CEFDA03-1015

Task Title: TW2-TMSM-COOLINL: MOCK-UPS FOR THE TF AND CS TERMINAL REGIONS AND COOLING INLETS

INTRODUCTION

The Euratom-CEA Association is requested through the contract EFDA 03-1015 to assist the EFDA Close Support Unit Garching and the Superconducting Coils and Structures Division of the ITER International Team (ITER-IT) in the detailed design and manufacture of relevant mock-ups for some critical areas of the Toroidal Field (TF), Central Solenoid (CS) and Poloidal Field (PF) coil windings.

Mechanical testing at cryogenic temperatures of the mock-ups under relevant loads and number of cycles will be carried out at FZK Karlsruhe (TW3-TMSM-CRYTEST) and ENEA Brasimone (TW1-TMS-SHKEYS). Euratom-CEA is requested to design the mock-ups in close collaboration with these two Groups and EFDA/ITER, coordinate the testing activity and report on the final test results. Euratom-CEA is responsible for the definition of the testing conditions (loads, number of cycles, temperature, etc.) under review and approval of EFDA/ITER.

The work include three main activities:

- Design, manufacture and assistance to testing of mock-ups and samples of the Toroidal Field (TF) coil helium inlet.
- Design, manufacture and assistance to testing of mock-ups and samples of the Central Solenoid (CS) helium inlet.
- Design, manufacture and assistance to testing of mock-ups and samples of the bonded tails at the extremity of the windings of the Poloidal Field (PF) coils.

2004 ACTIVITIES

DEVELOPMENT OF THE TF COIL HELIUM INLET

Design

The TF coil conductor consists of a circular Nb_3Sn cable-in-conduit with a central cooling channel cooled by supercritical helium. The material used for the conductor jacket is stainless steel. The jacket inner diameter is 40.2 mm and the jacket wall thickness is 1.6 mm. The winding uses a one-in-hand conductor (about 800 m long) in a double pancake configuration inserted into a radial plate.

The cooling inlets are located at the two innermost turns of each double pancake into the joggle region where the conductor from the first pancake come out of his radial plate groove to go into the groove of the second pancake. The total length of the inlet region is 700 mm.

The design of the ITER TF helium inlet is developed on the basis of ITER drawings which defines the space allowed for the inlet region.

The helium pipe connected to the inlet has to fit into the double pancake thickness without interference with the coil case.

Taken into account these space limitations, the proposed design for the inlet is as follows:The conductor jacket is locally cut on a length of 98 mm. The cable wrapping is removed at this location.

The sub-cable wrappings is cut only at the outer surface of the cable. A grid in two halves with a thickness equivalent to the jacket plus the wrappings is placed on the bare cable.

The two halves of the grid are spot welded one against the other but the grid is not welded to the jacket ends to allows cable deformation independent to the grid during TF coil operation. The grid uses two inner longitudinal grooves to distribute helium all along the length of the inlet.

The helium is then distributed on all the cable outer area by a set of grooves on the inner circumference of the grid. The grooves have a depth of 0.5 mm. The width of the grooves at the inner circumference of the grid is limited at 2 mm with a pitch of 8 mm.

This layout limits the unsupported length of the strands to 2 mm and then avoid the risk of strands deformation due to Lorentz forces when the coil operates.

The mechanical stiffness of the inlet is insured by two half shells which are then placed to recover the grid and are longitudinally welded one against the other. These longitudinal welds have to be performed without welding of the grid with the shells to allows independent deformation of the shells under the hoop force during TF operation with respect to the grid.

The shells are then welded on the conductor jacket at their two ends. All the shells welds have to be helium tight.

A special helium pipe has been previously welded on to the corresponding half shell using an elliptic shape to reduce the stress concentration around the hole. Figure 1 shows this design.

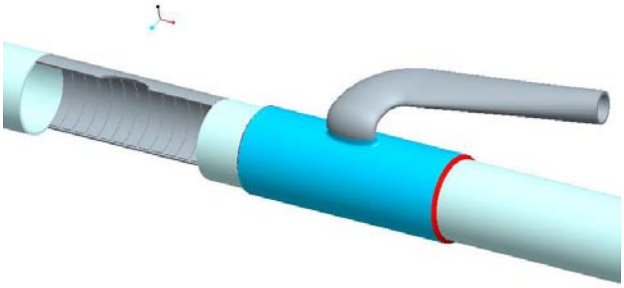

Figure 1 : TF inlet design proposal
(The mechanical shells are shifted to show one half grid)

The strain experienced by the TF coils at helium inlets during operation is $\varepsilon \sim (6 \pm 5) \times 10^{-4}$, where 6.10^{-4} is the essentially static strain due to the toroidal field alone and $\pm 5.10^{-4}$ is the cyclic out-of-plane strain (translated into stress, this gives a stress of $\sigma \sim 120 \pm 100$ MPa).

Normally, the number of cycles should be 1 200 000 (factor 20 on the ITER number of cycles) but to reduce the number of cycles to 30 000, it was suggested to double the strain (this strain corresponding to an average tensile stress $\sigma \sim 440$ MPa).

Analysis

A 3D straight FEM model was built for global analysis and a 2D local model was built for analysis of the weld between the shells and the jacket. After optimization of the geometry, the maximum stress around the elliptic helium hole remains to be lower than 700 MPa when a peak value at the shells weld location of 858 MPa appears on the jacket. These values have been considered to be acceptables by EFDA.

Manufacture

The components for the manufacture of five mechanical and hydraulic mock-ups have been fabricated and delivered to CEA (figure 2).

Four mock-ups will be completed in 2005 for welding procedure determination and mechanical qualification in the FzK facility while one hydraulic mock-up will be tested in the OTHELLO test facility for pressure drop measurement and flow distribution characterization among petals.

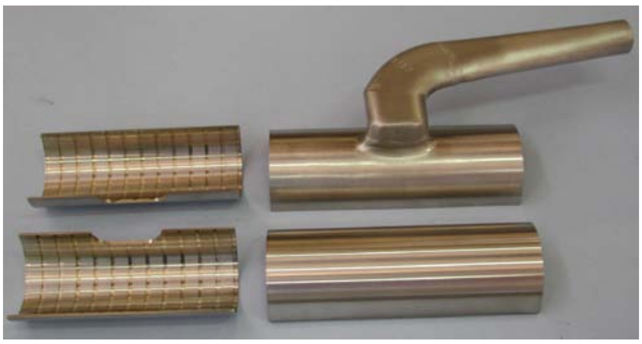

Figure 2 : The components of a TF inlet

DEVELOPMENT OF THE CS COIL HELIUM INLET

Design

The CS conductor consists of a Nb_3Sn cable-in-conduit with a central cooling channel, cooled by supercritical helium. The material used for the conductor jacket is stainless steel. The jacket inner diameter is 33.2 mm and the jacket outer square section is 49.9 mm × 49.9 mm.

The CS modules are wound as hexa-pancakes (6 pancakes with a single conductor length) and quad-pancakes (4 pancakes with a single conductor length). Helium inlets are at the crossover regions on the inner bore between each double pancake and outlets are at the crossover regions and joints on the outside. The high field region is therefore cooled by the coldest helium. There are three helium inlets for each hexa-pancake and two for each quad-pancake.

The main issue associated with the CS helium inlet is its structural behaviour. This is because the inlets are located at the CS inner diameter, where cyclic tensile stresses are highest. In the CS jacket, the maximum stress occurs at initial magnetization and reaches 470 MPa in the vertical sidewalls of the jacket. This stress is due to the combined effect of the toroidal hoop stress and the vertical magnetic load acting on the CS stack. The helium inlet region requires, therefore, a local reinforcement to allow the opening in the conductor jacket without excessive stress intensification. The inlet must also provide a good distribution of helium in the six sub-cables of the conductor. A design of this inlet was suggested by ITER-IT to achieve these requirements. The inlet is manufactured by machining an elongated narrow slot for the helium inlet. This slot must be long enough to allow direct access for the helium to the sub-cables. A cover with a structural reinforcement around the helium inlet opening is then welded above the slot.

Analysis

A FEM model relevant to this proposed design was previously built and has led to an optimization of the design to reach a maximum stress concentration factor of 1.30.

To qualify this design on a mechanical mock-up, with an average stress in the inlet region of 405 MPa, a tensile force of 664 kN would be necessary which is not compatible with the FzK test facility capability of 500 kN. In addition, EFDA asked to reduce the number of cycles from 1 200 000 to 30 000 by doubling the loading.

The mock-up design was adapted to the facility capability by a reduction of the mock-up cross section by cutting longitudinally the conductor in order to test only the cover side part. A comparison of the stresses distribution between a complete and reduced mock-up was performed [1]. This reduction of the mock-up leading to a modification of the mock-up bending, a shift of the pulling point was needed to get representative stress concentration factor on this reduced mock-up. A FEM analysis was performed to adjust the mock-up cross section as well as the shift value to be representative (figure 3).

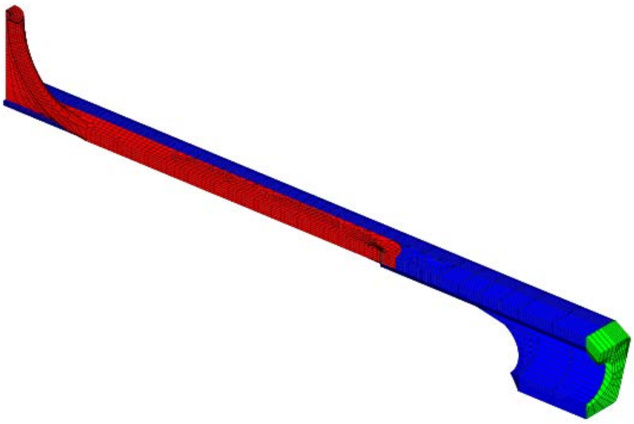

Figure 3 : F.E. Model of the reduced CS mock-up

The complete design drawings of the corresponding mechanical qualification mock-up were issued. In parallel, a manufacture test was performed on a similar PF conductor sample with square jacket and has qualify the feasibility and machining process for the narrow groove manufacture (figure 4).

