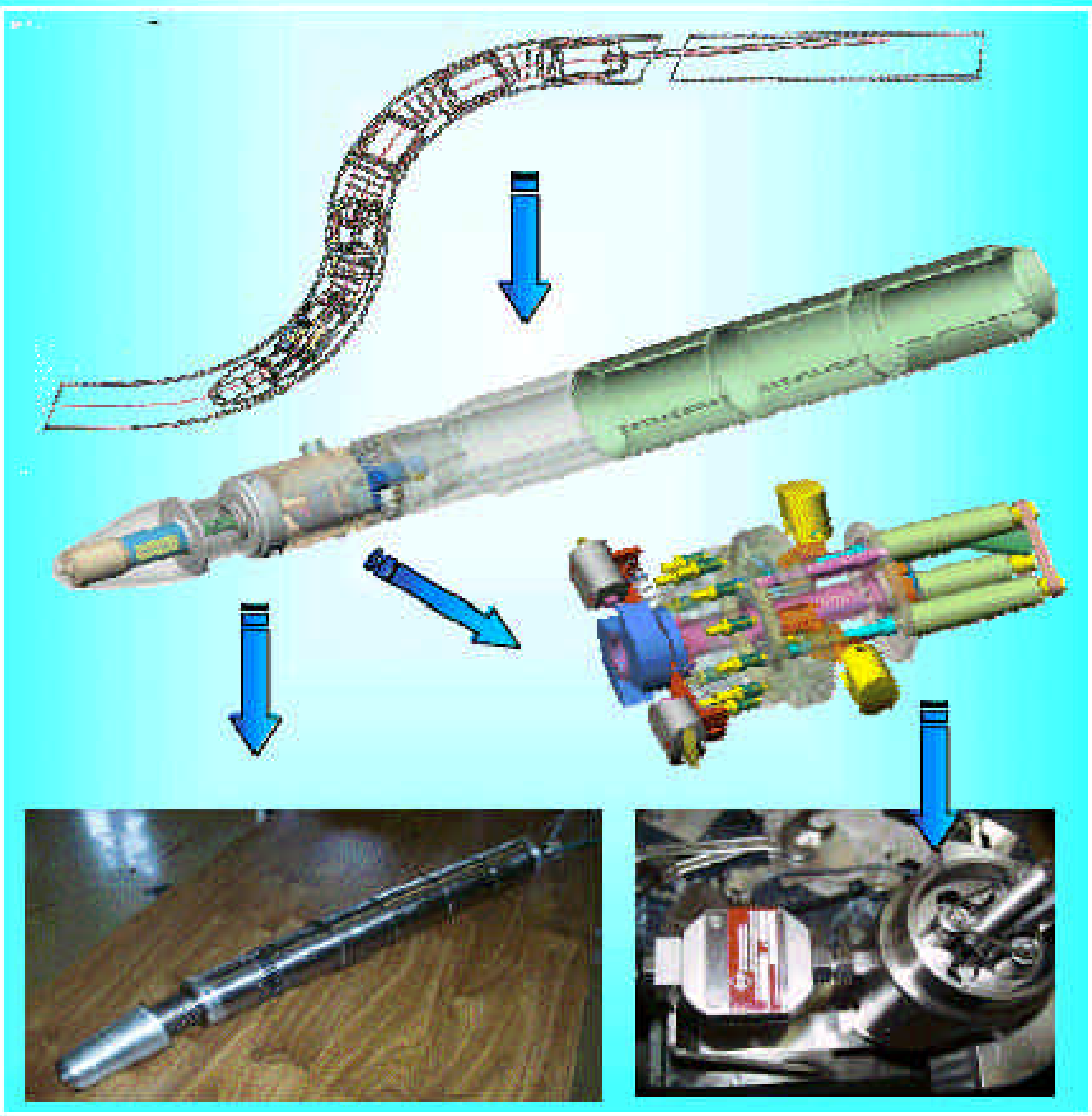
FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA 1999

Compiled by : Ph. MAGAUD



ASSOCIATION CEA/EURATOM
DSM/DRFC

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Cover : Carrier and bore tools for 4" bend pipes

CNET 96-432

Task Title : TECHNICAL SPECIFICATIONS FOR MODELLING, TESTING AND ANALYSIS OF FULL SIZE ITER JOINTS

INTRODUCTION

Within the framework of NET contract #94-345, CEA was in charge of designing the EU proposal of joints for the ITER coils, a full size prototype sample (FSJS) was then designed. Within the framework of the ITER TF Model Coil manufacture, three joint samples were fabricated in industry under technical monitoring by CEA. The first sample, called the SS-FSJS, uses an ITER type Nb_3Sn cable-in-conduit embedded in a thick steel square jacket (ITER CS1 type).

