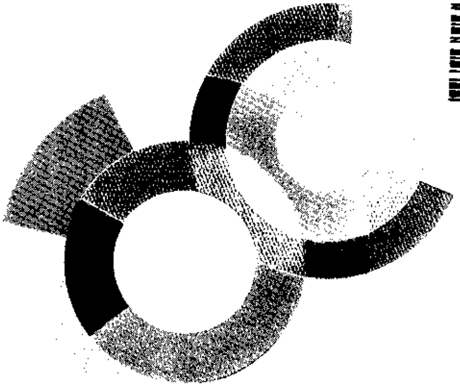

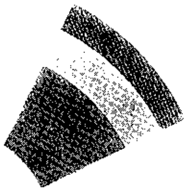

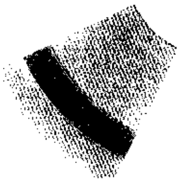

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TEST RESULTS AND ANALYSIS OF TWO EUROPEAN FULL-SIZE CONDUCTOR SAMPLES FOR ITER

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Test Results and Analysis of Two European Full-Size Conductor Samples for ITER

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Abstract-- **The European Home Team is responsible for the design, the fabrication and the test of the Toroidal Field Model Coil (TFMC) of the International Thermonuclear Experimental Reactor (ITER). Within this task, three full-size samples had to be fabricated by industry and to be tested in the SULTAN facility (Villigen, Switzerland). Each sample is composed of two parallel straight bars of full-size conductor, connected at bottom through a joint. This paper reports on the test results and analysis of the first two samples. We present the results of the critical current measurements performed on each conductor leg, the results of the measurements of the joint DC resistance and of the joint quench temperature, the results of joint loss and conductor loss measured under pulsed magnetic field. The results are analyzed through comparisons with predictions given by theoretical models. Conclusions are drawn for the expected performances of the TFMC and of the ITER coils.**

Index terms— **fusion, superconductor, cable, tests**

I. INTRODUCTION

Within the frame of the ITER TFMC project, two full-size conductor samples were fabricated in industry and tested in the SULTAN facility (CRPP, Villigen). Each sample allowed for testing two conductor legs and one joint. Mainly DC tests were performed with transport current up to 100 kA under magnetic field up to 11 T. In addition pulsed field losses could be studied thanks to additional pulse coils (field variations up to 0.5 T). These tests were used not only to assess the capabilities of the TFMC conductor and joints but also to bring practical information on the behaviors of the ITER conductors and joints.

II. SAMPLES PRESENTATION

The lack of space does not allow to give here a detailed description of the samples, this information can be found in [1,2]. Basically, each sample is composed of two straight bars of conductor, connected at bottom (the sample is tested in the vertical position) by a joint, and having at top two terminals for connection to the facility transformer. The test of the joint is allowed by lifting up the sample. The first sample is called the SS-FSJS, the second one is called the TFMC-FSJS.

A. Conductors

Both conductors are round twisted multistage cables embedded in steel jackets. The final conductors are ITER type cables-in-conduit with central channel, the external shape of the jacket is square in the SS-FSJS and circular in the TFMC-FSJS. Except for the jacket material (steel instead of Incoloy), these conductors are ITER relevant. On the other hand, the TFMC-FSJS makes use of the real TFMC conductor. The main features of these conductors are given in table I.

TABLE I
CONDUCTOR CHARACTERISTICS

	SS-FSJS	TFMC-FSJS
Strand diameter (mm)	0.81	0.81
Number of Nb_3Sn strands	1152	720
Superconducting strand type	internal tin	internal tin
Copper non-copper ratio	1.51	1.51
Number of pure copper strands	0	360
Cable twist pitch (mm)	440	440
Local void fraction (%)	36.5	36.5
Central spiral (id x od) (mm)	10 x 12	10 x 12
Cable diameter (mm)	38.7	37.5
Jacket outer dimension (mm)	□ 51	ϕ 40.7

B. Joints

Both sample joints were fabricated according to the twin-box design proposed by the EU for the ITER coils and retained for the joints of the TFMC. After a specific preparation, each cable end is compacted in a joint box machined in a copper-steel plate bonded by the explosive method [2]. In the SS-FSJS, the joint is made by soldering with PbSn the two copper soles of the joint boxes as in the TFMC inner joints (but with an intermediate copper wedge) [2], while in the TFMC-FSJS, the joint is made by

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welding (with electron beam) copper pins to both copper soles as performed in the TFMC outer joints [3].