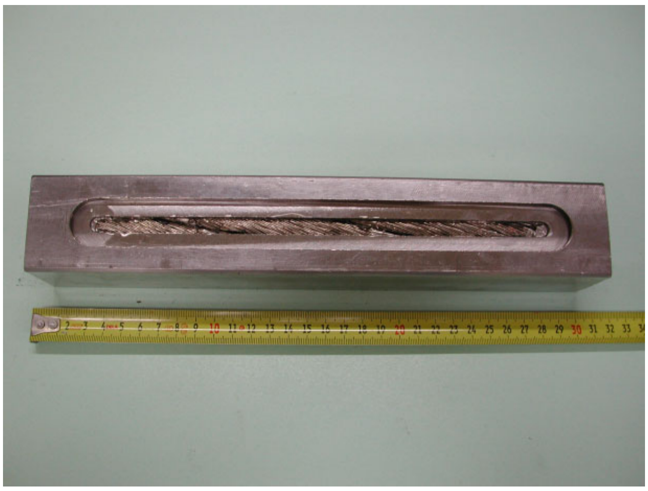

Figure 4 : Manufacture test of the narrow groove

A more fabricable value of the radius of the ends of the groove of 2 mm instead of 1 mm has been chosen. in agreement with EFDA. This increases very locally the stress concentration factor from 1.30 to 1.57.

No samples of CS conductor being available during year 2004, the manufacture and tests of this mock-up have been delayed

DEVELOPMENT OF THE BONDED TAILS OF THE PF COIL WINDINGS

Design

The ITER PF coils design of the winding packs consists of a stack of double pancakes made of NbTi cable-in-conduit conductor, with a square section jacket in stainless steel 316LN.

Electrical joints are necessary for the connections between double-pancakes and the terminals; at each joint, a structural element is required to transfer the operating hoop load on the conductor. In the present design, this is provided by a conductor tail welded to the conductor jacket and bonded to the adjacent turns of the pancake. The load is therefore transmitted to adjacent turns and to the bulk of the coil, through shear stresses in the insulation.

The highest hoop load occurs in PF5 Coil, and it results in a tensile load in the conductor jacket of 250 kN and a tensile stress of 150 MPa. This is also the load to be carried and transmitted by the bonded tail. In the framework of the CEA/EFDA Contract 00-541 a design was developed using a hollow profiled tail.

The scope of the present task is to develop the manufacturing and assembly of the coil tails to the level of an industrial process and, ultimately, to build a mock up, representing the main features of the coil tail, and to subject it to fatigue tests, at LN temperature, at the ENEA (Brasimone, Italy).

Manufacture

At first the work has concentrated on qualifying the process for manufacturing the prototype tails, within the strict tolerances required, and four tails have been produced (figure 5).

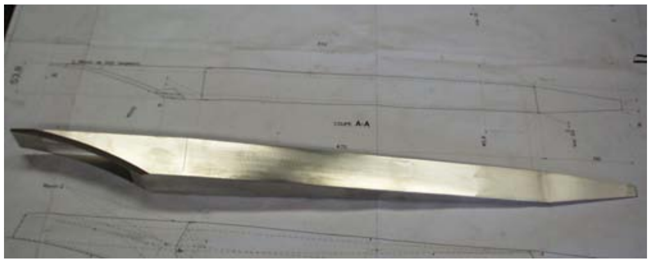

Figure 5 : Manufacture of a prototype PF Coil

This has been followed by the process qualification of welding the tails to the PF conductor jacket, bent at 500 mm radius, as foreseen for the PF pancake conductor exits (figure 6). All parts have been manufactured with the nominal dimension as PF5 coil and have been made in steel 316LN especially forged.

Figure 6 : Coil Tail welded to a mock-up PF conductor exit

At present the overall mock-up, inclusive of parts representative of the adjacent conductor is in the process of been assembled and impregnated. The mock-up includes two of the coil tails previously manufactured and steel plates simulating the inertia of the adjacent conductors (figure 7). Further stress analysis performed on the mock-up F.E. model has highlighted tensile stresses in the G10 epoxy-glass fillers caused by the cool-down to LN temperature.

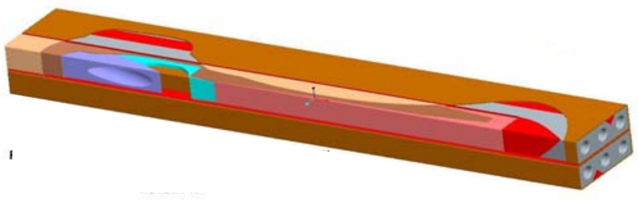

Figure 7 : PF Coil Tail mock-up for fatigue testing

To reduce the filler thermal contraction and overcome this problem, the mock-up filler parts will be made with special G10 at high (80 %) glass content. In parallel a structure has been designed and it is being fabricated, to interface the mock-up to the test machine, such to convert the compressive force of the machine in tensile force applied to the mock-up The limited space to bolt the mock-up to the structure and the application of the pre-load on the bolts has required the manufacture of special Inconel 767 tensioners. The applied test load will be twice the nominal for 60 000 cycles.

CONCLUSION

The task COOLINL is devoted to design and fabrication of mock-ups for three different items: the TF helium inlet, the CS helium inlets and the PF bonded tails. During the year 2004, the following actions were performed:

The TF inlet design was defined. Local and global FEM analysis were performed for optimization and have led to acceptable stress level with a double loading to reduce the number of cycles. The components for the fatigue life as well as for the hydraulic mock-ups were manufactured. The fatigue life as well as hydraulic qualification is planned in 2005.

A CS inlet, design of a reduced mock-up compatible with the test facility capability and the doubling of the loading imposed by EFDA was defined. A corresponding FEM analysis was performed to get representative stress concentration level with respect to the real complete inlet. The mock-ups manufacture was delayed due to the unavailability of CS conductor samples.

The components for the PF tail mock-up were manufactured. A FEM of the PF tail mock-up was built and has led to define the final design and the materials for the structure of the fatigue life mock-up. All the components are under fabrication. The mock-up assembly and tests are planned in 2005.

REPORTS AND PUBLICATIONS

[1] P. Decool - EFDA contract 03-1015 : CS cooling inlets comparison between A full and a half mockup - Note AIM/NTT/2004.004.

TASK LEADER

Patrick DECOOL

DSM/DRFC/STEP
CEA-Cadarache
F-13108 Saint-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

CEFDA03-1120

Task Title: TW3-TMSC-ASTEST: TESTS OF ADVANCED Nb_3Sn STRANDS EXTENSIVE CHARACTERIZATION OF INDUSTRIAL ADVANCED Nb_3Sn STRANDS DEVELOPED FOR ITER TF COILS SYSTEM

INTRODUCTION

This action is part of a global R&D program extension devoted to the Nb_3Sn material. Nb_3Sn is the superconducting material used in the ITER TF and CS Coils.

However the models built in the framework of the ITER EDA phase (CSMC, CSIC, TFMC, TFCI) has shown reduced performances compared to those expected and consequently a specific EU R&D program was launched.

An action was started with industrial companies to stimulate them in developing a new generation of superconducting strands with specifications adapted to the ITER TF Coils system:

- I_C(4.2 K, 12 T) > 200 A with a target value of 280 A.
- Q_{hyst} < 500 mJ.cm^{-3}.

Six companies were concerned : Alstom (F), Outokumpu Italy (I), Outokumpu Finland (FIN), EAS (D), SMI (NL), Oxford Instruments (GB).

The strand qualification is planned in two steps :

- a global assessment of all EU stations involved in this task, for which a benchmarking strand from SMI is tested in all laboratories. Results are then compared and must remain within a defined scattering to be accepted,
- two strands are tested by each EU laboratories with possibility of cross-checking between laboratories.

The tests involve :

1. geometrical measurements with diameter, filament twist pitch and Cu/nonCu ratio,
2. electrical measurements with J_C(4.2K, 10-14 T),
3. magnetic measurements with Q_{hyst}(+/- 3 T).

Actions #1 and #3 are planned to be performed at CEA Cadarache while action #2 is to be performed at CEA Saclay.

2004 ACTIVITIES

QUALIFICATION OF THE EU LABORATORIES FACILITIES

The test facility used for the electrical measurements is the CEATACES test facility, located at CEA Saclay in the DAPNIA laboratory. The test facility used for the AC losses magnetic measurements is the SUSI facility located at CEA Cadarache.

All required tests were performed with the SMI strand. It is to be noted that less characterizations were planned for this qualification step (no filament twist pitch or strand diameter). Test mandrels were provided by CEA, handling and heat treatments were performed by CEA.

Geometrical tests

The cross section micrography is shown in figure 1.

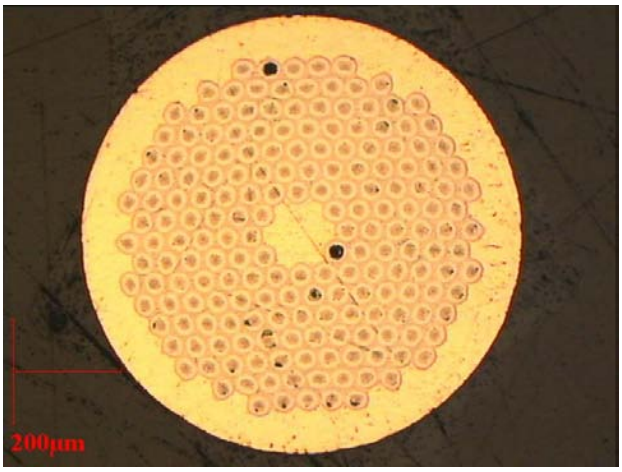

Figure 1 : Micrographic view of the SMI strand cross-section.

Cu/nonCu ratio has been evaluated to 0.827.

Electrical tests

For those tests, stability measurements were encountered and were solved by the addition of strand extra lengths in the Cu/Ti transition part of the mandrel. Results are shown in figure 2.

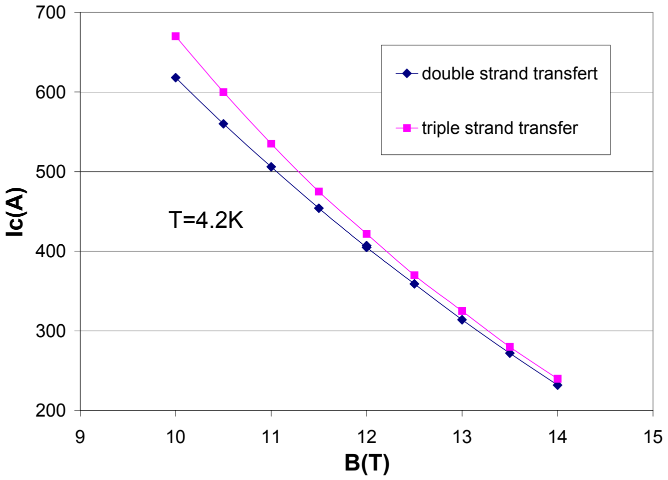

Figure 2 : Critical current results for two SMI samples. The difference between samples lays in the strand extra length added for stabilization

Magnetic tests

Q_{hyst}(+/- 3T) have been evaluated to 1370 mJ.cm^{-3}

This step was completed and the corresponding deliverable report was sent to EFDA [1]. All results were compared between EU laboratories and found acceptable by EFDA. CEA was thus allowed to enter the second step of the strands qualification process.