The lower joint is similar to the inner joints of the TFMC : each cable end is compacted in a copper-steel joint box machined in a copper-steel plate bonded by the explosive method, and the two copper soles of the joint boxes are soldered together with PbSn. The second sample, called the TFMC-FSJS, uses the TFMC conductor which is an ITER type Nb_3Sn cable-in-conduit embedded in a thin steel circular jacket (ITER TF type).

The lower joint is similar to the outer joints of the TFMC : the joint boxes are identical to those of the first sample, but the copper soles are connected thanks to transverse copper pins welded by electron beam to both soles. The third sample, called the TF-FSJS, uses the TFMC cable embedded in a thin Incoloy 908 jacket, fully relevant to the ITER TF coils.

The lower joint is similar to the SS-FSJS joint except for the use of Incoloy-copper joint boxes machined in an Incoloy-copper plate bonded by the explosive method. The joint itself is made by soldering with PbSn the two copper soles of the joint boxes. The three samples were tested in the SULTAN facility (CRPP Villigen, Switzerland), the tests concerned the DC resistance, the quench temperature and the pulsed field losses of the joint, as well as the critical current, the quench current and the pulsed field losses of both conductor legs.

Contract 96-432 was dedicated to the modelling of the DC behaviour of the joint (and of the conductor) and to interpretation and analysis of test results of the three above full size joint samples. In addition, this contract covered the participation of CEA in the tests and in the data analyses of these samples. It should be noted that because the US Home Team could not test the SS-FSJS in PTF (MIT, Boston), this test was replaced in the contract by the test of the TF-FSJS in SULTAN (not initially included in this contract).

1999 ACTIVITIES

Our activities in 1999 were first dedicated to complete the analysis of the tests of the SS-FSJS [1]. It should be noted here that this analysis had to be partly redone later due to a mistake made by CRPP in the measurement of the sample current (about 25% too low) and which was discovered only in May 99. Second, we had to define the test program of the TFMC-FSJS [2], to participate in this test and to analyse the test results [4]. Third, we had to define the test program of the TF-FSJS [3], to participate in this test and to analyse the test results [5]. Finally, the application of our DC electrical model to the sample tests led us to validate and to improve this model, and to perform application of this model to the ITER TF coils and to the TF Model Coil [6].

JOINT TESTS

The DC resistances of the joints were determined using electrical measurements and were cross checked with calorimetric measurements. In order to adopt a more general point of view, the joint resistances have been plotted in fig. 1 as functions of the maximum magnetic field on the joints (i.e. SULTAN field + sample self field), which allows to include points without SULTAN field. It can be seen in this figure that, as soon as $B_{max} \geq 1$ T, the magneto-resistance effects are constant. This result is more remarkable than it first looks because it shows that no decohesion has been observed between superconducting strands and copper sole in all joint boxes as the exploding electromagnetic force increases.

It should be first noted that the SS-FSJS resistance is the lowest value ever measured so far on an ITER FSJS joint, second that this resistance is well in line with the values measured on subsize joints, and third that the TF-FSJS resistance is also well in line with all these results, taking into account the lowest number of superconducting strands in the cable (720 instead of 1152 in the SS-FSJS). Finally, only the TFMC-FSJS joint resistance appears too high (compared to the TF-FSJS), although remaining low enough for its use in the TFMC. This result, which has been confirmed on a subsize joint, 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.

