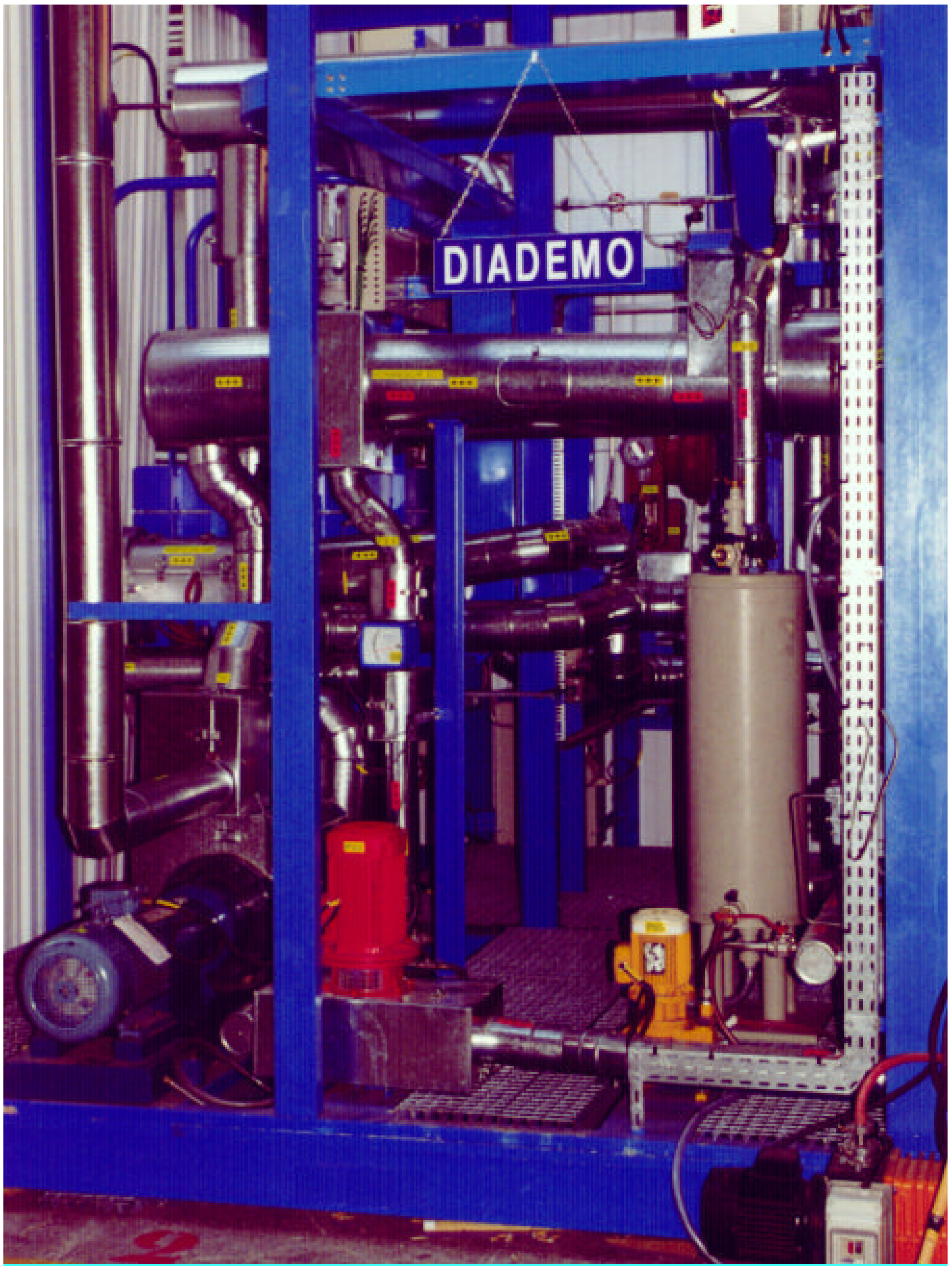
FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA

1998

Compiled by : P. MAGAUD and F. LE VAGUERES



ASSOCIATION CEA/EURATOM
DSM/DRFC
CEA/CADARACHE
13108 Saint-Paul-Lez-Durance (France)

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ASSOCIATION CEA/EURATOM
DSM/DRFC
CEA CADARACHE
13108 Saint-Paul-Lez-Durance (France)

Tél. : 33 - 4 42 25 46 59
Fax : 33 - 4 42 25 64 21

Cover : DIADEMO experimental device for double-wall tube validation

CNET 94-345

Task Title : DESIGN STUDY ON ITER JOINTS

INTRODUCTION

The conductor joints in the ITER CS and TF coils must function under conditions of pulsed current and pulsed external field. Rapid variation of external field and current is known to be able to cause a quench of the coil originating at the joints, due to eddy current heating and circulating currents. Furthermore, the joint resistance contributes significantly to the cryogenic load at 4.2 K, and must be balanced in the design against the losses and saturation of the joint. Several options can be considered for the design of the joint, compromising among the above aspects (joint performance) and the manufacturing issues.

The first part (Stage 1) of this work, performing a critical analysis of the ITER CS and TF joint design options and issuing a design of sub-size and full-size joint of each type, was completed at the end of 1994. The second part (Stage 2) of this contract covered the design in 1995 of the first EU full-size joint sample (SS-FSJS) to be tested in SULTAN (Switzerland) and in PTF (USA), and the monitoring of the industrial fabrication of the sample which was performed by Ansaldo (Italy). The inner joints of the ITER Toroidal Field Model Coil (TFMC) were designed according to the SS-FSJS joint design, therefore the fabrication of the SS-FSJS was also considered as a trial for the fabrication of the TFMC inner joints.

1998 ACTIVITIES

Our activities in 1998 were concentrated on the technical monitoring of the fabrication of the SS-FSJS at Ansaldo (Genoa, Italy). This sample was manufactured as a separate work package within the frame of the TF Model Coil contract by the AGAN consortium, therefore the overall monitoring was performed by the NET Team and CEA played only a role of technical support to the NET coordinator. In the consortium, Ansaldo was responsible for the sample R&D and manufacture.

The fabrication started in March 1996 and the sample was delivered beginning of November 1998 to the SULTAN facility (Villigen, Switzerland) for testing. Therefore the final report was completed at the end of 1998 [1]. Besides technical problems, a large part of the delay of the sample fabrication (more than one year) can be explained partly by the parallel fabrications of the TFMC and the SS-FSJS by the same company within a single contract, thus any priority put on the TFMC fabrication led practically to slow down the fabrication of the SS-FSJS. The long time (delivery end of Feb. 97) required by Ansaldo to get the tooling needed for the compaction tests and for the SS-FSJS fabrication gave also a substantial contribution to the delay. The fault which occurred in the oven in December 1997, during the heat treatment of the SS-FSJS and the first double pancake of the TFMC, contributed to postpone the final assembly of the sample in 1998.

Following the reparation of the oven, the heat treatment restarted beginning of February 1998 and ended on February 23. After the dismantling of the tooling, it was observed that all the joint boxes were deformed (bending) in the same way, with in addition a random deflective angle between conductor jacket and joint box. The deflection at each end of the two legs was too large (5 - 10 mm range) to be corrected by a simple machining of the joint box copper soles as foreseen in the design (2 - 3 mm available). The bending of the joint box has been attributed to residual stress in the heavy weld (5 mm deep) of the steel cover to the steel part of the copper-steel joint box, while the deflection angle has been attributed to a badly controlled welding process between joint box and conductor jacket. Obviously, substantial corrective actions had to be undertaken in order to recover a final sample geometry in agreement with the tolerances of the test facility, but the task was complicated by the handling of a reacted Nb_3Sn conductor on which only small local deformation could be accepted not to degrade the superconducting properties. Numerous discussions arose between CEA, NET and Ansaldo, and small qualification tests were performed both by CEA and Ansaldo, before the solutions proposed by CEA were finally accepted. For the most deformed upper joint, counter welds were successfully applied to the conductor jacket close to the joint to recover an acceptable overall alignment of the box with the conductor (see Fig. 1).