INDUSTRIAL STRANDS CHARACTERIZATION

The first strand from Oxford Instruments was provided to CEA by EFDA and all billets available were prepared for characterizations (Hysteresis losses, critical current, Cu/nonCu…).

Critical current tests were performed in early December 2004 at CEA Saclay and results can be seen in figure 3.

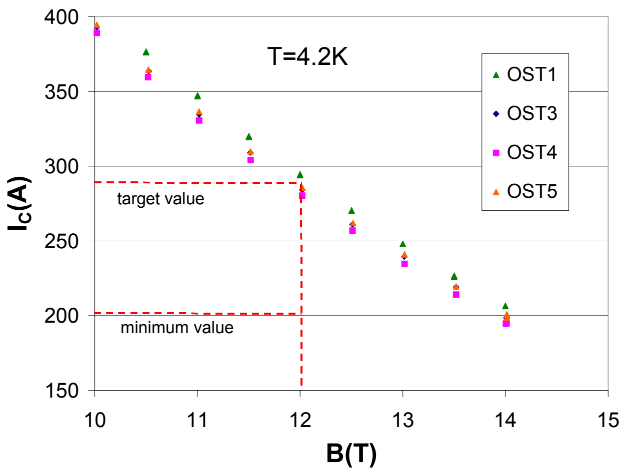

Figure 3 : Critical current results for four OST samples (four different billets)

The remaining tests on OST strands are planned for the first semester of 2005. All tests for the second strand will start as soon as it is received from EFDA in CEA Cadarache.

CONCLUSION

During the year 2004 the ASTEST actions progressed as follows:

- The benchmarking step was completed with the SMI strand. All tests were assessed by EFDA in comparison with all other EU laboratories involved. The CEA tests facilities were thus accepted for ITER advanced strands qualification.

- The critical current tests were achieved on the first industrial strand (Oxford Instruments) and the remaining are planned for early 2005.

REFERENCES

[1] L. Zani, H. Cloez, C. Meuris, P. Chesny, J-M. Gheller, L. Kulbicki, L. Vieillard - Task TW3-TMSC-ASTEST Deliverable 1 : Intermediate report on test of advanced Nb_3Sn strands - Note AIM/NTT-2004.014 (2004).

TASK LEADER

Louis ZANI

DSM/DRFC/STEP
CEA-Cadarache
F-13108 Saint-Paul-Lez-Durance Cedex

Tél. : 33 4 42 25 29 67
Fax : 33 4 42 25 26 61

E-mail : louis.zani@cea.fr

CEFDA04-1127

Task Title: TW4-TMSC-SAMAN1: MANUFACTURE OF SUB-SIZE SAMPLES

INTRODUCTION

The tests of the TF model coil in 2001 – 2002 have shown that the performance of the conductor was lower than expected [1]. This initiated in Europe an advanced strand procurement to take advantage of the progresses in Nb_3Sn during these last ten years. New high performance strands have been ordered by EFDA to industry.

In the framework of the SAMAN task, CEA has to explore the sensitivity of these high performance Nb_3Sn strands to stainless steel jacketing on subsize samples, as concern the critical properties. This will be done by ordering and manufacturing these samples in the industry and then by participating to the tests at FZK (Germany) in the FBI test facility. 2004 has been devoted to the writing of the specifications of these samples and to ordering their fabrication in the industry.

2004 ACTIVITIES

SCOPE OF SUPPLY

Strands of 'high performance' Nb_3Sn superconductor, meeting ITER specifications, have been produced by the industry. The contract to be placed in industry, within this task, concerns the manufacturing of sub-size conductor samples, made of these strands. The samples are required for a test program with two objectives :

1. Characterization of the cable performances, depending on cabling parameters. For this purpose, for each type of sample to be manufactured, one or more parameters are varied with respect to the reference parameter value.

2. Performance comparisons of conductors made with strands provided by different manufacturers. In this case, various samples, all of the same type, are to be manufactured with strands provided by five different strand suppliers.

The supply contract is divided in two lots according to these two objectives.

DESCRIPTION OF THE SAMPLES

This type of samples has been already manufactured in the framework of a previous contract [2]. A section of the sample can be seen in figure 1, in the particular case of 36 strands. The strands are taken in a jacket. Copper tubes are inserted at both extremities for the electrical contact to the current leads of the power supply.

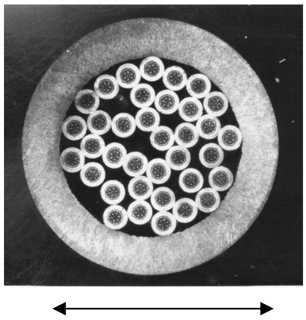

Figure 1 : Section of a sample manufactured in the framework of a previous task [2]

The sub-size cable samples to be manufactured as part of this contract are summarised in tables 1 and 2.

The samples for the sample characterization tests constitute the first lot. They are presented in table 1 This lot corresponds to a total of 24 samples plus 3 prototypes.

The samples for the superconducting strand manufacturer comparison tests, constitute the second lot. They are presented in table 2. This lot corresponds to a total of 20 samples.

EFDA will provide to CEA the strands to be used by the manufacturer :

(a) The Nb_3Sn superconductor strand, size Ø 0.81 mm.

(b) The copper strand size Ø 0.81 mm, (type : OFHC copper, chromium plated with 2µm plating thickness, unless otherwise specified for few samples with no chromium plating).

The manufacturer will be responsible for the supply of all other materials required, in particular :

(c) Type 316L stainless steel tube.

(d) Copper tube made of 'high purity' copper with RRR higher than 80 (RRR is the electrical resistance ratio between ambient temperature and 20 K ➔ R_{293K}/R_{20K}).

The manufacturer will be responsible for the cabling of the copper and Nb_3Sn strands and for the 'jacketing' of the cable with the stainless steel and copper tubes to its final dimensions. The cabling is to be performed 'without torsion', according to the standard practice in the cabling industry. For the jacketing with the steel and copper tube the preferred manufacturing method is by 'hammering'

Table 1 : Samples for characterization program (first lot)

1st Triplet made of :	Samples 3X3 Twist pitch 45/ 85mm Void fraction 32%		Samples 3X3X5 Cr coating				Samples 3X3X3X5 Twist pitch 45/85/125/160 mm Cr coating Void fraction 32 %
			Twist pitch 45/85/125mm			Twist pitch 35/65/110mm	
	Cr coating	No Cr coating	Void fraction 32 %	Void fraction 25 %	Void fraction 45 %	Void fraction 32 %	
0 Cu strand 3 SC strands	2		2				
1 Cu strand 2 SC strands	1 prototype + 2	2	1 prototype + 2	2	2	2	1 prototype + 2
2 Cu strands 1 SC strand	2		2				2
Total	8 + 1 prototype		10 + 1 prototype			2	4 + 1 prototype

Table 2 : Samples for supplier comparison assessment program (second lot)

1st Triplet made of :	Samples 3X3X5	Twist pitch 45/85/125 mm Cu-Cr coating Void fraction 32 %						Samples 3X3X3X5	Twist pitch 45/85/125/160 mm Cu- Cr coating Void fraction 32 %				
		SC Strand Supplier							SC Strand Supplier				
		A	B	C	D	E			A	B	C	D	E
1 Cu strand 2 SC strands		2	2	2	2	2							
2 Cu strands 1 SC strand									2	2	2	2	2

STATUS OF THE TASK

A call for tender has been sent in October 2004 according to the specifications presented above. The Nexans company (France) has been selected to manufacture the samples. The first prototypes are expected to be ready in June 2005.

CONCLUSION

2004 has been devoted to the writing of the specifications of the samples to be manufactured. A call for tender has been launched in industry based on these specifications; Nexans has been chosen and the first prototypes are expected to be delivered in June 2005.

REFERENCES

[1] J.L. Duchateau et al - Exploring the limits of a very large Nb_3Sn conductor: the 80 kA conductor of the ITER Toroidal Field Model Coil - 2004 Supercon. Sci. Techno. 17, p.241-249.

[2] W. Specking, J.L. Duchateau - First results of strain effects on critical current of incoloy jacketed Nb_3Sn CICC's - 1997 - 15th Conference on Magnet Technology Beijing (China).

TASK LEADER

J.L. DUCHATEAU

DSM/DRFC/STEP
CEA-Cadarache
F-13108 Saint-Paul-Lez-Durance Cedex

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

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

CEFDA04-1134

Task Title: TW4-TMSC-BARBEN: BENDING STRAIN EFFECTS OF SINGLE STRANDS Study of bending strain effect on critical properties of Nb_3Sn strands jacketed with stainless steel for various bending amplitudes and temperatures

INTRODUCTION

This action is part of a global R&D program extension devoted to the Nb_3Sn material. This task aims at investigating a possible influence of bending strain on strand performances. In order to perform tests on strands in relevant conditions to that occurring in a cable-in-conduit conductor, the tested samples will use jacketed single strands. For this 316L stainless steel tubes will be used for the jacket.

The bending efforts will be imposed by changing curvature radius of the jacketed strand (practically changing support mandrels radius).

Three main parameters will be explored:

1. the bending strain applied, typically for a maximum bending strain of 0.25 % and 0.5 % on the filamentary zone,
2. the strand structural parameters (manufacturer i.e. process, filaments twist pitch), in order to evaluate the reliability of previously developed models [1],
3. the temperature (no bending applied in these conditions).

Practically this work will be done in collaboration with ENEA Frascati (Italy). Critical properties of jacketed strands at T = 4.2 K and B = 12 T will be measured in an ENEA dedicated facility. The actions are globally shared as follows:

In a first step CEA should define on a typical jacketed strand a method for imposing a controlled bending strain. All needed tools and all method options should be performed at CEA except for the jacketed strand provided by ENEA. The qualification of the method will derive from comparative tests in the ENEA facility.

In second step CEA transfer the know-how to ENEA, which is in charge of the defined supports manufacturing and all samples handling (with various manufacturers and twist pitches). All critical current measurements will be performed in the ENEA facility.

In a third step CEA will characterize a defined jacketed strand at variable temperature with no bending applied. The final analysis of all experimental results will be achieved commonly between CEA and ENEA.

2004 ACTIVITIES

BENDING TOOLS AND PROCEDURE

Design

As mentioned earlier the bending will be applied by modifying sample curvature radius on its support mandrel. Two options are possible for bending: expansion (radius increase) or reduction (radius decrease). Besides, the strand ends for current injection may be unjacketed before or after heat treatment.

CEA decided to test each of those methods and the choice will be made after comparison of J_C(4.2 K, 12 T).