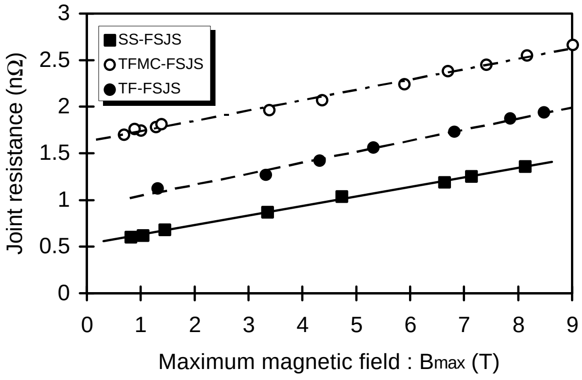

Figure 1 : Joint resistances as function of maximum magnetic field on joint

The values plotted in fig. 1 were measured at 4.7 K with rather high transport currents (50 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 found that all joints were able to operate at their theoretical current sharing temperatures with only an increase of their resistances, and that the quench temperatures were higher. The quench temperatures of the TF-FSJS joint have been found to be about 1 K higher than the values got on the TFMC-FSJS, which can be attributed to the lower strain in the Nb_3Sn filaments because of the use of an Incoloy-copper joint box instead of a steel-copper box. However, it should be noted that this gain is lower than expected from the fully bonded model (about 1.7 K).

The joint pulsed field losses were measured using the facility pulsed coils. For the SS-FSJS, the magnetisation relaxation time constant τ was found to be 2.5 s at 6 T, while the calorimetric method for one trapezoidal shot led to a much lower value of τ (0.44 s at 2 T), equivalent to a loss (per unit strand volume) time constant of : $n\tau = 2.2$ s. For the TFMC-FSJS and the TF-FSJS joints, sinusoidal waves with amplitude $\pm$ 0.1T were applied during 70 s to the joint. Loss power as function of frequency was measured by calorimetry and led respectively for the TFMC-FSJS and the TF-FSJS to loss time constants $n\tau$ of 1.10 s and 2.64 s at 1 T, and 0.36 s and 1.55 s at 6 T.

These values are much lower than expected (9.6 s at 1 T, 4.3 s at 6 T) which can be explained by the use of pulses with too high frequencies ($\geq$ 0.1 Hz) and they show that the SULTAN pulse coils are not suitable for measuring AC loss in joints. Note that the loss decrease at 6 T can be explained by current saturation in strands and by increase of copper resistivity.

CONDUCTOR 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 centred in the high field was measured and the same criterion as the one used for strand critical current (i.e. 10 μV/m) has been retained, results are presented in figs. 2 and 3.

We have plotted in figs. 2 and 3 the curves expected from strand properties (see Ic_th), assuming uniform current distribution among strands, at the peak field on the sample (including self field), and for the expected strain in Nb_3Sn (see ε_{ITER} in Table I).

As concerns the SS-FSJS, the experimental points have been found higher than the theoretical curves with both legs very similar (see Fig. 2), which is a normal result since the maximum field is applied only to a small area of conductor. For the TFMC-FSJS, the critical currents of the left leg were about 6% lower than the right leg which itself had critical currents equal or lower than the theoretical curves (see fig. 3).

This result has been attributed to the proximity of the degraded joint. Due to leaks detected on both legs of the TF-FSJS after three tests, only a few data are available, however they clearly show that the critical currents at 9 T were lower than the theoretical curve.

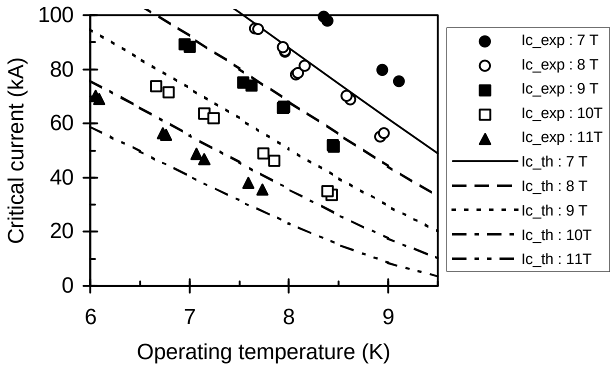

Figure 2 : Revised critical current of SS-FSJS conductor (both legs)

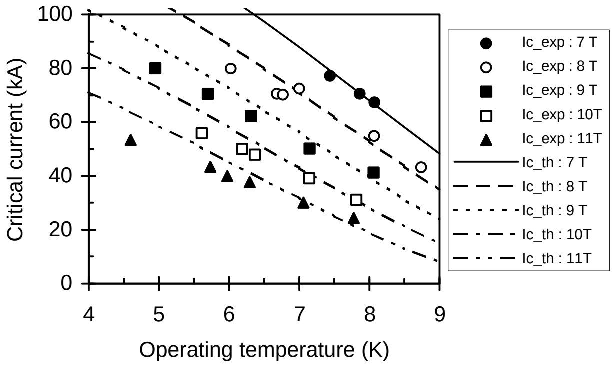

Figure 3 : Critical current of TFMC-FSJS conductor (right leg)

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 quench currents were all found above the theoretical critical currents (both legs), while for the TF-FSJS the only available point lies just on the critical curve.