Figure 1 : Counter welds on the jacket of leg 2 near the upper termination

For the lower joint (to be tested in high magnetic field), this solution could not be retained and a copper wedge had to be inserted and tin soldered between the two copper faces of the jointed boxes (see Fig. 2).

Figure 2 : Lower joint with inserted copper wedge after tin soldering

In addition, the copper soles of all the joint boxes had to be machined up to the maximum acceptable value to recover as much as possible a correct overall sample geometry. Obviously, at the end a final machining of the joint boxes was also needed to enter the facility dimensional tolerances. The mechanical assembly of the sample was thus completed at the end of September 1998. The rather substantial instrumentation of the sample was then installed in October, and the sample was delivered to the SULTAN facility on November 4, 1998 (see Fig. 3) for testing.

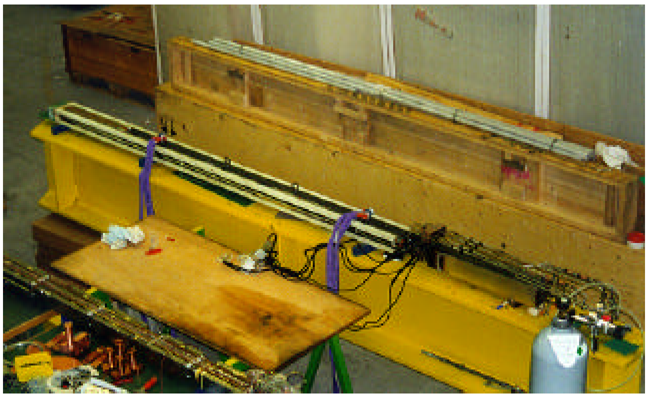

Figure 3 : SS-SS-FSJS ready for testing in SULTAN facility

CONCLUSIONS

The main achievement of this manufacture is a successful transfer of the technology developed for the subsize samples in a laboratory (at CEA/Cadarache) to a full size sample manufactured in industry. Although unexpected deformations of joint boxes occurred after heat treatment, a recovery procedure could be set up which allowed to proceed with the sample assembly leading to a final geometry compatible with the test facility requirements.

The actual fabrication of the SS-FSJS started in June 1996 with the first R&D work on the terminations and ended in October 1998. Although no major technical problem was encountered before the heat treatment, a significant time delay finally arose (about one year) which must be mainly attributed to the wish to carry out the R&D work on the SS-FSJS in parallel to the R&D on the ITER TF Model Coil to avoid any problem of technology transfer. The inclusion of the sample manufacture into the contract for fabrication of the first ITER TF Model Coil double pancake led, particularly at the beginning, to delay some operations on the SS-FSJS due to the lack of available manpower in Ansaldo. Finally the sample was delivered at the beginning of November 1998 to the CRPP for testing in the SULTAN facility .

From the technical point of view, only few critical issues concerning the joint fabrication were identified, they are mainly related to the characteristics of the full-size cable which could not be simulated during subsize joint fabrications. Thus the inner spiral tube of the cable had to be replaced by a thick plain tube in order to avoid buckling during the compaction process, on the other hand this change has been cleverly used to improve the cooling of the annulus area of the cable inside the joint (compared to the original design). Sometimes a slight modification introduced to improve the design led to further much heavier modifications, this was the case of the preliminary heat treatment of the joint box which led to machine deeper the compaction tooling to provide a better holding of the box side walls during the cable compaction, and then to modify accordingly the heat treatment beams. Also to be noted is the rather high force (about 200 tons) finally required to achieve the compaction, compared to the value (about 100 tons) estimated from subsize sample tests. Last but not least, the large deformations of all the joint boxes observed after heat treatment could not be expected at such levels from the subsize joint fabrications. These deformations have been attributed to residual stresses remaining after heat treatment, from initial stresses created during the deep welding of the steel cover. Such a phenomenon was also observed on the TFMC joint boxes, it can be reduced by applying a proper welding process and can be associated with a preliminary counter deflection angle between the conductor jacket and the joint box in order to recover an acceptable overall alignment after heat treatment.

The SS-FSJS was successfully tested in November and December 1998, the joint resistance was the lowest measured so far on this kind of joint (about 1.3 nΩ at 4 T), and both conductor leg critical currents were at the expected levels (see report on contract CNET 96-432).

REFERENCE AND PUBLICATION

[1] P. DECOOL et al. : NET Contract 94-345 : Final Report : Manufacture of the SS-Full Size Joint sample - Note NT/EM/98/61 - December 17, 1998.

TASK LEADER

D. CIAZYNSKI

DSM/DRFC/STEP
CEA Cadarache
13108 St Paul Lez Durance Cedex

Tél. : 33 4 42 25 42 18
Fax : 33 4 42 25 49 90

Task Title : ITER CRYOPLANT DESIGN EVALUATION

INTRODUCTION

The ITER cryoplant can be considered as a quite large extrapolation with respect to the worldwide previously built and tested helium refrigeration plants.

The total cooling capacity of about 120 KW is around 6 time larger than the largest existing helium refrigerators.

The typical working conditions of a tokamak machine caracterized by a pulsed cryogenic load are quite incompatible with a safe and efficient operation of the cryogenic refrigerators.

A large scattering between the various operating duties (cooling down, standby or full power operation) asks for a large operational flexibility.

Due to the relevant experience available within the EUROPEAN COMMUNITY, first, for the design and operation of the TORE SUPRA tokamak, then, for the building at CERN of large cryogenic plants for the LEP and LHC particule accelerators with the support of industrial firms (Air Liquide and Linde), the ITER joint central team has requested support from the EUROPEAN home team to get technical assistance for the ITER cryoplant design.

1998 ACTIVTIES

Only the first half of the year was devoted to provide technical assistance to The ITER JCT about the same topics than described in the 1997 activity report.

The results will be summarized hereafter and only specific points for which further studies were performed will be outlined.

PULSED OPERATION AND COOLING CAPACITY ADJUSTMENT

No more study was performed by 1998.

The solution investigated and reported in 1997 was kept as a reference with the following specificities :

- No additional helium storage dewar working as a thermal buffer is needed.
- The pulsed energy is kept stored where it is deposited (coils, cases, structures) then removed by controling several independant cooling circuits with the relevant algorithm and the adequat hierarchy to avoid coil quenching while keeping constant load to the refrigerator (cooling power shifted in time from one circuit to the other).
- Cooling capacity adjustment performed by using three different ways with graduated time constant :
  - . For short period of time or for periodic capacity check, electrical heater.
  - . For few hours transient regimes, LHe storage dewar with varying liquid level.
  - . For daily adjustment versus expected scenario, cooling cycle operating pressure adjusted from 11 b for standby to 15 b for normal operation.

(See for reference : ITER cryoplant and magnet system control for pulsed operation. Note SBT/CT/97-32, July 1997 by G. CLAUDET, P. ROUSSEL and V. KALININ).

80 K REFRIGERATION PLANT
FOR ITER THERMAL SHIELDS

In the proposal studied and reported in 1997, two independant 80 K cooling systems were considered :

- For 80 K shielding with heat loads of 500 kW in normal operation and 300 kW additional load for plasma vessel baking, a liquid nitrogen cycle was proposed and associated with a helium closed loop, activated by a room temperature circulator.
- For 80 K precooling inside the seven 4.5 K, 18 kW cold boxes, helium turbo-expanders are included in the helium Claude cycle to produce about 50 kW for each (350 kW total power).

A more centralised concept has been considered for two main reasons :

- A central 850 to 900 kW liquid nitrogen cycle would be better optimised than two independant sources.
- A full redundancy level should be obtained to provide the capability to keep cold the machine near 80 K in the case of any trouble coming from the cryoplant and cryodistribution system.