At CEA the heat treatment and testing mandrels have been designed for expansion and reduction options, trying to avoid any extra or uncontrolled strain (mainly torsion).

For reduction method the heat treatment is performed on a high diameter mandrel and transferred to the testing mandrel at low diameter (figure 1 left part) by help of an adapted set-up.

For expansion method, the transfer is to be held by an intermediate cone with specifically designed grooves to avoid torsion and follow as well as possible the natural spring expanding.

Manufacture

Manufacturing have been completed in early December. Jacketed strands were also provided at that date, allowing early handling tests.

Some pictures of the support pieces can be seen in figure 1.

The next action program is the completion of the additional tools required for the transfer method.

Then reduction method will be tested first on dummy samples after an ITER-like heat treatment. Basically three points will be investigated : jacket removal phase without damaging strand, soldering onto Cu pieces, the transfer and the maintain of strand onto the mandrel. This is expected to be completed about march 2005.

Figure 1 : Support systems for jacketed strands
Left picture is for the reduction method and right picture is for the expansion method.

EXPERIMENT FOR VARIABLE TEMPERATURE TESTS

The Variable Temperature Cryostat (VTC) already used for single strands characterization [2, 3] is required for the study of jacketed strands critical properties at various temperatures. A picture of a superconducting strand wounded onto the VTC test mandrel is shown in figure 2.

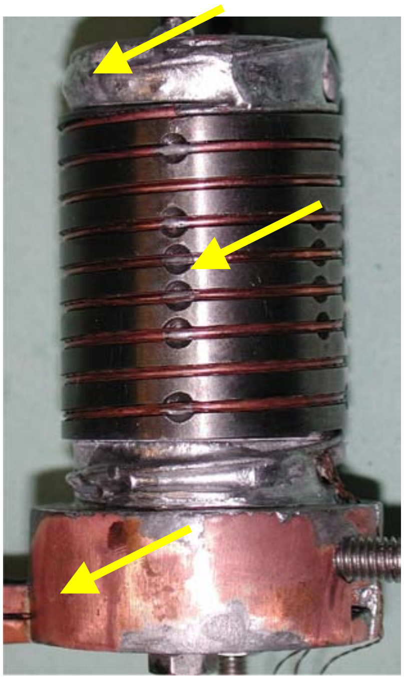

Figure 2 : Equipped mandrel for the VTC qualification at high temperature - The location of the three temperature probes (not visible on the picture) are shown by arrows

The system was recently upgraded as the regulation system was coupled with the acquisition system by adding a regulation module to the DAS Labview program (National Instruments). The qualification of this new configuration was quasi achieved with a testing campaign [4] in GHMFL laboratory (CNRS, Grenoble) performed in December 2004.

An example of temperature ramp obtained is given in figure 3 showing a satisfactory temperature homogeneity (< 30 mK).

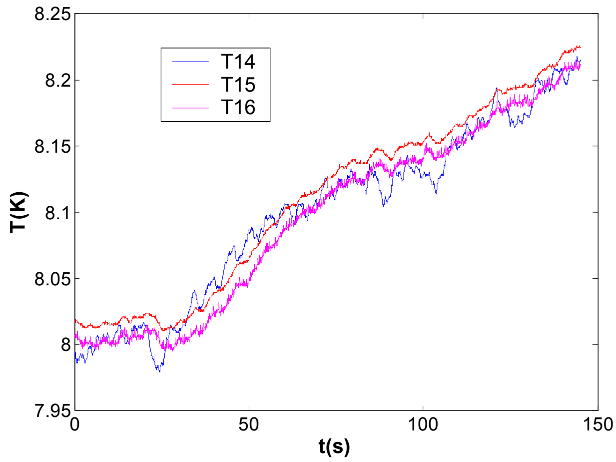

Figure 3 : Example of controlled temperature ramp performed with the Labview regulation system installed on the VTC set-up. The T14, T15 and T16 temperature probes are located at top, center and bottom of the mandrel

However an extra campaign would be required for statistics and for use with the stainless steel pieces required in the task, planned in CEA Cadarache between march and april 2005. The final measurements at GHMFL should occur before summer 2005.

CONCLUSION

During the year 2004 the BARBEN actions progressed as follows:

- The jacketed strands transfer method was defined with 4 options to be compared.
- The adapted mandrels for heat treatment and for measurements were designed and manufactured.
- The first OST superconducting strand was jacketed.
- The upgraded VTC facility was qualification was nearly achieved with a campaign in GHMFL (CNRS, Grenoble).

All remaining actions on this task are planned to be completed during the year 2005.

REFERENCES

[1] J.W. Ekin - Current transfer in multifilamentary superconductors. I. Theory, J. Appl. Phys. Vol. 49 n°6, pp.3406-3409 (1978).

[2] L. Zani, JP. Serries, H. Cloez, Z. Bej and E. Mossang - Characterization of transport properties variations with magnetic field and temperature of ITER-candidate NbTi strands, Physica C 372-376 pp. 1311-1314 (2002).

[3] L. Zani, E. Mossang, M. Tena, J-P. Serries and H. Cloez - J_C(B,T) characterization of NbTi strands used in ITER PF-relevant Insert and Full-scale sample, presented at ASC2004 (2004).

REPORTS AND PUBLICATIONS

[4] L. Zani, M. Tena, H. Cloez, J-P. Serries, S. Girard - Tâche BARBEN : qualification du système de régulation du Cryostat à température Variable en configuration Nb_3Sn, Note AIM/NTT-2005.003, (2005).

TASK LEADER

Louis ZANI

DSM/DRFC/STEP
CEA-Cadarache
F-13108 Saint-Paul-Lez-Durance Cedex

Tél. : 33 4 42 25 29 67
Fax : 33 4 42 25 26 61

E-mail : louis.zani@cea.fr

TW1-TMC-CODES

Task Title: DESIGN AND INTERPRETATION CODES
Determination of thermohydraulic properties of cable-in-conduit conductors with a central channel

INTRODUCTION

The thermohydraulics of cable-in-conduit conductors has to be well described, to allow proper design of the cryogenic system of ITER. The pressure drop of central channels representative of ITER has to be characterized. The recooling time of forced flow coils and the quench behaviour are driven by the heat transfer coefficient between the annular area and the central channel. This coefficient can hardly be theoretically evaluated; only experiments, possible at room temperature, can bring information about this coefficient.

These experimental activities are led at CEA Cadarache on dedicated facilities in collaboration with Politecnico di Torino.

2004 ACTIVITIES

MEASUREMENT OF CENTRAL SPIRAL PRESSURE DROP

The pressure drop measurements were carried out on central spiral samples tested in the OTHELLO test facility at Cadarache. The experimental work was completed in 2003. Following the previous qualification of the TFMC spirals (specially Showa and Cortaillod with inner and outer diameters equals to 10 and 12 mm respectively), with the determination of the friction factor as a function of the Reynolds Number, it seemed pertinent to characterize other spirals with different geometrical (hydraulic) parameter and to estimate the influence of these parameter on the friction factor.

New spirals were supplied by the Mécaressorts company, with inner and outer diameter respectively of 6 and 8 mm on one hand and 8 and 10 mm on the other hand. These spirals have been characterized and the friction factors determined experimentally in the OTHELLO test facility with pressurized nitrogen. Some friction factor fits indicating the tendency with the Reynolds Number could be given.The important results of these experimental measurements is that the S8, C8 and I8 spirals show a much higher friction factor –nearly 0.4- than the TFMC central spiral which was only between 0.1 and 0.2.

Spiral I8 $f_{EU,I8} = 0.54 \cdot RE^{-0.03}$

Spiral I10 $f_{EU,I10} = 0.36 \cdot RE^{-0.038}$

Nevertheless, the influence of the geometrical parameters considered is difficult to evaluate without a parametric study. The present design of the ITER Toroidal Field Cable In Conduit Conductor includes a central spiral with inner and outer diameters of 7 and 9 mm respectively (with a gap to twist pitch length ratio equal to 0.5). A first approximation of the friction factor of this type of spiral could be given, by linear interpolation of the previously tested central spirals results.

Spiral I9 $f_{EU,I9} = 0.45 \cdot RE^{-0.034}$ (interpolated)

Nevertheless, experimental tests (in the OTHELLO test facility) of such spirals samples would be very useful for a more precise determination of the friction factor and could be used for further parametric study and the assessment of refined theoretical models of the central spiral hydraulics.

EXPERIMENTAL EVALUATION OF THE HEAT TRANSFER COEFFICIENT BETWEEN ANNULAR AND CENTRAL CHANNELS OF ITER CONDUCTORS

An important parameter of the ITER magnets cryogenic cooling system is the recooling time. The cable-in-conduit conductor (CICC) being cooled by a high speed flow (1m/s) in the central channel in parallel with a slow speed flow (0.1m/s) in the annular area, the recooling time is depending on:

- The heat transfer coefficient between the two parallel channels.
- The fluid velocity in each channel.

A numerical and analytical model was developed to predict the temperature evolution along a CICC after a temperature step at the inlet. This model relies on the heat transfer coefficient between the two parallel channels, but also the heat transfer coefficient between the jacket and the water.

To evaluate this heat transfer coefficient , a new facility named HECOL and operating in relevant Reynolds number up to 70°C in pressurised water was built in 2003. A sample of TFMC conductor with Cortaillod spiral specially instrumented was used for the tests (figure 1).

After the first test campains, performed in collaboration with POLITO, experimental heat transfer coefficients have been determined. An upgrading of the facility was performed and a new test campaign showed poor accuracy of the temperature measurements.