Pulsed field loss measurements have led to rather confusing results because a value of $n\tau$ = 51 ms has been found on the SS-FSJS conductor using magnetisation technique, while a value of 5.4 ms has been found on the TFMC-FSJS using calorimetric method. This point needs to be clarified by a further cross check.

VALIDATION OF THE CEA DC ELECTRICAL MODEL

Before the application to the FSJS's tests the following improvements of the CEA DC electrical model were introduced :

- the statistics of contact points per strand in the joint has been obtained from a full size mock-up,
- the magnetic field gradient due to the self field and the strand/field angle have been taken into account,
- the lower joint has been modelled in details.

The comparisons between experiments and theoretical predictions have been made considering the whole voltage/current characteristics and not considering only the single value of the critical current. After a final improvement of the model through a better relevance to the cable structure, good agreement with the experimental curves of all the samples have been obtained.

The case of the TF-FSJS required a specific modification of the model (change in series resistance statistics at joint) to take into account the degraded performances of the joint welded by electron beam. The adjustment of the free parameters used in the model to fit the experimental characteristics of the three samples has led to give values to these parameters for the different conductors and joints used in these samples.

The case of the strain in the Nb_3Sn filaments is of particular interest and the results have been reported in table 1, where the values given by the model to fit the experimental results (ε_{exp}) are compared to the values determined according to the ITER rules from the fully bonded model (ε_{ITER}).

It can be seen that the two steel jacketed conductors have shown lower strains than expected, while the Incoloy jacketed conductor has shown higher strain than expected, although remaining lower than the steel conductors. Similar results have been found on the joints of these samples.

Table 1 : Estimated strain in Nb_3Sn filaments in the three samples

Sample	Conductor		Joint	
	ε_{ITER} (%)	ε_{exp} (%)	ε_{ITER} (%)	ε_{exp} (%)
SS-FSJS	-0.65	-0.59 ± 0.01	-0.75	-0.61 ± 0.01
TFMC-FSJS	-0.61	-0.49 ± 0.01	-0.75	-0.60 ± 0.01
TF-FSJS	-0.25	-0.41 ± 0.01	-0.32	-0.42 ± 0.01

APPLICATION TO ITER COILS AND TO TFMC

The application of the CEA DC electrical model to the ITER TF coils has shown that the current distribution among strands at peak field is quite uneven at the operating temperature (4.75 K) with about 10% of the strands which do not carry any significant current (in both single pancake and double pancake windings), although the DP winding leads to a more uniform distribution than the SP winding. The overload factor for strand current is thus about 1.5 in the SP winding against 1.3 in the DP winding, but the electric field along the most loaded strands remains below 1 µV/m in the SP winding against 0.1 µV/m in the DP winding. The current distribution (at peak field) is improving as the operating temperature increases and is almost uniform at 6.5 K in the SP winding against 6.0 K in the DP winding. Finally, the electric field along the strands tends to become more uniform among the strands as the temperature increases and reaches about 10 µV/m at 6.75 K for both windings, which is in agreement with the design temperature margin of 2 K.

The TFMC is not well placed as concerns the current distribution at peak field because of its single pancake winding and of its peak field located close to the inner joint. Moreover this joint is located in a rather high magnetic field and will compete with the peak field length to be the weakest point of the coil. For 80 kA in the coil alone, and at the operating temperature of 4.5 K, there are about 30% of strands which do not carry any significant current and the overload factor for strand current is about 2.5 (peak field and inner joint), although the electric field along the most loaded strands remains below 1 µV/m at peak field against 0.01 µV/m in joint. The current distribution is improving as operating temperature increases and the maximum electric field reaches 10 µV/m for about 8.3 K at peak field, against 8.1 K in the joint. However at these temperatures the current distribution is not yet uniform. Nevertheless, the coil should be able to reach its design current sharing temperature of 8.0 K.