This new concept will have to be more deeply investigated in a further study.

FAST COOLING OF THE TORUS CRYOPUMP

Due to tritium inventory any of the 16 cryopanels has to be regenerated by degassing near 80 K then cooled again at 4 K in a time cycle of about 5 minutes.

In the proposed solution using 300 K helium gas for fast heating and liquid helium filling for fast cooling the equivalent power consumption at 4 K was 37 kW.

A more advanced proposal was suggested by the CEA Grenoble team to save energy by considering serial coupling between one pump to be heated and an other one to be cooled in order to directly transfer enthalpy from one to the other.

Technical assistance given to the Garching European home team ended by July 1998 with the withdrawal of the US members (Kurt SCHAUBEL from vacuum pumping and fuelling group).

DETAILED DESIGN AND LAY OUT

No specific problem was associated with the lay out of the cryoplant itself for which relevant references were available from the EUROPEAN STATE OF THE ART (CEA-DESY-CERN-AIR LIQUIDE-LINDE).

The most questionnable part was about the cryodistribution system at which CEA technical assistance was mainly concentrated :

- From a preliminary failure analysis, it was shown that the needed 80 K redundancy was not satisfactorily given by using only one cryoline from the refrigerator building to the machine building.

- By using two different cryolines and by separately feeding, on one side, the auxiliary cryostats associated with the coils and, on the other side, those connected to the structures, it was shown that full redundancy can be obtained at 80 K and, in more, a limited redundancy level could be obtained at 4.5 K at least for standby operation.

(See for reference : ITER cryoplant and cryolines general lay out. Note SBT/CT/98-39, Draft 0 – April 1998 by G. CLAUDET).

- A further study was discussed and recommended, starting from a more detailed failure analysis in order to perform a conceptual design taking into account all the ITER specifications and lay out constraints.

DETAILED DESIGN DESCRITPION REPORT AND COST ESTIMATE

DDD 3.4 (cryoplant and cryodisribution system) was amended and completed up to mid 1998 in close contact with the JCT Naka group.

Cost estimate was also revisited and adjusted to help JCT in preparing several variants for reduced cost ITER options.

REFERENCE

[1] ITER CRYOPLANT DESIGN EVALUATION
ITER task agreement N34 TD 01
Net reference 96-409
Final report : SBT/CT/98-28, G. CLAUDET,
July 1998.

TASK LEADER

Gérard CLAUDET

DRFMC/SBT
CEA Grenoble
17, rue des Martyrs
38054 Grenoble Cedex 9

Tél. : 33 4 76 88 43 60
Fax : 33 4 76 88 51 71

E-mail : claudet@drfmc.ceng.cea.fr

CNET 96-432

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

INTRODUCTION

In the frame of the NET contract #94-345, CEA was in charge of designing the EU proposal of joints for ITER. Within this contract a full size prototype sample (FSJS) was designed. Two joint samples are now being manufactured in industry, the so-called SS-FSJS and TFMC-FSJS, in the frame of the TF Model Coil manufacture, under technical monitoring by CEA. During this phase an important experience has been gained on joint designing. Considerations on manufacturing process and assembly in relation with heat treatment, analyses of pulsed field losses and DC electrical resistance, have led to the present twin box concept which has been retained by ITER. Taking into account this concept, further work is needed to model the behavior of such a joint, as well in DC as in AC conditions. This work has to be done in a strong coordination with the test of the manufactured joints in order to assess the model with the experiments.

Contract 96-432 is dedicated to the modeling of the DC behavior of the joint and to interpretation and analysis of test results of the two above full size joints. In addition, this contract covers the participation of CEA in the tests and in the data analyses of these two EU full-size joint samples : the SS-FSJS in PTF (MIT, Boston) and in SULTAN (Villigen, Switzerland), and the TFMC-FSJS in SULTAN.

1998 ACTIVITIES

Our activities in 1998 were concentrated on the tests of the SS-FSJS in SULTAN during November and December. These tests were divided into three parts : firstly the tests of the joint with the sample lifted up in the facility in order to place the joint in the SULTAN magnetic field, secondly the tests of the two conductor legs with the sample in the regular position, and last new tests of the joint (sample lifted up) with reverse helium flow to simulate the TFMC inner joint operating conditions.

JOINT TESTS

The DC resistance of the joint was measured using electrical measurements and was cross checked with calorimetric measurements. In order to adopt a more general point of view, the joint resistance R_{joint} has been plotted in Fig. 1 as a function of the maximum magnetic field on the joint (i.e. SULTAN field + sample self field).

It can be seen in this figure that as soon as $B_{max} > 0.5$ T, the magneto-resistance effect is constant and the resistance can be written as follows (R in nΩ, B in T) :

$$R_{joint} = 0.68 + 0.129\ B_{max}$$

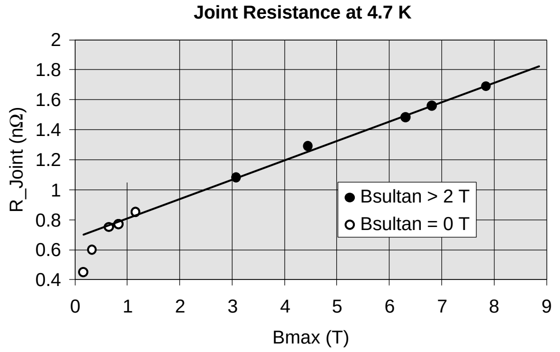

Figure 1 : SS-FSJS joint resistance as a function of maximum magnetic field on joint

This result is more remarkable that it looks first because, for a given transport current, the exploding electromagnetic force on the joint increases as B_{Sultan} increases, therefore this result shows that no de-cohesion has been observed between superconducting strands and copper sole in each joint box in spite of the high e.m. force.

It should be also noted that this resistance is the lowest value ever measured so far on ITER FSJS joint fabricated by other ITER parties (USHT and JAHT).

The joint resistance was measured under ITER TFMC joint operating conditions with increasing operating temperature. Thus, with 5.5 T in SULTAN and 80 kA in the sample (max. field on joint 6.8 T), a DC resistance of about 1.5 nΩ was measured, this value remaining constant up to an helium inlet temperature of 8.0 K. At an helium inlet temperature of 8.9 K, stable operation (without quench) was possible with a slight increase in joint resistance of 9%, which shows stable current transfer in the joint. Note that this operating point (at 4.5 K) corresponds to the working conditions of the inner joints of the ITER TFMC with 80 kA in this coil and no current in LCT.

Also with 6.7 T in SULTAN and 70 kA in the sample (max. field on joint 7.8 T), a DC resistance of about 1.7 nΩ has been measured, this value remaining constant up to an helium inlet temperature of 7.5 K. At an helium inlet temperature of 8.4 K, stable operation (without quench) has been possible with a slight increase in joint resistance of 7%, which shows again stable current transfer in the joint. Note that this operating point corresponds (at 4.5 K) to the working conditions of the inner joints of the ITER TFMC with 70 kA in this coil and 16 kA in LCT.

The measurement of the joint losses under pulsed field using the SULTAN pulse coils was not so fruitful because this system in not suitable for measuring loss time constant in the 1-10 s range.

Neither the area of the magnetization loop, nor the relaxation time constant, nor the calorimetric method give consistent values really usable, excepted an overall range of 1 to 5 s for the $n\tau$ value. The main reason of this difficulty is the too short time duration (ramp time and plateau) of the pulse which is provided by a pair of copper coils.

CONDUCTOR TESTS

The critical currents of the two conductor legs were measured for various magnetic field in SULTAN (7 to 11 T) at different operating temperature (6 to 9 K).

The values of the critical current have been found to be in agreement with the values calculated at the maximum magnetic field (including sample self field), using strand critical current (multiplied by the s/c strand number) with the expected strain in Nb_3Sn of $\varepsilon = -0.65\%$, within the full range of measurement (see Fig. 2).