III. JOINT TEST RESULTS

A. DC Tests

The joint DC resistances for the two samples are plotted in Fig. 1 as functions of the maximum magnetic field (i.e. applied field + self field). Each values has been calculated from the voltage drop measured at mid sample in order to eliminate the effect of the current transfer in the steel jacket on which the voltage taps are welded, although the voltage appeared to be quite uniform along the sample. Calorimetric measurements have confirmed these electric measurements but are less accurate. Note that the use of the maximum field is consistent with the joint "active part" location and thus allows to well include points obtained without external field ($B_{max} < 2$ T). It can be seen in Fig. 1 that the magneto-resistance is purely linear for each sample which shows no decohesion of strands on the copper soles as the Lorentz force increases. The resistance laws can be written as follow (R is in nΩ and B is in T) :

$$R_{joint}(\text{SS-FSJS}) = 0.54 + 0.10\ B_{max} \qquad (1)$$

$$R_{joint}(\text{TFMC-FSJS}) = 1.63 + 0.11\ B_{max} \qquad (2)$$

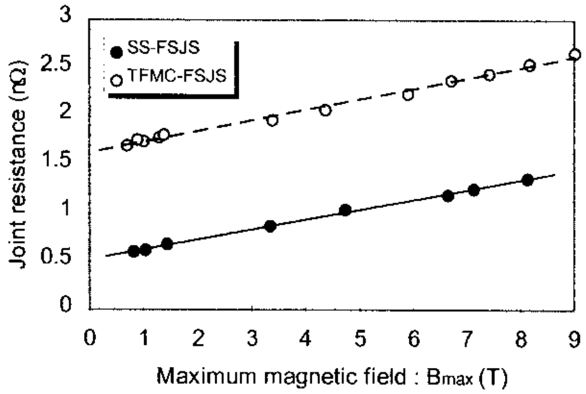

Fig. 1. Joint DC resistances (electric measurements)

The result obtained on the SS-FSJS is well in line with those expected for ITER joints from tests on subsize joint [1,4]. It can be noticed that the origin resistance (at $B_{max} = 0$) is about three times higher in the TFMC-FSJS than in the SS-FSJS, while a factor around 1.7 can be expected from the difference in the number of superconducting strands (see table I) and from the effective area of the electron beam weld. This result has been attributed to a degradation of the contact between the strands and the copper soles during the EB process due to possible oxidation and/or surface deformation, and/or lost of compressive stress, but none of these hypotheses has yet been validated.

The values plotted in Fig. 1 were measured at 4.7 K with rather high transport currents (from 30 kA to 100 kA). For a given field/current combination, as the temperature increases the joint resistance first remains constant then increases up to the quench of the joint. We have reported in table II the temperature T_{lim} up to which the resistance remains constant, then the ratio R_{cs}/R_{lin} of the joint resistance to the value plotted in Fig. 1 at the temperature of current sharing T_{cs} calculated from strand properties (at B_{max} and for a strain $\varepsilon = -0.75\%$ in the Nb_3Sn filaments), and finally the temperature T_q at which the joint quenches (average temperatures in the joint).

TABLE II
JOINT EXTENDED OPERATIONS

$B_{applied}$ (T)	I_{FSJS} (kA)	T_{lim} (K)	T_{cs} (K)	R_{cs}/R_{lin}	T_q (K)
		SS-FSJS			
5.5	99	8.1	8.3	1.02	> 9.2
6.7	87	7.5	7.7	1.01	> 8.7
9.0	68	-	6.6	-	8.3
		TFMC-FSJS			
4.5	80	6.7	8.8	1.07	9.5
5.5	80	5.5	7.9	1.06	8.3
6.7	70	< 5.0	7.5	1.11	8.1
7.4	45	6.0	8.0	1.09	9.4

It can be seen in table II that both joints were able to operate at their theoretical current sharing temperatures with only slight increases of the joint resistance, and that the quench temperatures were still higher. Comparing the two samples, the TFMC-FSJS appears again degraded which is in relation with the degraded resistance and could be due to a degradation of the current distribution among strands.

B. Pulsed Field Tests

For the SS-FSJS, only single trapezoidal pulses were used, then direct measurements of the magnetization relaxation time constant have led to a value : $\tau = 2.5$ s, while the calorimetric method (helium enthalpy increase) has led to a much lower value : $\tau = 0.44$ s. The latter gives a loss (per unit strand volume) time constant of : $n\tau = 2.2$ s.

For the TFMC-FSJS, sinusoidal waves with amplitude ± 0.1T were applied during 70 s to the joint. Loss power was measured by calorimetry (helium temperature increase). We have plotted in Fig. 2 the loss per cycle as function of the wave frequency, for background fields of 1 T and 6 T.