CONCLUSIONS

The tests of the three European full-size joint samples have confirmed the validity of the CEA twin-box concept for the ITER coils, using a steel-copper joint box for steel jacketed conductors and an Incoloy-copper joint box for Incoloy jacketed conductors. Very good results have been obtained as concern the joint DC resistance and the temperature margin, although a "degradation" has been observed on the joint connected with electron beam welding. No reliable information regarding joint loss under pulsed field has been gained because of the limitation of the SULTAN pulsed coils.

The joints have also allowed a good test of the associated conductor legs showing critical currents more or less at the level of the usual design criterion.

The CEA electrical model has been validated and improved by the FSJS tests and has led to rather unexpected values of the strain in Nb_3Sn for the different conductors : the steel conductors having lower strain than expected and the Incoloy conductor having higher strain than expected, although lower than the steel. From the work performed to model the full-size samples, the models used for the ITER TF coils (single and double pancake windings) and the TFMC have been greatly improved, thus the predicted performances of these coils can now be seen with more confidence. The current distributions at nominal operating conditions appear then less uniform than predicted before for all the coils. However, the temperature margins under steady state regime remain all satisfactory and in agreement with the original designers expectations.

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[2] D. CIAZYNSKI - TFMC-FSJS Testing Program in SULTAN - Note NT/EM/99/30 - May 28, 1999.

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[5] D. CIAZYNSKI, J.L. DUCHATEAU, A. MARTINEZ, T. SCHILD - NET Contract 96-432 : Report on Analysis of Experimental Results - Note AIM/NTT-1999.060, October 10, 1999.

[6] D. CIAZYNSKI - NET Contract 96-432, Final Report : Report on Final Application to ITER Coils and to TFMC - Note AIM/NTT-1999.067, December 13, 1999.

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M40

Task Title : DESIGN WORK ON MAGNET R&D

INTRODUCTION

The aim of the task is to perform the design work linked to the R&D for the magnet program in Europe, in close cooperation with the other european laboratories. This includes the participation to the ITER TF Model Coil (TFMC) programme [1]. The conceptual design of the TFMC was issued in 1995 [2] and the AGAN consortium (Ansaldo, GEC Alsthom, ACCEL, Preussag Noell) was selected as manufacturer at the end of 1995. After completion of the manufacture, the coil will be delivered to FzK (Karlsruhe, Germany) were it will be tested in the TOSKA facility. The delivery of the coil in Karlsruhe is scheduled for July 2000.

1999 ACTIVITIES

MANUFACTURE OF THE TF MODEL COIL

The manufacture of the double pancakes was completed at Ansaldo in April 1999 and the last one delivered to Alstom on 7 May 1999. The double pancakes were then stacked one above the others with glass-cloth sheets in between. The stacking was impregnated with epoxy resin and polymerized at the beginning of June 1999 (Fig. 1).

Figure 1 : Stacking of TFMC double pancakes

A set of pin holes was then drilled in the outer terminations (Fig. 2) and copper pins inserted. The double pancake assembly was then shipped to DCN Indret, where the copper pins were electron beam welded to the copper soles of the outer terminations (Fig. 3). The winding-pack was then ground insulated with glass-polyimide and glass-cloth tapes wrapped around the double pancake assembly [3], [4].

Figure 2 : Pin hole drilling in TFMC outer terminations

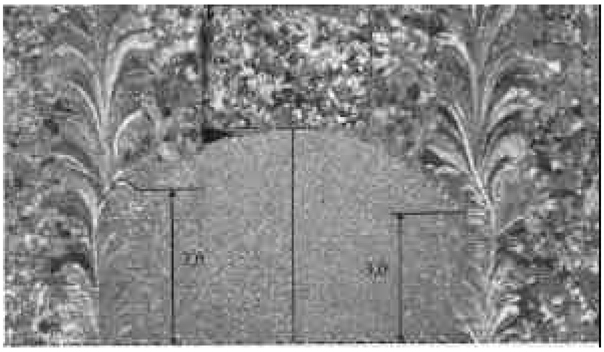

Figure 3 : Electron beam welding of outer terminations

The winding-pack was then impregnated with epoxy resin and polymerized. After demoulding a set of dimensional, electrical and hydraulic tests were performed (Fig. 4).