Although the full analysis of the results will need further investigation, it should be already noted that considering the maximum field on the conductor is the way used for dimensioning ITER superconducting magnets.

It should be noted that these critical currents are not quench currents but they do really correspond to current sharing with an average electric field of 0.1 µV/cm (i.e. 4.4 µV over a cable twist pitch length of 44 cm) along the conductor length located in SULTAN high field. It should be also noted that the two legs exhibited so similar behaviors that it was possible to perform both measurements at the same time. Last but not least, below about 80% of the critical current, no measurable voltage was found along the conductor.

Again, with the conductor legs, the pulsed field losses were not easy to measure because of the constant ramp down of the pulsed field with the maximum ramp rate (only ramping up is variable) and the difficulty to get an accurate numerical compensation of the main field (data acquisition frequency will have to be significantly increase for next tests). Nevertheless, from the magnetization relaxation signal, a loss time constant between 60 and 160 ms has been found, which is within the expected range.

REVERSE FLOW EXPERIMENT

This last experiment was mainly devoted to thermohydraulic measurements with the lower joint located at helium inlet as in the inner joints of the TFMC. Temperature evolution in the joint and after the joint has been measured for helium heat slug at inlet and with or without current in the joint. Results will be compared to theoretical models and will help to adjust unknown parameters in codes to be able to predict joint behavior in the TFMC. During these tests it was observed that the joint could operate without quench (but with a slight extra Joule heating) at the critical current of the conductor under same magnetic field, which is a good news for the operation of the TFMC. Complementary measurements will be performed on the next sample (TFMC-FSJS).

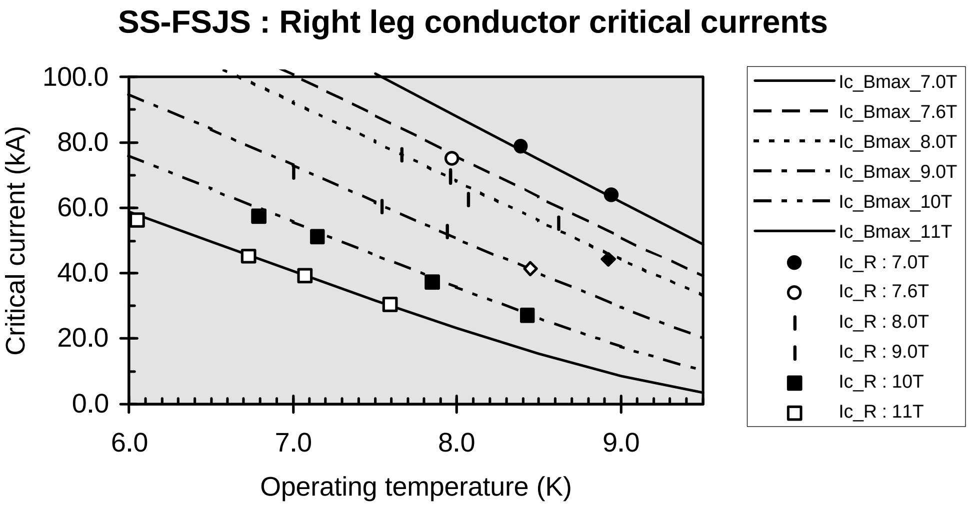

Figure 2 : Critical current measurements (Ic_R) of right leg compared to Ic_Bmax

CONCLUSIONS

The first European full-size joint sample, so-called SS-FSJS, was successfully tested in November and December 1998 in the SULTAN test facility. The joint exhibited the lowest value ever measured on this type of sample (1.3 nΩ at 4 T) and was able to be operated up to the critical current of the conductor without quench. The two conductor legs showed very similar behaviors with stable critical currents in agreement with expected values from strand properties at maximum magnetic field. A significant analysis work remains to be done and comparisons with more sophisticated theoretical models will be very fruitful [2]. On the other hand, pulsed field operation have shown to be disappointing in SULTAN and losses measurements will need a serious improvement (if possible) in the future tests. As a general conclusion, the results gained with the tests of the SS-FSJS in SULTAN give confidence in the good behavior of the inner (high field) joints of the TFMC.

REFERENCE AND PUBLICATION

[1] D. CIAZYNSKI - NET Contract 96/432 : SS-FSJS Testing Program in SULTAN - Note NT/EM/98/51 - October 10, 1998.

TASK LEADER

B. TURCK

DSM/DRFC
CEA Cadarache
13108 St Paul Lez Durance Cedex

Tél. : 33 4 42 25 47 45
Fax : 33 4 42 25 49 90

M29

Task Title : CONDUCTOR FABRICATION
ITER Conductor R&D and monitoring

INTRODUCTION

The ITER PF coils are made of NbTi superconductor. A solution is investigated for NbTi CICC to control losses at an acceptable level [1]. It is to design the strand with a resistive layer inside the copper crown surrounding filamentary area.

This would have the advantage to be a cheap solution. To test this method, three NbTi strands have been manufactured with a 10µm copper nickel layer. The location of the resistive layer is different for each strand in order to evaluate the effect of the location on the efficiency of the layer. Three 36 strands CICC have been realised to perform interstrand resistance and AC losses measurements.

1998 ACTIVITIES

SAMPLES DESCRIPTION

Three NbTi strands have been produced by GEC Alsthom, with three different locations of a CuNi30% resistive barrier of 10µm thickness. Each strand has a 0.81 mm diameter.

The CuNi barrier location is characterised by the thickness of copper remaining around the barrier (see Table 1). The barrier location associated to sample #1 is adjusted during the billet assembly (see Fig.1 strand #1 cross section).

The barrier location of samples #2 and #3 is adjusted after the extrusion process by shaving the external copper shell. This produces only a very small variation of the inter-filaments distance and filament diameter. Residual Resistance Ratio and Non Copper Ratio have been provided by the manufacturer.

The cable manufacturing and jacketing has been done by Shapemetal Innovation. The cable is a 3x3x4 multistage CICC with A316LN stainless steel jacket (see Fig.2). The specified void fraction is 33 %(see Table.1). The final outer diameter of the cable is 8.52±0.02 mm.

A scattering can be noticed in the last twist pitch length (from 120 mm to 160 mm) compared to the specified value 120 mm. It has to be noticed that a scattering has also been observed along a cable length. This remark is very important because coupling losses are proportional to the square of the twist pitch length.

Figure 1 : Cable cross-section

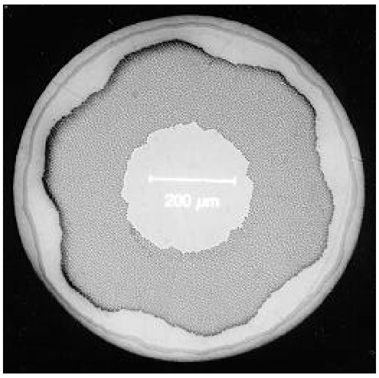

Figure 2 : Strands #1 cross section

Table 1 : Samples description

	Units	#1	#2	#3
(Cu+CuNi)/NbTi		1.52	1.38	1.23
RRR		130	137	132
Copper sheet thickness	µm	22	14	0
Twist pitch pattern	mm	30x86x140	30x80x160	29x76x120
Void fraction	mm	33.2%	32.8%	34.8%

MEASUREMENTS

Losses

For each strand, hysteresis and coupling losses have been measured by a magnetisation method. Magnetisation is measured using two compensated pick-up coils and a pulsed solenoid providing a ±3 T trapezoidal field for rates between 0.3 T/s and 6 T/s. The hysteresis reference volume is the non copper volume (copper nickel is included in copper volume).