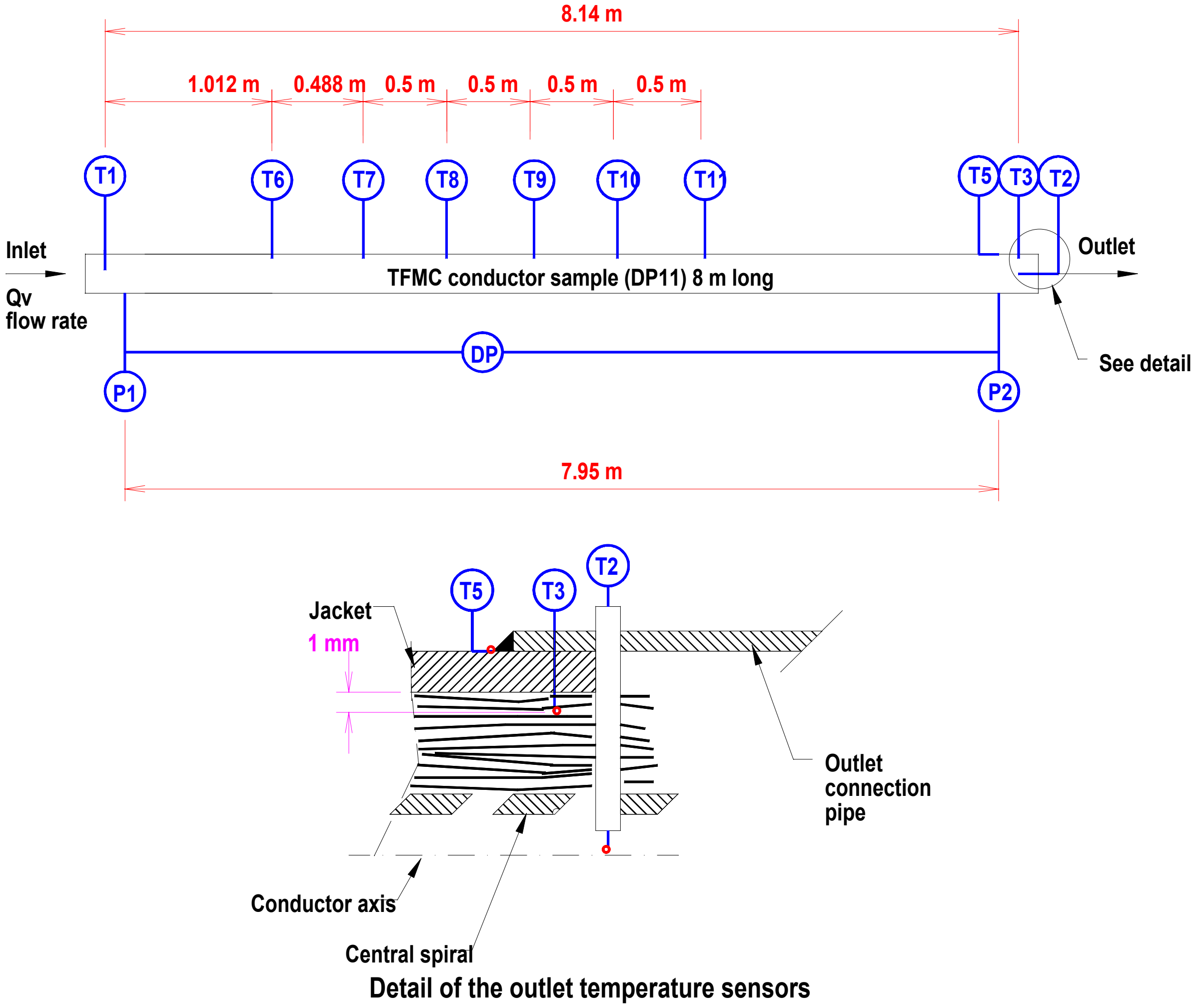

Figure 1 : Sample instrumentation for heat transfer measurement

At the beginning of 2004, an upgraded version of the data acquisition system providing more accuracy was installed, the conductor sample was insulated and a calibration of all the temperature sensors was performed. A final test campaign was engaged with transient tests by imposing a temperature step at the inlet. The corrected temperature evolution was measured at different location along the conductor (figure 2).

For the evaluation of the global heat exchange coefficient in CICC, the convective heat exchange was first determined with the Reynolds-Colburn analogy. A steady state model, with a characteristic space constant Λ was then developed and presented. This parameter governs the mixing temperature between the two channels of the CICC and permits to express the annular channel temperature as well as the central hole channel temperature in a heated zone and non-heated zone.

From the measurement of the characteristic space constant on our sample and applying this model within the HECOL test conditions, the global heat exchange coefficient of ITER CICC type conductor was determined between 15000 and 30000 W/m².K as an increasing function of the fluid volumetric mass flow rate (0.2 up to 1.8 l/s) and with the temperature (or Prandtl number) as parameter.

The convective heat exchange coefficient in each channel (h_{convb} and h_{convh}) as well as the bundle mass flow ratio α and the characteristic space constant Λ could also be determined.

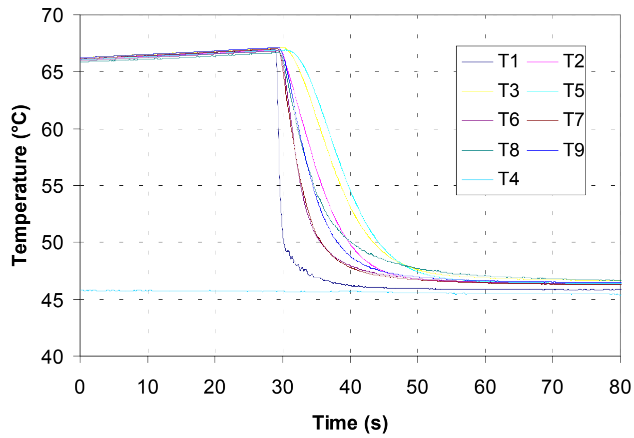

Figure 2 : Corrected temperatures for a typical shot from 65 down to 45 °C at 1.5 l/s

The results obtained with a corresponding thermohydraulic transient numerical tool (code M&M) confirm the global heat transfer coefficient range presented with the steady state model application.

Furthermore, the steady state characteristic space constant model, with the corresponding heat transfer correlation were applied to cold tests, specially the PF-FSJS. A good agreement of the calculated analytical value of the space constant on one hand and the experiments on the other hand was observed.. Typically, the global heat transfer coefficient h_perfor for the PF-FSJS is between 300 and 450 W/m².K. For the TFMC tests, in the TOSKA test facility, the global heat transfer coefficient h_perfor is comprised between 400 and 600 W/m².K.

As for the PF-FSJS experiment, it would be interesting to perform some steady state tests in the HECOL test facility in order to verify the characteristic space constant predicted by the model with experimental results by measurements of the temperature profile along the conductor. These steady state tests would be worthwhile by varying the mass flow rate (Reynolds number), the water temperature (Prandtl number) and the sensor locations (radial direction); with heating on a determined length, they also are representative of what happens on the CICC during nuclear heating of the TF Coils.

CONCLUSION

During the year 2004, an analysis of the tests of seven central spirals relevant to ITER type conductors tested in GN2 at room temperature in the OTHELLO test facility during the year 2003 was carried out. This analysis led to conclude that the smaller diameter spirals (8 mm) presents friction factor about twice higher than the old larger ITER spirals (12 mm). An interpolation led to predict the friction factor of the new ITER spirals design. However, a set of spirals much closer to the new ITER spiral design would be very useful for a more precise determination of the friction factor and could be used for further parametric study and the assessment of refined theoretical models of the central spiral hydraulics.

For the evaluation of the heat transfer coefficient between annular area and central channel of ITER cable-in-conduit conductors, the dedicated experimental facility HECOL which operates in pressurized water at 70°C was upgraded and the accuracy of the last results was satisfactory. A steady state model, with a characteristic space constant Λ was then developed and has confirm the results obtained with a corresponding thermohydraulic transient numerical tool (code M&M) on the global heat transfer coefficient range.

The steady state characteristic space constant model, with the corresponding heat transfer correlation were applied to cold tests. A good agreement of the calculated analytical value of the space constant on one hand and the experiments on the other hand was observed.

It was suggested to perform some steady state tests in HECOL to verify the characteristic space constant predicted by the model. A final report on all these task activities was issued [1].

REPORTS AND PUBLICATIONS

[1] Task CODES: Deliverable 4, Experimental investigation to determine the heat transfer coefficient between annular area and the central channel of ITER-FEAT conductors as an input to codes development, S. Nicollet, H. Cloez, P. Decool, J.L. Duchateau, A. Martinez, M. Tena, B. Renard, J.P. Serries.

TASK LEADER

Patrick DECOOL

DSM/DRFC/STEP
CEA-Cadarache
F-13108 Saint-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

TW1-TMS-PFCITE

Task Title: POLOIDAL FIELD CONDUCTOR INSERT (PFCI)

INTRODUCTION

Within the framework of the ITER project, the EU PT has been asked to manufacture a model coil, called Poloidal Field Conductor Insert (PFCI), to be tested in the JAERI test facility in Naka, Japan. The development, manufacture and testing of the PFCI coil shall support the design of the ITER PF conductors and coils.

The main objective of the model coil tests is to get a complete knowledge and understanding of the behaviour of high current NbTi cable-in-conduit conductors and related joints under operating conditions as foreseen for the ITER Poloidal Field (PF1 & PF6) coils. A conductor representative of the ITER PF1 & PF6 coils shall be wound in a single layer coil and equipped with a numerous instrumentation composed of inductive heaters, voltage taps, temperature and pressure sensors, strain gauges, etc. The coil shall be inserted inside the bore of the ITER CS Model Coil (CSMC) at the JAERI test facility in Naka (Japan) and tested in 2005.

The coil winding features a square conductor with a NbTi superconducting cable inserted in a thick wall, stainless steel jacket. Superconducting joints are required to connect the coil to the current leads. Another joint is located at an intermediate location in the winding to test an ITER-relevant joint under magnetic field operating conditions similar to the ones foreseen in the ITER PF coils. The upper and lower terminations shall connect the winding to the existing CSMC Insert busbar system of the Naka facility, as well as to the cryogen supplies.

The work of CEA within task PFCITE covers the following items:

- Participation to definition and review of the test procedure.

- Participation to operational campaigns of the PFCI and reporting of the results.

- Analysis of the results, including thermo-hydraulic, electro-magnetic, and structural simulations of the real operating conditions of the coil.

- Analysis of impact of results on ITER PF coils design.

The NbTi cable for the PFCI was delivered to Ansaldo in August 2002 from the Russian Federation, the jacketing was completed at Ansaldo in June 2003. Fabrication of the coil is running at Tesla (UK) under monitoring by EFDA/CSU Garching, however problems in the joint design and fabrication were discovered during the tests of the PFCI-FSJS in SULTAN.

A new R&D was then launched at Tesla to get an acceptable joint resistance (i.e. ≤ 5 nΩ) and new tests by CRPP on small pieces of improved joint look satisfactory. The coil (including impregnation) should be completed by mid March 2005. The fabrication of the mechanical structure is carried out in parallel (expected to be ready in Feb. 2005). Final acceptance and shipment to the CSMC test facility are foreseen end of March 2005, and assembly in the Naka facility during summer 2005. Testing programme at JAERI should start end of 2005.

2004 ACTIVITIES

For 2004, our activities were reduced because of the delay taken in the fabrication of the PFCI at Tesla (UK). The model developed by CEA to predict joint performance under transient (code JUST) was applied to the study of the behaviour of the PFCI intermediate joint in the reference pulse field scenario. The JUST code is now considered as one of the tools to be used for the analysis of the PFCI test results [1].