Figure 4 : TFMC winding-pack after polymerization

They showed that the measured values were all within the specifications. The coil case was machined in order to prepare the insertion of the winding-pack into it (Fig. 5). The operations of insulation and outer joint welding required much more time than expected, which as a consequence shifted the expected delivery of the coil to summer 2000.

Figure 5 : Machined TFMC case

TFMC-FULL-SIZE-JOINT-SAMPLE

A prototype joint sample of the outer joints, called TFMC-FSJS, was manufactured by the AGAN consortium and tested at CRPP (Villigen, Switzerland) in the SULTAN facility [5]. This prototype sample was built using a TFMC conductor, the legs had been manufactured and heat treated by Ansaldo and Alstom performed the assembly and the installation of the instrumentation. This sample incorporated copper pins welded by electron beam to the termination box copper sole, so as to be relevant to the outer joints of the TFMC. The measured joint resistance could be fitted with the law : Rjoint (nΩ) = 1.63 + 0.11 B_{max}. This low value qualified the electron beam joining technology for the TFMC outer joints.

TF-FULL-SIZE-JOINT-SAMPLE

A prototype joint sample, called TF-FSJS, was manufactured by Ansaldo and tested at CRPP in the SULTAN facility . This prototype sample was built using a TF conductor, with the same cable as the TFMC conductor, but with an incoloy 908 jacket. The terminations boxes were made out of an incoloy/copper explosion bonded plate.

The heat treatment of the legs was performed after shot peening of the outer surface and with inner circulation of argon with very low oxygen content. The joining technology used tin-lead soldering, in a similar way to that used for the TFMC inner joints . The measured joint resistance could be fitted with the law : Rjoint (nΩ) = 0.93 + 0.12 B_{max}. This value is fitting well with the expected resistance for the inner joints of the TFMC. A comparison of the results of joint resistance measurements performed for the three EU prototype samples is shown in Fig. 6.

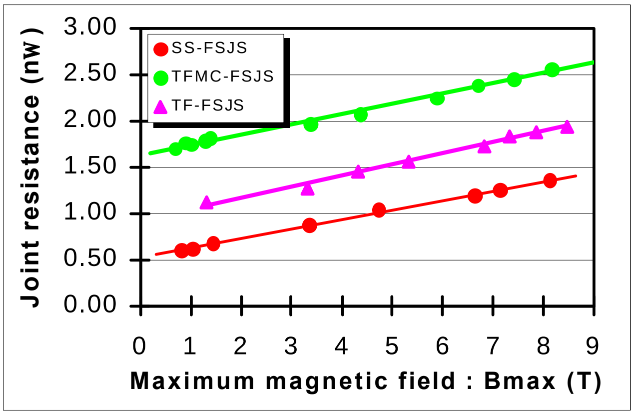

Figure 6 : FSJS resistance

TFMC CONDUCTOR HYDRAULIC CHARACTERISTICS

The thermohydraulic analyses of the TFMC require a modeling of the conductor taking into account two hydraulic circuits in parallel : the bundle channel and the central channel. The hydraulic characteristics of the bundle channel had already been determined. Those of the central channel were determined from pressure drop measurements performed with pressurised nitrogen in the OTHELLO facility on several central spirals [6]. The variation of the friction factor versus the Reynolds number is shown in Fig. 7 for both types of spirals used in the TFMC conductor.