The coupling losses reference volume is the strand. Coupling losses per volume unit, Q_C, are usually characterised by a time constant nτ :

$$Q_C = \frac{n\tau \dot{B}^2}{2\mu_0} \quad (1)$$

For each cable, hysteresis and coupling losses have also been measured using the same method as for strands. A superconducting dipole provides a +2 T trapezoidal field for rates between 0.02 T/s and 2 T/s. Two cable lengths are used for these measurements, 240 mm and 400 mm. In order to be installed on the sample holder an epoxy frame has been impregnated on the conductor jacket. It means that every conductor has been heat-treated before losses measurements, typically at 120°C during 3 hours. All these measurements are summarised in Table 2 ($n\tau_M$ is the measured time constant). It has to be noticed that there is a factor ~2.5 between the hysteresis losses on strands and cables because the applied pulsed fields were different. A discrepancy can be observed between measurements on same samples (30% for #1, 40% for #2, 5% for #3). It could be explained by the difficulty to measure low hysteresis losses on samples with high time constant. It is important to notice that the strand time constant is not negligible compared to the cable time constant.

Inter-strand resistance

On each 240 mm long cable, inter-strand resistances have been measured in every triplets. These measurements have been performed under DC field from 0 T to 4 T and for a DC current from 50 A to 300 A by step of 50 A.

Table 2 : Losses results

		Units	#1	#2	#3
Q_H	strand	mJ/cm^3	107	127	128
	240mm cable	mJ/cm^3	55	36	/
	400mm cable	mJ/cm^3	60	59	53
$n\tau_M$	strand	ms	4.8	5.8	7.0
	240mm cable	ms	38	46	/
	400mm cable	ms	32	34	12
$n\tau_0$		ms	72	88	11
$n\tau_R$		ms	10	17	7

No influence of the transport current on the resistance has been measured. A 20% increase of the resistance has been noticed between 0 T and 4 T from samples #1 and #2. The #3 inter-strand resistance appears to be independent of field. Measurements are summarised in Table 3.

Discussion

The time constant design value of ITER conductors is 100 ms. It means roughly a value of 50 ms for our sub-size cables.

Table 3 : Inter-strand resistance

nΩ.m		#1	#2	#3
B_{DC}=0 T	Max	35	21	295
	Mean	45	22	330
	Min	65	26	394
B_{DC}=4 T	Max	41	23	295
	Mean	53	26	329
	Min	78	30	394

As 35 ms and 40 ms were measured for samples #1 and #2, it appears that an inner copper nickel barrier could ensure a sufficient inter-strand resistance to reduce coupling losses to the required level. The strand with an external copper nickel barrier has a very low time constant, 12 ms, that is of the same order of magnitude as the strand time constant, 7 ms. It is important to note that the time constant should not be reduced too much in order to ensure the current redistribution capability in case of current imbalance among strands.

CONCLUSION

It has been demonstrated in this study that a CuNi resistive barrier can ensure sufficiently low coupling losses in large twisted NbTi cables. To be efficient this barrier should be nearly external. For ITER application, on the one hand external CuNi barrier can be achieved in practical NbTi composites, on the other hand plating solutions using chromium or Nickel are also possible. Both kinds of industrial solutions will be explored and economically compared in a next Euratom contract led jointly by ENEA/Frascati and CEA/Cadarache.

REFERENCE

[1] T. Schild, J.L Duchateau. AC losses dependence on a CuNi layer location in NbTi CICC. Physica C 310 (1998) p.247-252

TASK LEADER

JL. DUCHATEAU

DRFC/STEP
CEA Cadarache
13108 St Paul Lez Durance Cedex

Tél. : 33 4 42 25 49 67
Fax : 33 4 42 25 26 61

Task Title : CONDUCTOR FABRICATION
ITER Conductor R&D coordination

INTRODUCTION

The frame of this task is the coordination of the European activity in the field of ITER magnet R&D.

This coordination consists in monitoring the tasks of several European laboratories and industry and in preparing new tasks in relation with ITER tasks. For 1998 the laboratories and industries included in this activity were : University of Twente, University of Padova, University of Create, University of Torino, CEA Cadarache, CEA Saclay, FZK, ENEA ,CRPP and Outokumpu. About 16 different contracts have been covered.

Meetings were organised in the different laboratories and industries to monitor the fabrications, to prepare the experiments or to discuss the results. A central meeting was organised in March 1998 at Cadarache with the four parties of ITER. About 10 nationalities were present to discuss ITER design criteria, taking into account the recent results of R&D and try to reduce the cost of the machine. Main results of this activity are presented there.

1998 ACTIVITIES

CONDUCTOR PERFORMANCES

- For the PF coils of ITER, due to the low field in the region, NbTi can be used for the conductor. To control the losses at an acceptable value an internal CuNi layer can be used situated in the outer copper shell of the composite. Three 36 strands samples have been produced, with three different locations of the CuNi layer. The conclusions of the losses and contact resistance measurements at CEA Cadarache, is that the internal layer solution is at the upper limit of the ITER specifications for the PF coils. Other solutions like coatings have to be studied.

- Mechanical cycling has been performed at Twente University on two full size ITER samples. It turned out that this cycling is greatly affecting the conductor time constant. There is roughly a decrease by a factor of three, starting from a virgin sample. The explanation is probably that the oxygen diffuses through the copper matrix during the heat treatment of the sample at the closed contacts between strands. Starting from a low value of the contact resistance, some reoxydation could then take place during the cycling and the associated strand movement.

  The losses are quite within the ITER specification in this condition, but the current redistribution between strands could be affected if the resistance is too high. Friction losses have been also evaluated during the cycling using hysteretic cycles. These results have been used as an input in the theoretical homogenous model developed by University of Padova.

- Concerning losses measurement on full size samples, a cross checking has been performed at CEA Saclay on the full size Japanese conductor, to confirm the low value of the coupling time constant of full size conductors already obtained at Twente University. A factor of three between the calorimetric measurements at Saclay (55 ms) and at Twente (108 ms corrected to 162 ms to have the correct superconducting strand reference section) can be pointed out. It can be perhaps put in relation with the evolution along the time of this time constant due to the reoxydation of the contact surfaces of the strands after heat treatment.

JACKET MATERIAL MECHANICAL PROPERTIES

The quality of the incoloy-copper bonding has been studied at CEA Cadarache on mechanical samples. The mechanical behaviour of this joint at cold temperature is quite comparable to the stainless steel-copper bonding behaviour. The limitation is always associated to the copper and not to the joint.

This study has demonstrated the ability to manufacture an incoloy version of the European connection box. Dummy joint boxes were manufactured, then heat treated under vacuum. The joint design will have to take into account the deformations due to the differential thermal contraction and stresses relaxation occuring after heat treatment and thermal cycling of incoloy-copper explosion bonding material.

TEST COIL PERFORMANCES

New tests have been performed on the 12 T CICC magnet. It is believed that critical current reduction in multistrand cable superconducting cables in non steady state condirion is caused by non uniform current distribution among strands. This current imbalance has been pointed out on this experiment, for different ramp rates, by means of numerous local miniature field sensors located in a few positions along the conductor. It has been shown that severe current nonuniformity exists in the cable and that induced current loops are generated which decay with very long time constants. (up to 10^4-10^5 s). The next step is now for this coil to be tested at nominal field in the Sultan test facility.

CONNECTIONS

Model

An electrical model has been developed at CEA Cadarache to predict the behaviour of a conductor associated to its connections at the two ends, in steady state. This model takes into account the unequal distribution of current among the strands in the connection due to the contact with the copper sole and the current redistribution process occurring all along the length of the conductor.

This current redistribution is a function of the conductance between the strands and of the critical properties of the strand. These characteristics cannot always be obtained from experience.

This model is a theoretical basis to work out data coming from Sultan experiments, but also to predict the behaviour of the ITER TF coil.

Tests

A Japanese conductor has been tested at Sultan with a so-called lap joint. A very high unacceptable resistance of more than 100 nΩ has been pointed out on the lower joint.