The reference pulse field scenario consists of a discharge of the CSMC from 21.2 kA to zero, with a decay time constant of 20 s, without current in the PFCI. Figure 1 shows the power dissipated in the intermediate joint during the discharge, with a separation of the contributions due to the radial field variation and to the axial field variation. It can be seen in this figure that the two contributions are almost equivalent in term of peak power which is quite different in the ITER PF6 joints due to a relative higher radial field variation.

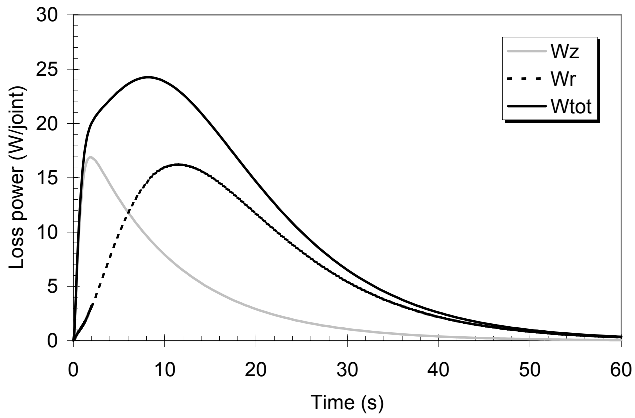

Figure 1 : Computed loss power in the ITER PFCI intermediate joint during a CSMC discharge from 21.2 kA within 20 s: contribution of radial field variation (Wr), contribution of axial field variation (Wz), total loss power (Wtot)

The helium outlet temperature at the joint is shown in figure 2, where it can be seen that the temperature increases of about 1 K at the maximum. Figure 3 gives the minimum temperature margin in the joint during this scenario. In figure 3, DTcs_o corresponds to the margin with the average current (here equal to 0) in the strands, while DTcs+ includes the loop current flowing through the strands.

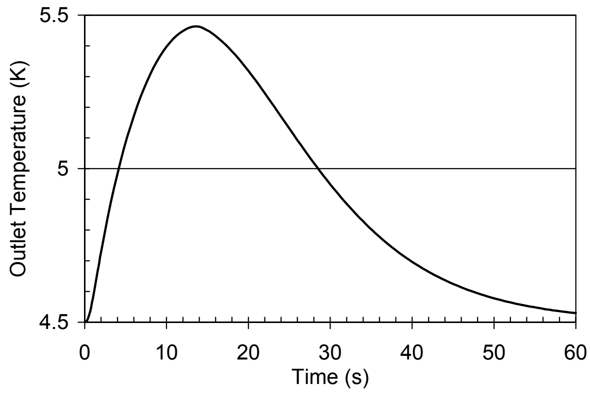

Figure 2 : Computed evolution of helium outlet temperature in PFCI intermediate joint during a CSMC discharge from 21.2 kA within 20 s

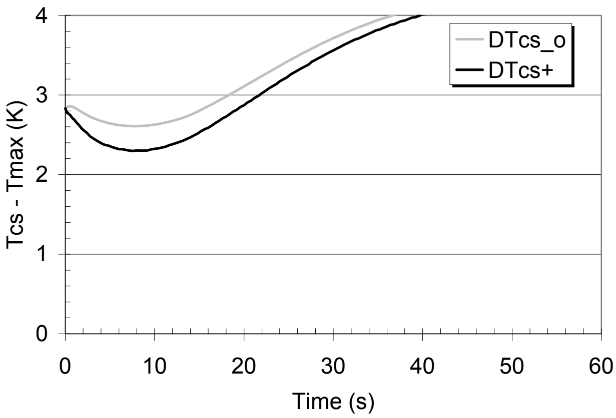

Figure 3 : Computed evolution of temperature margin in PFCI intermediate joint during a CSMC discharge from 21.2 kA within 20 s (DTcs_o with transport current only, DTcs+ with adding loop current)

CONCLUSIONS

The Poloidal Field Conductor Insert is under fabrication in industry and should be tested in the CSMC facility (Naka, Japan) end of 2005. CEA is participating in the definitions of both the PFCI instrumentation and the testing programme. The model developed by CEA (code JUST) for the analysis of the ITER PF joint behaviours was applied to the PFCI intermediate joint during the reference pulse field scenario.

This analysis has shown that radial and axial field variation will give equivalent contributions at variance with the ITER PF6 joints in which the former is predominant, and that the helium temperature rise will be quite measurable (≈ 1 K). This model is a part of the useful tools to be used for the assessment of the testing programme as well as for the PFCI test analysis.

REFERENCES

[1] R. Zanino et al - Preparation of the ITER Poloidal Field Conductor Insert (PFCI) Test - presented at the 2004 Applied Superconductivity Conference, October 3-8 Jacksonville FL (USA).

TASK LEADER

Daniel CIAZYNSKI

DSM/DRFC
CEA-Cadarache
F-13108 Saint-Paul-Lez-Durance Cedex

Tél. : 33 4 42 25 42 18
Fax : 33 4 42 25 26 61

E-mail : daniel.ciazynski@cea.fr

TW2-TMST-TOSKA

Task Title: TFMC TESTING WITH THE LCT COIL

INTRODUCTION

In the framework of the TOSKA Task, CEA was asked by EFDA to participate to the testing of the ITER Poloidal Field Conductor Insert Full Size Joint sample (PFIS) in the SULTAN facility at CRPP in Villigen. The PFIS was tested in 2004.

This sample aimed to test electrically both the conductor and the joints used in the Poloidal Field Coil Insert (PFCI) to be tested in the CSMC facility (JAERI, Naka, Japan). The PFIS as well as the PFCI were designed by EFDA which also followed up the fabrication in industry at TESLA (UK).

The two conductor legs are identical except that one leg (W) has the regular ITER geometry with steel wraps around the last but one cabling stage (petal), while the other leg (NW) has no such wraps and thus requires a slightly higher compaction to keep the final void fractions equivalent (see Figures 1a and 1b). The conductor with wraps is identical to the one used in the fabrication of the PFCI.

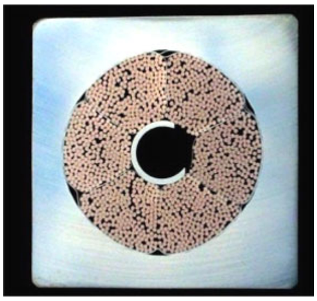

Figure 1a : Cross-section of PFIS left leg conductor (with wraps)

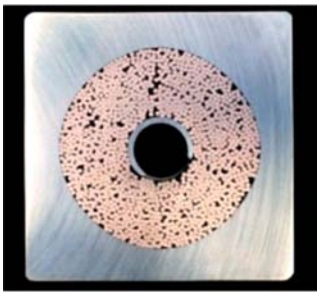

Figure 1b : Cross-section of PFIS right leg conductor (w/o wraps)

Both legs make use of the same NbTi strand, fabricated by Bochvar VNIINM (Moscow, Russia). This strand is 0.73 mm in diameter (see table 1).

2004 ACTIVITIES

MEASUREMENT OF RRR ON PFIS JOINT SLEEVES

During the first PFIS Test Group meeting, CEA pointed out that the electrical resistivity of the joint copper sleeves was not known. A high resisitivity of the CuCrZr could be expected with a significant impact on the joint resistance. CEA and CRPP received each a piece of joint sleeve from Tesla for measurement.

The results are summed up in table 2.

Table 2 : Results of resistance measurements on a piece of PFIS copper sleeve

T (K)	Current (A)	Voltage drop (μV)	Resistance (μΩ)	Resistivity (10^{-8} Ω.m)
300	7.46	1059 ± 12	142.0 ± 1.6	2.40 ±0.03
4.2	74.5	3920 ± 65	52.6 ± 0.9	0.891 ±0.015

The residual resistivity RRR rati is therefore: RRR = 2.69 ± 0.02, i.e. RRR ~ 2-3. The CEA measurements are also consistent with the CRPP measurements giving a resistivity of about 9.5×10^{-8} Ω.m at 4.2 K and a RRR of about 2.6.

The contribution to the joint resistance can be estimated to $3.7\ 10^{-9}$ Ω, therefore not negligible when dealing with joint resistance within the nΩ range.

Table 1 : PFIS and ITER PF coil conductor characteristics

	$PFIS_W$	$PFIS_{NW}$	ITER PF1&6
NbTi strand diameter (Ni coated), mm	0.73	0.73	0.73
Ratio of copper to non copper sections	1.41	1.41	1.6
Cabling pattern	(3x4x4x5x6)	(3x4x4x5x6)	(3x4x4x5x6)
Number of strands	1440	1440	1440
Cu cross section, mm^2	353	353	371
Non-Cu cross section, mm^2	250	250	232
Cable space diameter, mm	37.53	36.89	38.2
Cabling twist pitches, mm	42/86/122/158/≈ 500	42/86/122/158/≈ 530	45/85/125/165/425
Steel spiral for central channel, mm	10 x 12	10 x 12	10 x 12
Estimated void fraction, %	33.5	34.3	34.5
Outer conductor size, mm×mm	50.35 x 50.45	49.82 x 49.78	53.8x53.8

JOINT RESISTANCE

The bottom joint resistance was found to be unexpectedly high during the conductor test, this was also the case for the two upper termination resistances, with one of them (the left one) being particularly high. The measured values are reported below:

- Hairpin (bottom) joint resistance ≈ 10 nΩ
- $PFIS_W$ (left leg) termination resistance ≈ 18 nΩ
- $PFIS_{NW}$ (right leg) termination resistance ≈ 6 nΩ

These high values cannot be explained only by the use of high resistivity copper sleeves and likely a high (and not reproducible) resistance between strands and copper sleeve has to be considered. Such a high interface resistance is related to the manufacturing process of the joint.

The high bottom joint resistance played a negative effect in the test of the conductor legs by preventing to operate the conductors at low temperature and high current, and by perturbing significantly the current sharing experiment (non linear increase of current ➔ non constant inductive voltage, and increase of operating temperature as current increases).

Finally, the tests of the bottom joint in SULTAN (usually performed by lifting up the sample) were cancelled due to the poor behaviour of this joint.

ELECTRICAL TESTS

The PFIS conductor performances have been found to be lower than expected by any models for both legs. Better predictions are obtained using the CEA strand data compared to the VNIINM data (i.e. using lower strand performances) [1]. CEA performed a comparison of the results provided by different models issued by different institutions and laboratories [2].

Dramatic current limitation (quench) can be explained by highly uneven current distribution among petals as well as among strands inside petals.

Uniformity can be improved by current redistribution among petals and strands which can explain the better stability of the unwrapped conductor leg and the better performances measured on both legs at low current. However, no model is presently capable to explain the full behaviour of the PFIS conductors.