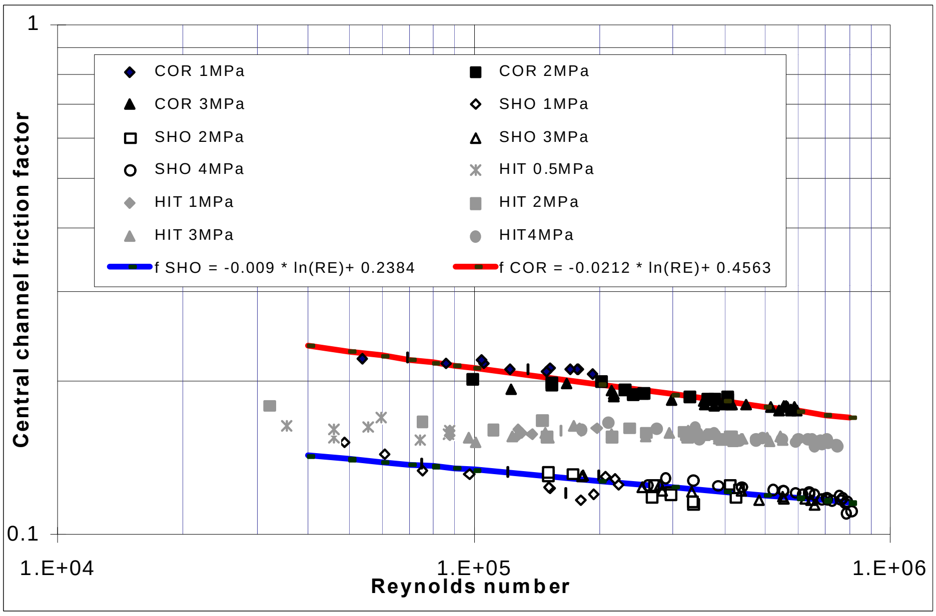

Figure 7 : Central channel friction factor

CONCLUSION

The manufacture of both TFMC winding-pack and case was completed. At the end of 1999, the coil was ready for insertion of the winding-pack inside the case Owing to longer time needed than expected for insulation and outer joint elding, the coil delivery is now expected for summer 2000.. The results of the tests of the prototype joint samples showed very low resistance both for inner and outer joint types, which gives confidence for the achieved resistance in the TFMC joints. Pressure drop measurements allowed to build an hydraulic model of the TFMC pancakes taking into account the dual channel system for the conductor.

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[5] Test results and analysis of two European Full-Size conductor samples for ITER, D. Ciazynski et al., MT16, Ponte Vedra Beach, 26 September – 02 October 1999

[6] Dual channel cable-in-conduit thermohydraulics : influence of some design parameters

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Task Title : CONDUCTOR R&D Development of NbTi conductors for ITER PF coils

INTRODUCTION

The development of NbTi conductor has to address several questions:

- Characterisation of NbTi strands in a range of temperature between 3.5K and 7K.

- Control of the conductance between strands by strand surface coating or CuNi internal barrier at the proper level in the range 10^7 $(\Omega m)^{-1}$. The solution has to take into account the temperature of the curing step.

- Connections: design and fabrication procedures have to be confirmed and tested in the connection test facility on subsize conductors in JOSEFA. The strand-copper sole contact cannot be treated as for Nb3Sn due to the absence of high temperature heat treatment.
  The removal of the coating if any has to be specifically addressed.
  The impregnation heat treatment occuring after the connection fabrication of real coils and the final joint soldering has to be considered.

- Conductor behaviour: The operation margin can be assessed on subsize conductors in JOSEFA.

The development can be led on cable and jacket dimensions compatible with the existing fabrication tools (cabling + jacketing) and the existing test facilities.

1999 ACTIVITIES

MANUFACTURE OF SUBSIZE SAMPLES FOR AC LOSSES MEASUREMENT

The present part of the task was the procurement of 5 sub-size NbTi samples manufactured using different selected coatings of the strand or CuNi barrier strand. For the samples manufacture, five different strands were manufactured by Alstom with the characteristics presented in Table 1.

The sample using internal CuNi barrier (#10) was previously manufactured in the frame of task M29 [1]. The four others samples were manufactured by SMI using the previously described strands (#13, 14 15 and 16). The cabling was performed using a 3x3x4 cabling pattern (36 strands) as it was performed for sample #10 (see Table 2).

Table 1 : Strands characteristics

NbTi strand type	Reference number (CEA)	Diameter	Quantity
Internal CuNi barrier (*)	10	0.81 mm	From material ordered during task M29 (200 kg)
Bare wire	13	0.81 mm	350 m
Nickel plating	14	0.81 mm	350 m
Stabryte plating	15	0.81 mm	700 m
Chrome plating	16	0.81 mm	350 m

(*) The strand #10 with internal CuNi barrier was previously manufactured and fully characterized in the frame of the task M29 [1].

An oxidation heat treatment was performed on the half length of cable using the strand #15 (stabryte plating) before the jacketing in order to control the electric conductivity of stabryte by oxidation.

This heat treatment was performed in a CEA oven under dry circulating air at 200°C during 8 hours. Figure 1 shows a view of the cable on its support after the heat treatment.

Note that the second half length of cable using strand #15 was also oxidised in the same atmosphere but with the following heat treatment cycle 172°C x 7h + 212°C x 1h. This second length was not jacketed and was kept as a backup.