The European SS-FSJS has been tested. This sample was aimed to validate, for ITER, the twin box concept developed by CEA Cadarache. CEA has made the connection concept by using a full size Nb3Sn ITER conductor, then has monitored the fabrication at Ansaldo (Genova, Italy) in the frame of the TF model coil fabrication. The CEA has been in charge of organising the tests at the Sultan CRPP test facility (Villigen, Switzerland). The results were very good. One of the most significant results is the following :

The connection resistance does not exceed 1.5 nΩ for 80 kA current in a field of 6.8 T with a temperature up to 8.2 K.

CURRENT LEADS

Studies are carried out jointly by CRPP and FZK to promote HTSC current leads for ITER and reduce the associated losses. During the first stage of the contract on 1-2 kA leads, Bi-2223 tapes electrically stabilised by AgAu material were selected for the further development program because of their larger safety margin than bulk material. In a next step one 10 kA current lead has been received from the industry and another one is being manufactured at FZK. The first one will be tested in 1999 at FZK.

OTHER STUDIES

Starting from their general contribution on eddy currents in ITER during normal scenario and disruptions last year , University of Create has provided this year more refined calculations on points specified by ITER. These points were mainly field maps in the TF magnet during disruptions, additional results on pre-loading flanges and lower OIS (Outer Intercoil Structure) during the normal scenarios and disruptions and poloidal eddy currents induced by a plasma disruption. The conclusion for this last point was that the thermal effects of the poloidal eddy currents are negligible compared to those of the toroidal eddy currents.

CONCLUSION

The very good results obtained on the SS-FSJS has pointed out that a solution was quite available for the ITER connections. The research community is now quite conscious that current distribution among strands is really a problem for large Cable in Conduits and can bring instabilities. As a matter of fact, Niobium Titanium conductor could be specially affected by this problem due to the very low critical temperature. R&D is now urgently needed for the NbTi conductor of the PF ITER coils and in particular to control the inter strand conductance at the right level.

TASK LEADER

JL. DUCHATEAU

DRFC/STEP
CEA Cadarache
13108 St Paul Lez Durance Cedex

Tél. : 33 4 42 25 49 67
Fax : 33 4 42 25 26 61

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 autumn 1999.

1998 ACTIVITIES

TF MODEL COIL ENGINEERING DESIGN

The analyses performed by AGAN to assess the TFMC Engineering Design have been provided and submitted for examination to CEA and FzK [3]. In addition to the reference case of no-bonding between winding-pack and case, two cases have been investigated : half-bonding and full bonding. All cases show that when both coils are operated the stress criteria are not exceeded.

MANUFACTURE OF THE TF MODEL COIL

A main part of the activity of AGAN concerning the manufacture of the TFMC [4] during the year 1998 was the manufacture of the double pancakes (Fig. 1).

Figure 1 : TFMC double pancake completed

The heat treatment was completed on 26 February 1998 for the pancakes of the first double pancake (DP1) and on 30 September 1998 for those of the last double pancake (DP5).The last radial plate was delivered to Ansaldo on 12 May 1998.

The impregnation of the Dummy Double Pancake (DDP) was completed on 10 August 1998 and that of DP1 on 26 October 1998, which enabled their delivery to Alstom in November 1998. The impregnation of DP2 was completed in November 1998. The manufacture of the double pancakes was delayed by several months due to several problems :

- repeted breakdowns of the oven heat treatment which interrupted the heat treatment of the pancakes,
- time needed longer than expected for adjustment of parameters for laser welding (Fig. 2) of the covers of the radial plates,

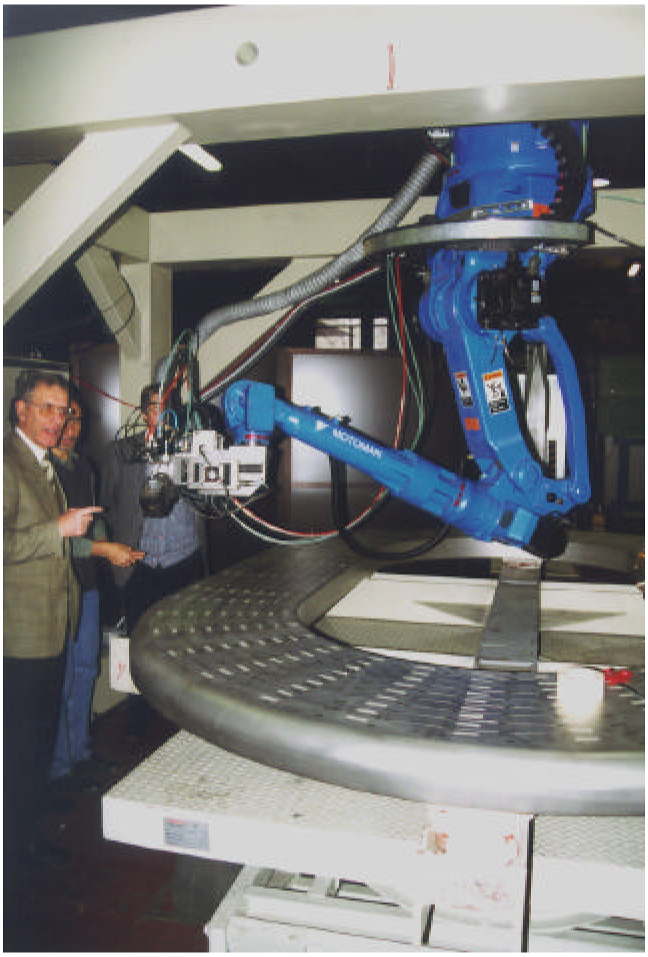

Figure 2 : Laser welding of TFMC radial plate covers

- modifications required for the impregnation tool (Fig. 3), in order to meet the specifications on the double pancake thickness and flatness.

Figure 3 : TFMC double pancake impregnation tool

TFMC-FULL-SIZE-JOINT-SAMPLE

A prototype joint sample of the outer joints of the TFMC is planned to be tested at CRPP (Villigen, Switzerland) in the SULTAN facility [5]. The legs of this TFMC-Full-Size-Joint-Sample (TFMC-FSJS) have been manufactured and heat treated by Ansaldo and delivered to Alstom on 20 November 1998 for assembly and installation of the instrumentation. This sample will incorporate the technology of copper pins welded by electron beam to the termination box copper sole.

TF MODEL COIL MAGNETIC FIELD CALCULATIONS

A detailed model of the TFMC was built with the TRAPS code to perform a precise calculation of the magnetic field on the conductor. The maximum field values are shown in Table 1 and the variation of field along the DP1.1 pancake inner turn when the TFMC is operated with the LCT Coil is shown in Fig. 4. As it can be seen, a strong magnetic field gradient arises through the conductor cross-section.

Table 1 : Maximum field on TFMC conductor

Operating conditions	Single mode I_{TFMC} = 80 kA, I_{LCT} = 0 kA	Operation with LCT I_{TFMC} = 70 kA, I_{LCT} = 16 kA
Maximum field	7.80 T	9.02 T

TFMC OPERATING DIAGRAM

The TFMC operating diagram has been revised (Fig. 5), taking into account the precise field calculations presented above and the results of the experiments performed at FzK on samples made with the TFMC conductor subcables.

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 cable area and the central channel.This needs to determine the hydraulic characteristics, in particular the friction factor, of each of these circuit. Pressure drop measurements have been performed at Cadarache in the OTHELLO facility with samples of the actual TFMC conductor in order to determine these friction factors [6]. The friction factor of the cable area is determined by closing the central channel in inserting a plastic tube in it and the friction factor of the central channel is derived by substracting the pressure drop of the cable area from that of the full conductor (Fig. 6).