The interpolation of the PFIS DC experimental results, rescaled with the NbTi area with respect to the ITER PF coils (at B_{max} = 6 T, T_{op} = 5.0 K) are compared to the PF-FSJS conductor test results and to the ITER operating specifications in table 3.

It can be seen in this table, that the PF-FSJS conductors had better performances than the PFIS (the worst PF-FSJS leg being better than the best PFIS leg), although the PF-FSJS itself did not reach the ITER operating specifications. It should be also noted that the PF-FSJS conductors have their original ITER wraps.

The explanations for these poor performances lie in the lower strand properties (as compared to ITER operating specifications) and to highly uneven current distribution in the PFIS, likely due to an uneven contact resistance distribution between cable and copper sleeves, also related to a high joint resistance.

Table 3 : Comparisons between sample performances and ITER PF coil specifications

Conductor	PFIS wrapped	PFIS unwrapped	PF-FSJS EM leg	PF-FSJS Alstom leg	ITER PF1&6
T_q (K)	5.80	6.05	6.25	6.40	6.50
ΔT_{margin} (K)	**0.80**	**1.05**	**1.25**	**1.40**	**1.50**

THERMOHYDRAULICAL TESTS

The central channel of Cable in Conduit conductors is self-justified to reduce the cryogenic power associated with helium circulation and hence the operating costs. But the inhomogeneity in the He flow within the cable, brings complexity and a discrepancy in temperature between the central and annular channels under heat load. The thermohydraulics of cable samples can be explored at low temperatures in the Sultan facility at CRPP/Villigen, using the same sample (PFIS) as for the superconductivity critical properties investigations.

Due to the thermometer layout of the PFIS, this study was carried out using only the AC loss deposition provided by a dipole on a conductor section. The two legs of the PFIS are asymmetric because the superconducting strand petals are directly inserted in the jacket in the right leg, whereas they are wrapped in stainless steel tape in the left leg (see figures 1a and 1 b). The eddy currents created by the AC field and generating heat have a reduced intensity on the left leg relevant to the ITER conductor design.

Results and theoretical expectations according to the steady state model developed by CEA [3] for heat transfer coefficients are summarized in table 4 for each leg at 10 g/s with AC heating.

Though this kind of heating is instructive given its representativeness of AC losses in the final coil use, these experiments do not provide accurate thermal results concerning the space constant Λ, and associated heat transfer coefficient h between the two conductor channels. The reason is mainly that the exact length of the heat deposition and its homogeneity is uncertain.

On the PFIS experiments, AC losses heat up the right leg without wrappings more than the left, as expected. The minimum power used in these 10 g/s experiments is 25 W/m assuming a deposition length of 0.4 m. The left leg temperatures heat up especially less than expected. The PFIS AC loss upstream temperature is slightly rising even at very low power, which is disturbing and may be also a sign of wide heating length.

Table 4 : PFIS AC power, characteristic length Λ and resulting heat transfers at 10g/s

Expected values	**Λ=0.48 m** h=418 W/m²K hp=13.1 W/mK			
AC frequency	4 Hz	3 Hz	2 Hz	1 Hz
Left leg W=	37 W	25 W	15 W	10 W
(wraps) Λ=	0.7 m	0.75 m	0.8 m	1 m
h=	285 W/m²K	265 W/m²K	250 W/m²K	200 W/m²K
Right leg W=	54 W	36 W	21 W	14 W
(no wraps) Λ=	0.35 m	0.35 m	0.4 m	0.4 m
h=	570 W/m²K	570 W/m²K	500 W/m²K	500 W/m²K

It is not possible to experimentally evaluate the respective channel mass flow rates. We can evaluate channel mass flow balance, but there remains some uncertainty in the empirical law used. Similarly, it is not possible to evaluate mass exchange between annular and central channels. Of course the respective mass flows strongly influence physical phenomena and experimental evaluation of heat transfer rates.

The next conductor tests in Sultan will be instrumented with an annular heater on the conductor and thermometers in an appropriate way similar to the PF-FSJS configuration in order to have enough close downstream data and derive thermal parameters in a more accurate way.

CONCLUSION

In the framework of the TW2-TMST-TOSKA task, CEA has participated to the tests and the analysis of the PF Insert Sample (PFIS). Final report has been delivered to EFDA [4].

Two campaigns have been devoted to these tests: one for electrical tests and the other for thermohydraulical tests.

The first conclusion of these tests is that the measured joint electrical resistance exhibits a very high value (10 nΩ), which is far above that measured for the PF-FSJS (1.6 nΩ), previous NbTi joint sample developed in Europe in the framework of Task M50. Consequently, the ITER specification (< 2 nΩ) is not met and the PFIS joint design is not qualified. The poor electrical performances in comparison with expectation were found partly due to the lower strand properties and partly due to highly uneven current distribution induced at the level of the joint.

As for the thermohydraulical tests, a simple method for estimation of the heat exchange between central channel and annular region has been defined by CEA. This method is based on the observation of the temperature distribution downstream during steady state heating of a piece of conductor. This study delivered heat exchange coefficients which are acceptable for ITER conductors but with insufficient accuracy. This has to be improved by testing further samples with extended instrumentation.

REFERENCES

[1] L. Zani et al. - Jc(B,T) characterization of NbTi strands used in ITER PF-relevant insert and full-scale sample - to be published in IEEE Trans. Appl. Supercond., June 2005.

[2] D. Ciazynski et al. - DC Performances of ITER NbTi Conductors: Models vs. Measurements - to be published in IEEE Trans. Appl. Supercond., June 2005.

[3] S. Nicollet et al. - Evaluation of the ITER cable-in-conduit conductor heat transfer - presented at 20th Int. Cryo. Eng. Conf. Beijing, 2004.

[4] J.L Duchateau et al. - Task TW2-TMST-TOSKA : Deliverable 4 Final report on the testing of a full size joint sample - February 2005 Internal CEA Note AIM/NTT- 2005.002.

TASK LEADER

J.L. DUCHATEAU

DSM/DRFC/STEP
CEA-Cadarache
F-13108 Saint-Paul-Lez-Durance Cedex

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

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

TW3-TMSC-ELRES

Task Title: EXPERIMENTAL ASSESSMENT OF THE EFFECT OF ELECTRICAL RESISTANCES ON THE V-I CHARACTERISTICS OF SUPERCONDUCTIVE CABLES

INTRODUCTION

Task ELRES aims at investigating experimentally the effect of the joint-to-strands resistance values and of different percentages of joint-to-strand connections on the possible variation of the "global" V-I characteristic of a NbTi ITER-type cable, limited at the last but one stage. The samples will have different joint resistances and different fraction of directly connected strands. This activity also investigates the effect of the strand-to-strand transverse resistances, which have been shown to change considerably with cycling and to affect the values of critical current and "n" parameter of s/c cables.

Five joint samples have to be fabricated and tested, each sample contains two different legs which leads to test in fact 10 different legs. The first three joint samples are fabricated using already existing conductor lengths remaining from task M50. Extra conductor lengths (with a different cable void fraction) are fabricated in industry using already existing NbTi strands. The last two joint samples are fabricated using this new conductor. The samples are tested (V-I or V-T characteristics) in the JOSEFA facility at Cadarache. Complementary tests are carried out to measure conductor interstrand resistances.

The task activities can then be summarized as follows:

- Definition of samples and of testing procedure.
- Fabrication of 3 samples using existing (from task M50) conductors.
- Fabrication of new conductor lengths using existing (from task M50) NbTi strands.
- Fabrication of 2 samples using new conductor lengths.
- Test of 5 samples in the JOSEFA test facility (CEA Cadarache).
- Additional characterization of samples (interstrand resistances).

2004 ACTIVITIES

The definition of the samples and of the testing procedure was performed in 2003. Also during this year the qualification of detailed manufacturing processes (Nickel removal, insulation of contacts) was carried out. Therefore our activities in 2004 were concentrated on the fabrication and the tests of the samples.

FABRICATION OF NEW CONDUCTORS

Using remaining NbTi (Alstom and Europa Metalli) strands from task M50, new conductor lengths (about 2 x 10 m) had to be fabricated to complete task ELRES (these lengths are referred as the ELRES conductors). This fabrication included the multi-stage cabling of 108 strands as well as the compaction of the cable inside a 316L steel jacket. The final void fraction of the cable was fixed to 32 % (slightly lower than the 36 % of the M50 conductors) in agreement with EFDA, so as to introduce a variation in the interstrand resistances.

The manufacture of these two lengths was started at NEXANS in December 2003. Unfortunately, the first samples were rejected since their twist pitches did not fulfil the technical specification for cabling. Some trials with additional lengths of strand provided by CEA were performed at the beginning of year 2004. An acceptable cable geometry was finally reached with regard to the specification and the two additional lengths were produced and delivered to CEA at the end of May 2004.

FABRICATION OF FIVE SAMPLES

During the manufacture of the first batch of three samples (using the M50 conductors) some cracks were detected at the TIG weld locations between termination box and cover, and between jacket and termination. These cracks were located on all of the legs being in manufacture, a non-conformity in the materials used was suspected. A first try to re-melt the weld being not successful, investigations and welding tests have shown that this was not due to the jacket or terminations material. A further detailed control of the welding filler rods has finally shown that some rods of high Nickel content filler had been mixed with the regular filler foreseen for the welds.

All the welds were then milled and welded again with the good filler material. Note that in the case of the cover/termination weld, the milling and new welding were performed in parallel in a way not to release the compaction pressure inside the terminal. The visual inspection was then satisfactory. After a dye penetrant test which did not show any crack, a final helium tightness test was performed with vacuum inside the legs and helium atmosphere outside. A leak rate lower than 10^{-6} $Pa.m^3.s^{-1}$ was then measured.

The five samples with their names and characteristics are given in table 1. A picture of the five samples completed is presented in figure 1.

Table 1 : Definition and characteristics of the ELRES samples

Sample name	ELRES-0	ELRES-1	ELRES-2	ELRES-3	ELRES-4
Left leg conductor	Int CuNi strand M50	Int CuNi strand M50	Int CuNi strand M50	Int CuNi strand ELRES	Int CuNi strand ELRES
Right leg conductor	Ni plated strand M50	Ni plated strand M50	Ni plated strand M50	Ni plated strand ELRES	Ni plated strand ELRES
Joint insulated area (default)	0 %	25 %	50 %	25 %	50 %

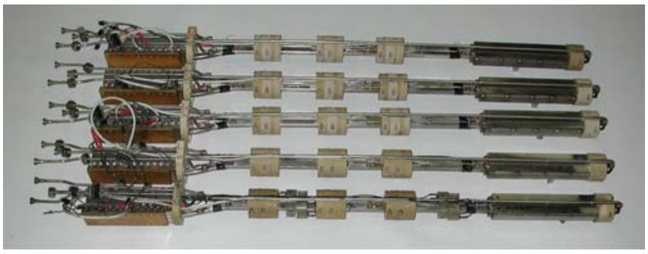

Figure 1 : The five ELRES samples completed and ready for testing

All the left legs make use of the Alstom (AL) NbTi strand with internal CuNi barrier, and all the right legs make use of the Europa Metalli (EM) NbTi strand with Ni plating. The first sample (ELRES-0) is the reference sample, without default in the bottom joint. The other samples have an unconnected length (25% or 50% of total overlapping length) in their bottom joints.