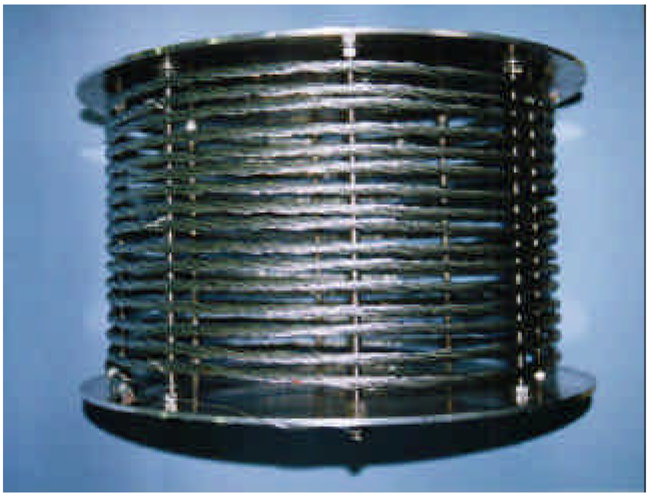

Figure 1 : The stabryte coated cable (#15) after oxidation heat treatment on its support

Each cable (#13 to #16) was then jacketed with a 1 mm thick 316L steel tube and compacted up to a void fraction of 34±1% as it was also performed for sample #10.

The final general characteristics of the samples are summarised in Table 2. The characteristics of sample #10 were previously measured in the frame of task M29.

Table 2 : Samples characteristics

	Internal CuNi barrier	Bare wire	Nickel plating	Stabryte plating	Chrome plating
Sample reference	10	13	14	15	16
Cabling pattern	3 x 3 x 4	3 x 3 x 4	3 x 3 x 4	3 x 3 x 4	3 x 3 x 4
Void fraction	33.2 %	34 ± 1 % (*)	34 ± 1 % (*)	34 ± 1 % (*)	34 ± 1 % (*)
Strand twist pitch	8 mm	18 mm	15 mm	16 mm	16 mm
Twist pitch stage 1	30 mm	25 mm ± 10 % (*)	25 mm ± 10 % (*)	25 mm ± 10 % (*)	25 mm ± 10 % (*)
Twist pitch stage 2	86 mm	70 mm ± 10 % (*)	70 mm ± 10 % (*)	70 mm ± 10 % (*)	70 mm ± 10 % (*)
Twist pitch stage 3	140 mm	120 mm ± 10 %	120 mm ± 10 %	120 mm ± 10 %	120 mm ± 10 %
Available length	3 m	≈ 6 m	≈ 6 m	≈ 6 m	≈ 6 m

(*) Theoretical characteristics

UPGRADING OF THE EXISTING VARIABLE TEMPERATURE CRYOSTAT TO ALLOW TESTS AT TEMPERATURE LOWER THAN 4.2K

This activity is planned in the year 2000.

MANUFACTURE OF TWO SAMPLES OF SUBSIZE CONNECTIONS AND CONDUCTORS RELEVANT TO PF OPERATION WITH SEVERAL VERSIONS OF CONNECTIONS

This activity is planned in the year 2000.

UPGRADING OF THE EXISTING JOSEFA TEST FACILITY FOR THE TEST OF TWO SUBSIZE CONNECTIONS

A new control system for the test facility JOSEFA was ordered by the end of 1999. This installation will be operational at the beginning of the year 2000 and will allow to test the NbTi subsize samples for the connections as well as for the conductor performances.

EQUIPMENT FOR A FULL SIZE NbTi CONDUCTOR RELEVANT OF PF ITER COILS

The beginning of this activity is planned during the year 2000.

CONCLUSIONS

During the year 1999, five NbTi samples devoted to AC losses and interstrand contact resistance to address the problem of the coating of the strand were manufactured.

These samples were cabled using different NbTi strands such as bare wire, nickel plating, stabryte, chrome plating and internal CuNi barrier. The stabryte cable was oxidised in dry air before jacketing. The jacketed samples were then sent to the University of Twente for tests. One sample (Bare wire) will be tested during the year 2000 in parallel at CEA for cross checking.

The upgrading of the test facility JOSEFA was engaged and will allow to test the subsize NbTi samples for the conductor as well as for the connection performances.

REPORTS AND PUBLICATIONS

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