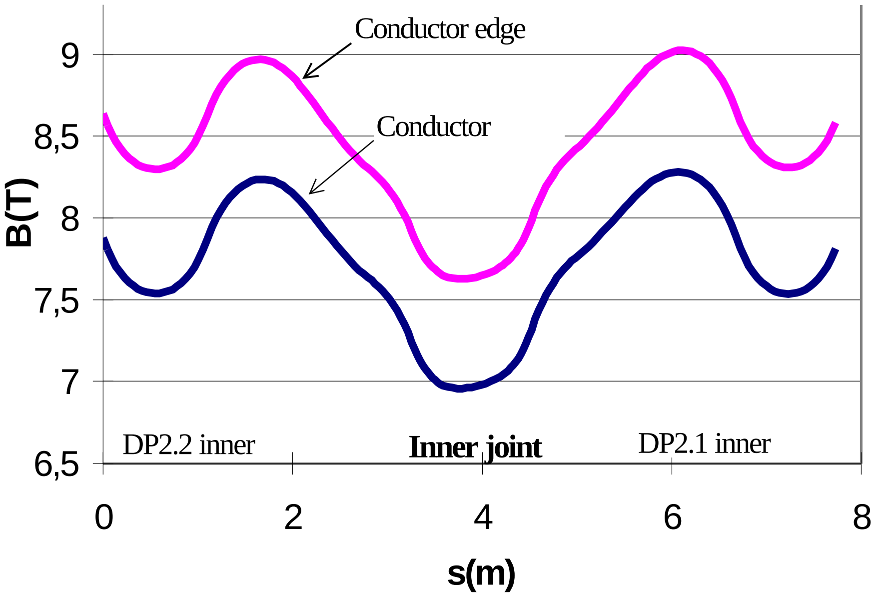

Figure 4 : Magnetic field along DP2 inner turns (I_{TFMC} 70 kA, I_{LCT} 16 kA)

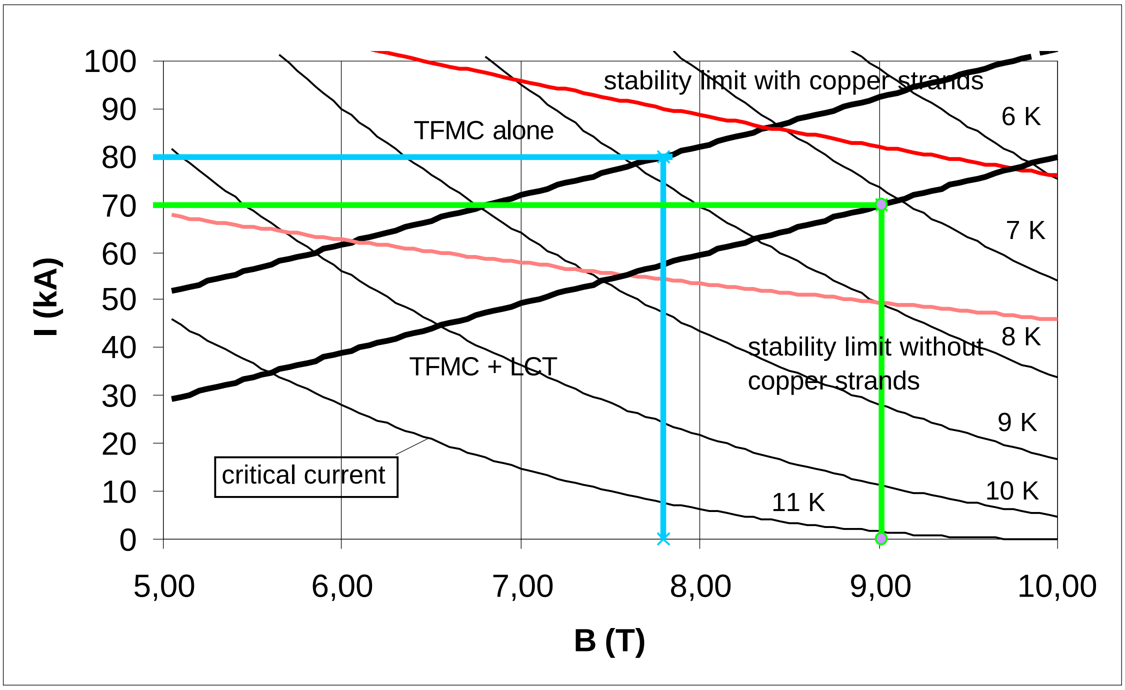

Figure 5 : TFMC operating diagram

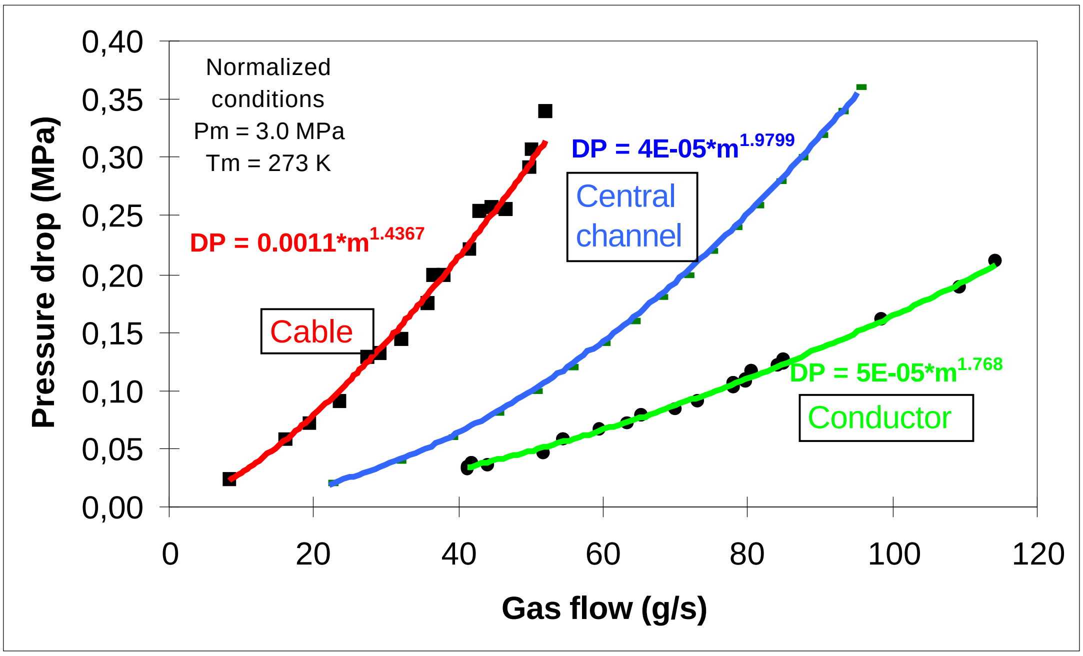

Figure 6 : Pressure drop measurements on TFMC conductor

QUENCH TRIGGERING CALCULATIONS

Resistive heaters will be installed on DP1 pancakes helium inlet in order to heat locally the helium circulating inside the conductor. The heat slug will propagate inside the conductor and a quench will be triggered inside the pancake. In order to check that the quench will occur in the conductor and not in the joint area, a dedicated thermohydraulic model was built to investigate the heat slug propagation. The temperature along the conductor is computed at each time step and compared to the conductor current sharing temperature. As shown in Fig. 7, when both coils are operated, the quench will arise first in the conductor, but the margin between minimum T_{CS} value in conductor and joint is very small (Table 2). The model will be assessed by comparison with the SS-FSJS test results and parameters adjusted.