The samples are fully instrumented with 5 temperature sensors (T in figure 2), 14 voltage taps on the conductor legs (RV and LV in figure 2), 2 voltage taps on the bottom joint (RV8 and LV8 in figure 2), 2 pick-up coils for magnetization measurement (RPU1 and LPU1 in figure 2), 4 sets of 4-quadrant Hall probes (2 sets H1-H4 and H5-H8 per leg, see figure 2) for current distribution measurement.

The reference sample ELRES-0 was delivered in September 2004 for testing. The last sample (ELRES-4) was delivered end of November 2004 for testing.

A report on the manufacture of the samples was issued and delivered to EFDA by the end of 2004 [1].

IMPROVEMENT OF THE JOSEFA FACILITY

The cryogenic part of the JOSEFA facility was modified (simplification of the hydraulic paths) and repaired. In addition, a new data acquisition system, based on a 16-bit National Instruments system controlled under Labview™, was installed.

This system allows measurements with the required accuracy for plotting V-T or V-I characteristics of samples (the critical field of 10 µV/m corresponds to a voltage drop of 1.7 µV over 170 mm in these experiments). The facility was ready in September 2004 for testing the first sample.

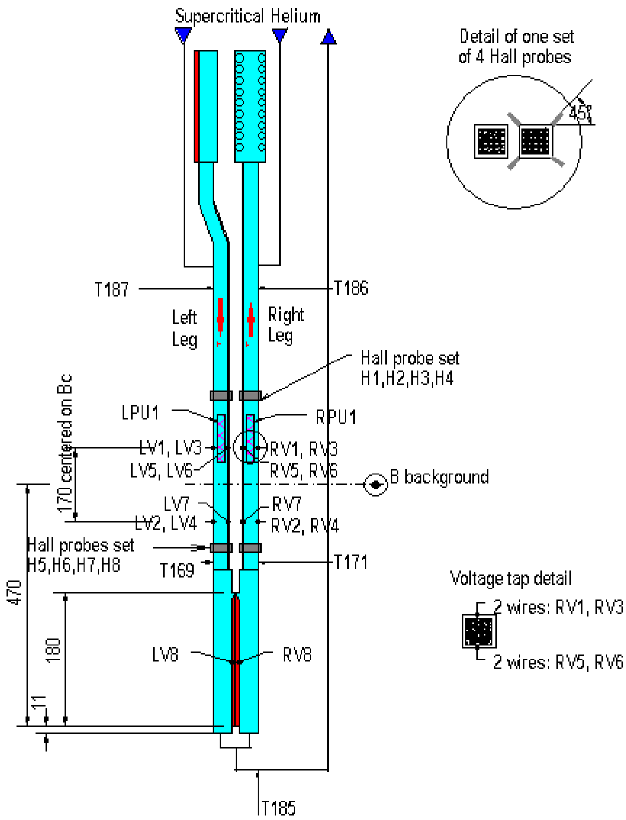

Figure 2 : Scheme of instrumentation of an ELRES sample

TESTS OF THE SAMPLES

Only the first reference sample ELRES-0 could be tested in 2004. this test was also the full test of the upgraded JOSEFA facility. The V-T characteristic was preferred to the V-I characteristics because its interpretation is direct, as a matter of fact, the variations of the self field and of the Joule heating in the joints (and in the current leads) tend to pollute the V-I characteristics (i.e. increase of field and temperature with current).

However, it became rapidly obvious that the plot of a correct V-T characteristics required a very low temperature gradient along the tested leg (< 0.05 K between T187 and T169, or between T186 and T171, see figure 2). Indeed, the situation is much more difficult (and much more accurate) in the ELRES samples than in the SULTAN samples, because the electric potential on the jacket is very close to the strand potential due to the lack of wrappings in the conductor.

In the SULTAN samples, the voltage taps located on the steel jacket pick an average (among the strands) cable voltage because of the high electric resistance between the strands and the jacket, then the V-T characteristics almost always looks nice, in fact blurred (there is no significant cross electric gradient). In the ELRES samples, each voltage tap picks a voltage close to a strand voltage, and there may be a high voltage cross gradient on the jacket if the electric field is not uniform along the strands (in case of thermal gradient for example). This phenomenon is particularly clear when comparing the two voltage drops (V1-V2) and (V5-V7) corresponding to taps located on opposite conductor sides.

In the perfect situation (uniform current distribution among strands and uniform temperature profile along the measured length), each strand develops the same voltage drop along the measured length and as a consequence (V1-V2) is equal to (V5-V7). This is the situation generally observed at low transport current (see figure 3). As soon as there is a significant temperature gradient along the measured length, the strands are no more equipotential and (V1-V2) is not equal to (V5-V7), this is the case shown in figure 4, which is generally (but not systematically) observed at higher transport current. A way to smooth the curves is then to consider the average value between these two voltage drops, one then recovers more or less a SULTAN-like experiment (see figure 4 for the effect of averaging on scattered curves). Note that the voltage threshold of 1.7 µV corresponds to the critical electric field criterion of 10 µV/m.

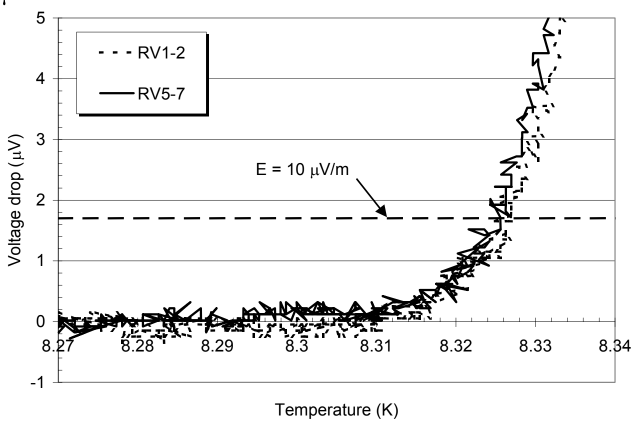

Figure 3 : Measured voltage drops on ELRES-0 at 2 T and 1 kA

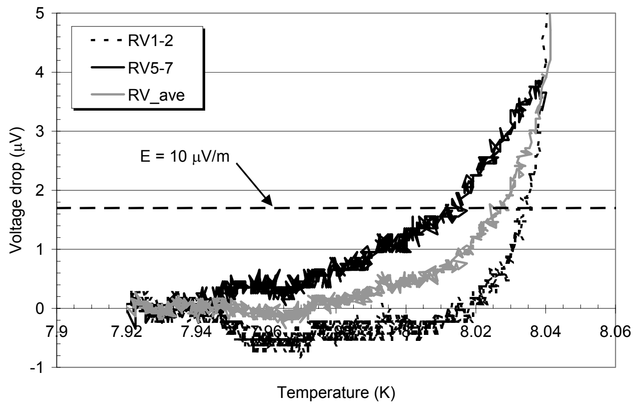

Figure 4 : Measured voltage drops on ELRES-0 at 2 T and 5 kA (RV_ave is average between RV1-2 and RV5-7)

The ELRES-0 conductor critical current @ 10 µV/m under a 3.4 T field are plotted in figure 5. Also plotted is the expected performance using the strand characteristics under the same magnetic field (extrapolation from strand experimental range using fitting curves). The surprisingly better performances of the conductors can be explained by some inaccuracy in the extrapolation of the strand performances. Note that the two legs behave similarly which is logical with regard to the similar strand performances. Note also that generally the conductors were stable up to 6 kA at the critical electric field (although limit at 6 kA) and that no degradation of transport properties were observed at variance with the full size NbTi conductors tested in SULTAN (PF-FSJS and PFCI-FSJS).

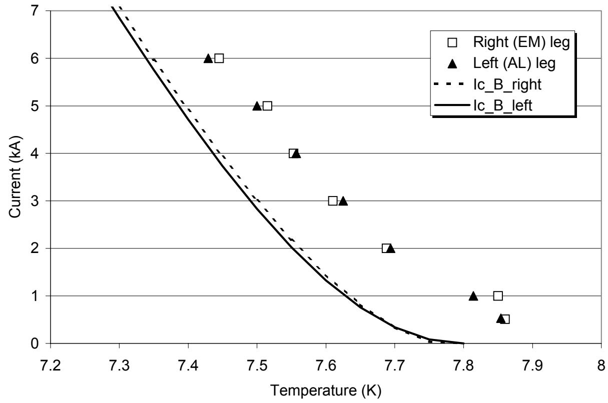

Figure 5 : Critical current on ELRES-0 sample compared to extrapolations from strands (Ic_B) at 3.4 T

The half-joint resistance is about 2.9 nΩ on the left leg while it is about 1.0 nΩ on the right leg. These values are rather low (extrapolated to below 0.9 and 0.3 nΩ respectively for a full size joint resistance) which shows that the contacts between strands and copper soles are good. The higher value on the left leg is explained by the internal CuNi barrier which cannot be removed from the strands at variance with the Ni plating.

CONCLUSIONS

The fabrication of the five ELRES samples (including the two samples with the new conductor delivered by NEXANS) was completed at the end of 2004. the fabrication report was delivered to EFDA in December 2004.

The first reference sample ELRES-0 was tested successfully at the end of 2004, this test was also the test of the full upgraded JOSEFA facility.

The second sample ELRES-1 was tested successfully in January 2005. Due to the maintenance programme on the cryogenic system during the shut down of Tore Supra, helium supply will not be available before mid March 2005. The 3 remaining samples should be tested in the JOSEFA facility between mid March and May 2005. The final report should be delivered by the end of May 2005.

REPORTS AND PUBLICATIONS

[1] P. DECOOL and H. CLOEZ - Task TW3-TMSC-ELRES : Milestone #2 Manufacturing of Samples (Cable and Joints) - CEA Note DRFC (STEP/GCRY), AIM/NTT-2004.029, December 15, 2004.

TASK LEADER

Daniel CIAZYNSKI

DSM/DRFC
CEA-Cadarache
F-13108 Saint-Paul-Lez-Durance Cedex

Tél. : 33 4 42 25 42 18
Fax : 33 4 42 25 26 61

E-mail : daniel.ciazynski@cea.fr