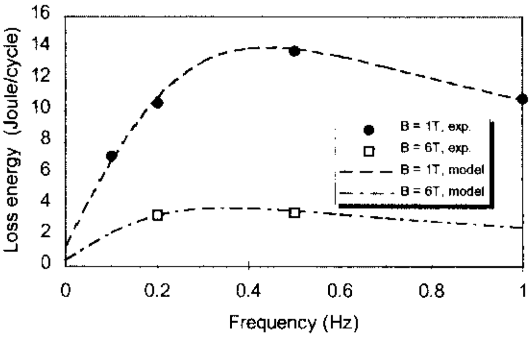

Fig. 2. TFMC-FSJS joint : pulsed field losses

Assuming a system with a single time constant τ, the loss can be theoretically calculated, including hysteresis loss in Nb_3Sn filaments [5]. We have fitted the experimental results of Fig. 2 by adjusting τ and the associated volume V in our model (see Fig. 2 and table III).

TABLE III
VALUES OF TFMC JOINT MODEL PARAMETERS

	fit from experiment			expected values [4]		
B (T)	τ (s)	V (cm³)	nτ (s)	$n\tau_c$ (s)	$n\tau_E$ (s)	nτ (s)
1	0.36	510	1.10	1.9	7.7	9.6
6	0.45	135	0.36	1.9	2.4	4.3

Note that nτ is defined in the usual way from the loss per unit strand volume (i.e. for 334 cm³), with n = 2.

The good fit at 1 T (up to 1Hz) is rather surprising since the loss is expected to come from a combination of the coupling currents in the cables and of the eddy currents in the copper soles (with respectively associated $n\tau_c$ and $n\tau_E$ as well as total nτ given in table III). It can be seen in this table that the measured losses are much lower than expected and that the decrease at 6 T comes from a decrease of V instead of τ. For coupling loss, higher interstrand resistance can be invoked associated with current saturation at 6 T, for eddy current loss higher copper RRR can be invoked. However, only transient regimes with strongly magnetic coupling could explain such results.

IV. CONDUCTOR TEST RESULTS

A. DC Tests

By lowering the sample in the SULTAN field, the critical current of each conductor leg could be measured. The voltage drop over one cable twist pitch length centered in the high field was measured and the same criterion as the one used for strand critical current (i.e. 0.1 µV/cm) has been retained. The results are presented in Fig. 3 and in Fig. 4 (see Ic_exp). Measurements were performed either with increasing temperature or with increasing current.

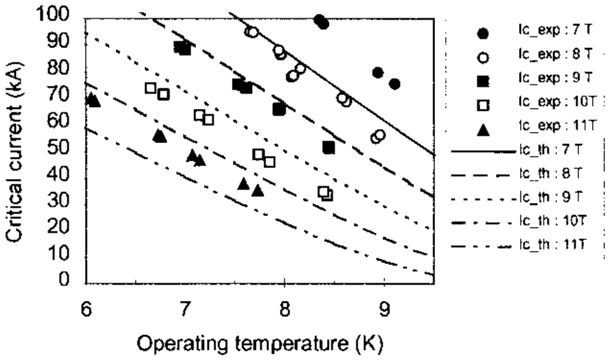

Fig. 3. Critical current of SS-FSJS conductor (both legs)

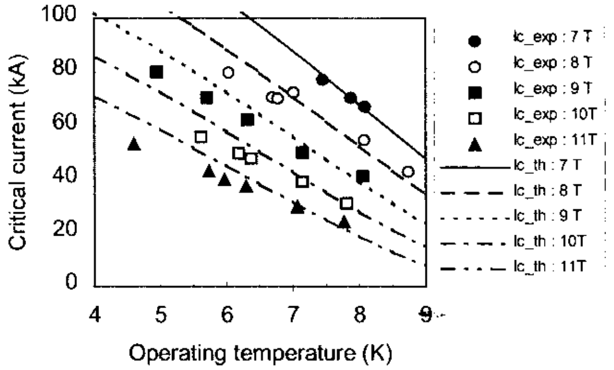

Fig. 4. Critical currents of TFMC-FSJS conductor (right leg)

Note that for the SS-FSJS the two legs were very similar while for the TFMC-FSJS, the left leg was about 6% lower in critical current.

We have plotted in Figs. 3 and 4 the curves expected from strand properties (see Ic_th), at the peak field on the sample (including self field), and for the expected strain in Nb_3Sn (i.e. ε = -0.65% in the SS-FSJS and ε = -0.60% in the TFMC-FSJS). It can be seen that the critical currents of the first sample are above the theoretical curves which looks normal because the peak field is located only on a small area of the cable. On the other hand, the TFMC conductor reached hardly the theoretical curves, which has been explained by a poor uniformity of the current distribution among strands due to the joint (see sec. III.A).

Only a few quench experiments were performed on the SS-FSJS, they generally led to quench currents about 10% in excess of the critical currents. On the TFMC-FSJS, every test was continued up to quench and the results are reported in Fig. 5 (see Iquench).