Table 2 : Current sharing temperature in DP1.2 during heat slug propagation

I_{TFMC}=80 kA ; I_{LCT}= 16 kA	Joint	Conductor
Bmax(int)	8.23 T	9.68 T
Bmin(int)	7.95 T	8.23 T
Tcsmax(int)	6.91 K	7.48 K
Tcsmin(int)	6.65 K	6.16 K

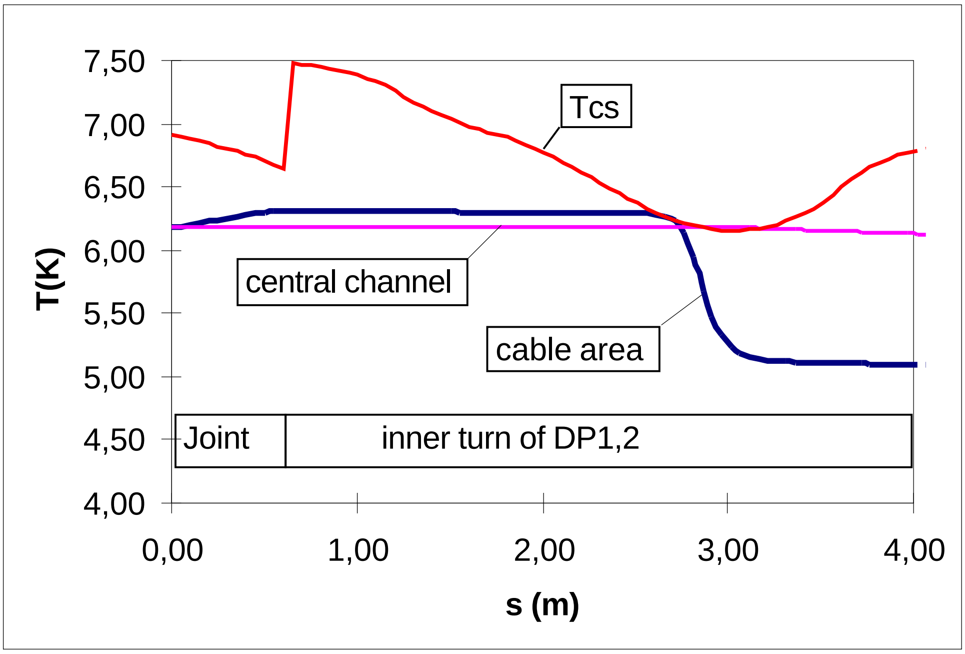

Figure 7 : Heat slug propagation inside DP1.2 (I $_{TFMC}$ 80 kA, I $_{LCT}$ 16 kA)

CONCLUSION

The assessment of the TFMC Engineering Design has been completed and the manufacture of the double pancakes has well progressed, despite some delay. The preparation of the testing included in 1998 magnetic field calculations, measurement of hydraulic characteristics of the conductor and analysis of the heat slug propagation.

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TASK LEADER

P. LIBEYRE

DSM/DRFC/STEP
CEA Cadarache
13108 St Paul Lez Durance Cedex

Tél. : 33 4 42 25 46 03
Fax : 33 4 42 25 26 61

E-mail : libeyre@drfc.cad.cea.fr

Task Title: WINDING AND INSULATION DEVELOPMENT
Joint Development

INTRODUCTION

The task was divided into threedifferent parts, the first part deal with measurements of ITER strand critical currents under field having angles with regard to the wire axis, the second part was concerned with the modification of the Cadarache test facility for testing subsize joints under parallel field and with the test of an already existing subsize joint sample (from task MWIN-2) under parallel field, this part also covered an extra test on a modified subsize joint sample for the TF Model Coil. The third part was devoted to fabrication and characterization tests of an incoloy-copper plate bonded with the explosive method, foreseen for the fabrication of the ITER joints.

1998 ACTIVITIES

PART 1: TESTS OF NB$_3$SN STRANDS UNDER VARIOUS FIELD ANGLES

This part was completed in 1997.

PART 2

Completion of tests of one modified MWIN-2 subsize joint sample for the TFMC

This activity was completed in 1997.

Modification of the Cadarache joint test facility to allow parallel field testing

The Cadarache joint test facility previously developed within task MWIN-2 for testing subsize joints under transverse field was upgraded by the addition of an extra assembly where the dipole has been replaced by a solenoid. This NbTi helium bath cooled solenoid can provide a maximum field of 7.5T with a maximum ramp rate of 0.5T/s over about a 500mm length and with an available bore diameter of 80mm. It allows to test under parallel field the electrical resistance and AC losses of subsize joints like the ones developed within the task MWIN-2. The test facility JOSEFA available in Cadarache has been fully operational since March 1998 to perform tests on subsize samples like joints both in transverse and parallel field.

Completion of test of one MWIN-2 (Phase II) sample under parallel field

One subsize joint sample previously tested within task MWIN-2 in transverse magnetic field was again tested in parallel magnetic field in the CEA test facility JOSEPHA which has been upgraded to allow testing in parallel field up to 6T of subsize joint samples cooled by supercritical helium. DC resistance measurements with high transport current up to 10 kA and with high ratio to the critical current were performed. Joint losses under pulsed field as well as stability tests under varying magnetic field were also carried out.

The tests results have been compared to the previous results gained under transverse magnetic field.

No sensible modification of the joint resistance has been found.

The quench temperatures have been found to be in agreement with the theoretical values of the current sharing temperatures Tcs, calculated using the average angle ($\alpha = 20°$) between strand axes and cable axis, and are therefore higher than under transverse field ($\alpha = 90°$).

The pulsed field loss measurements have shown a nτ value of about 0.1 s inside the joint which is consistent with previous experimental values determined within task MWIN-2 and which shows that the main contribution to the losses comes from pure eddy currents in the joint copper soles.

The stability tests were perturbed by problems of quench occurring at the connection between the sample and the current leads of the facility (due to local overheating). Nevertheless a minimum critical energy boundary of 286 mJ/cm^3 for a temperature T_0 = 9.5K was measured which is in agreement with theoretical models and with preceding results under transverse field. This result also shows that no substantial limit of the joint stability margin has been observed due to unexpected phenomenon, such as induced circulating currents.

PART 3

Fabrication of an incoloy-copper plate by the explosive bonding

This activity was completed in 1997

Characterization of the incoloy-copper assembly

Samples for tensile and shear tests as well as full size joint box mock-ups using the EU design for joints have been manufactured using the explosion bonded incoloy-copper plate.The shear and tensile tests were performed before and after heat treatment simulating the Nb3Sn reaction heat treatment at 300K and 4K. The results were compared to those gained during the previous qualification program of steel-copper assembly bonded by the explosive method. The mechanical behaviour of the incoloy-copper bonding was found to be as good as it was for the steel-copper bonding which means the breakage never occurred at the interface, the mechanical limits were always given by the copper itself. Two full size dummy joint boxes were heat treated under vacuum simulating the Nb_3Sn reaction. Dimensionnal measurements and leak tests before and after LN_2 thermal cycling were performed. As it was found with steel-copper material, no cracks on the joint boxes using incoloy-copper bonded material was found. The deformation after heat treatment shows a bending of the boxes due to differential thermal contraction between copper and incoloy added to a first pre-bending of the boxes due to stress relaxation of incoloy. This bending appears towards the copper sole in the straight part in a range of a 20m radius and towards the opposite direction in the pre-bended part of the joint boxes within the same range. These deformations were not observed on the steel-copper joint box mock-up. So, particular attention will have to be paid in the fabrication of joints using incoloy-copper explosion bonded material in order to take into account the deformations due to differential thermal contraction and stresses relaxation occurring after heat treatment of incoloy-copper explosive bonded assembly.

CONCLUSIONS

Part 2 of the task was completed by the availability of the upgraded Cadarache joint test facility for testing subsize joint sample in transverse and now in parallel magnetic field. The test of a previously manufactured subsize joint sample in parallel field has not shown any degradation of the joint performances by comparison with the previous tests in transverse field (higher Tcs and low losses).

Due to the important delivery delay of the incoloy plates, part 3 of the task could be completed at the end of 1998. Now the Incoloy-copper bonding has been fully characterized and leads to confirm the validity of the EU concept for ITER joints. These results have allowed to start the fabrication for tests of a TF Full Size Joint Sample using the ITER TF incoloy jacketed conductor and the Incoloy-copper bonding technology for the joint.

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TASK LEADER

P. DECOOL

DSM/DRFC/STEP
CEA Cadarache
13108 St Paul Lez Durance Cedex

Tél. : 33 4 42 25 43 50
Fax : 33 4 42 25 26 61

E-mail : decool@drfc.cad.cea.fr