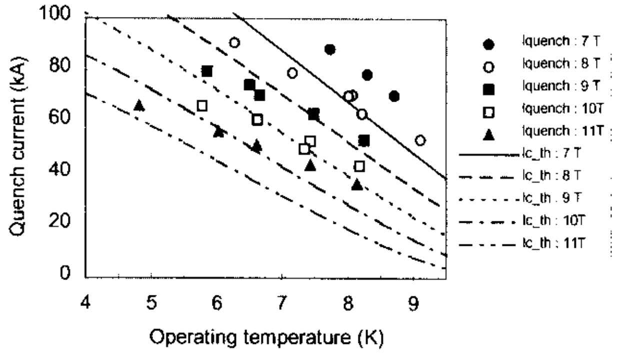

Fig. 5. Quench currents of TFMC-FSJS conductor (right leg)

It can be seen in Fig. 5 that all the quench points lie above the theoretical critical currents (idem for left leg) and that they are well above the experimental critical currents (see Fig. 4). This result tends to show that there is no degradation in term of transport current capability but rather a premature current transfer due to the proximity of the joint thus leading to low critical currents.

B. *Pulsed Field Tests*

On the SS-FSJS single trapezoidal pulses were used, then magnetization relaxation time constant have led to a value : $\tau \approx$ 30-80 ms, while the losses calculated from the area of the magnetization loop have led to : $n\tau = 51$ ms.

For the TFMC-FSJS the same method as for the joint was used and the results are plotted in Fig. 6. Using again a simple model, one get there : $n\tau = 5.4$ ms (see Fig. 6). It can be seen in this figure a clear increase of the loss when a transport current flow through the cable at 6 T, this phenomenon which appears as an apparent increase of the hysteresis loss is certainly due to the saturation of current in several strands. In the model, they have been simply replaced by an increase of 0.82 J/cycle (left leg) and of 0.55 J/cycle (right leg). Since τ is quite low, this saturation effect must be certainly associated with a strongly uneven current distribution among strands in the cable.

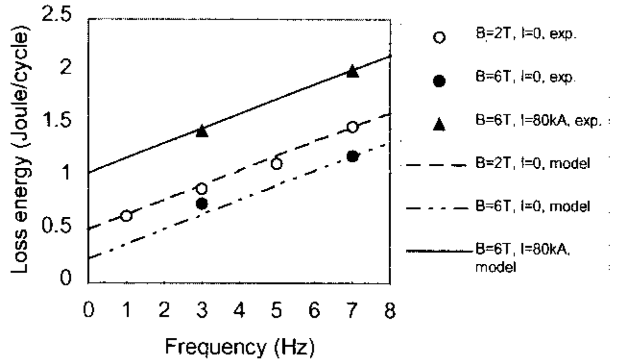

Fig. 6. TFMC-FSJS conductor : pulsed field losses (left leg)

Some direct measurements of the relaxation time constant were performed on the TFMC-FSJS legs too, values of $\tau \approx$ 50-100 ms were observed, which again appear quite high compared to the value obtained with calorimetric measurements.

V. DISCUSSION

Experiments seem to show the influence of the joint on the conductor critical current measurements. This is not surprising since the high field region is located very close (about 13 cm) to the joint which determines current distribution among strands, and in which main current transfer occurs. Such results show the difficulty to extrapolate sample results to a real ITER coil in which peak field region is located very far from the joints. On the other hand, considering the quench current appears rather not reliable and optimistic, indeed the quench is a thermal instability depending on operating mass flow rate, pressure, and above all on conductor length under high field (due to heat accumulation along length). We have developed a model based on an electrical network, taking into account a realistic current distribution among strands, the self field of the sample, and interstrand resistances [6]. The interest of such a model is to get intrinsic values of parameters from the SULTAN tests for further extrapolations. The first simulations performed with this model have given a value of $\varepsilon = -0.59\%$ in the SS-FSJS conductor but have shown that experimental V(I) curves cannot be fully found with only one constant value of the interstrand resistance (i.e. it should increase with current) which can be explained by the cable multistage structure.

VI. CONCLUSIONS

The tests of the first two European full-size conductor samples for ITER have confirmed the good behavior of the EU joint design for the ITER coils. For the SS-FSJS joint, very good results well in line with the subsize joints have been obtained, while the relative degradation observed on the TFMC-FSJS joint has been attributed to the electron beam welding of the copper soles. As the former joint is a model of the TFMC inner (high field) joints and the latter is a model of the TFMC outer (low field) joints, we can be confident in the good behaviors of the coil joints.

The SS-FSJS conductor exhibited quite high critical currents in agreement with basic strand properties, while the TFMC-FSJS conductor showed again some relative degradation which has been explained by the effect of the joint. On the other hand, high quench currents have been found on this sample. Extrapolation to a real ITER coil is not straightforward and requires a complex model which is yet under improvement.

The pulsed field losses measured by calorimetry under sine wave have been found to be much lower than expected and than measured previously, as well for the joints as for the conductor legs. Although the measurements seem to be correct, further investigation will be needed to cross-check these values.

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