CEFDA03-1015

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

INTRODUCTION

The CEA Cadarache Magnet Group 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 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). 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. 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 includes 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.

2005 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 was 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, a design for the inlet was proposed and accepted by IT and EFDA (figure 1).

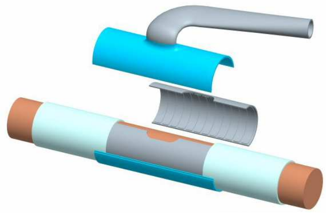


Figure 1: TF inlet design proposal (One half distribution grid and one half mechanical shell are shifted for better understanding)

Analysis

A 3D straight F.E.M. 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 acceptable by EFDA.

Mock-ups manufacture

The components for the manufacture of five mechanical and hydraulic mock-ups were fabricated in 2004.
Two mock-ups TF-IN1 and 2 were used for determination of the welding parameters. An assembly procedure was issued which allows to perform the inlet manufacture without overheating of the conductor and with respect to foreseen final layout. TF-IN3 and 4 were manufactured according to the determined procedure and were equipped with specific attachment ends in order to be tested for fatigue life qualification in the FZK test facility (figure 2.).

A last mock-up, TF-IN5, was built at the middle of a straight available TFMC conductor for hydraulic qualification. An intermediate report was issued at this step [1].

Figure 2: One mock-up for fatigue life qualification

Fatigue life qualification

The strain experienced by the TF coils at helium inlets during operation is $\varepsilon \sim (11 \pm 3)\times10^{-4}$, where 11.10^{-4} is the essentially static strain due to the toroidal field alone and $\pm 3.10^{-4}$ is the cyclic out-of-plane strain. Translated into stress, this gives a stress of $\sigma \sim 220 \pm 60$ MPa and a corresponding load F = 43.5 ± 11.8 kN.

The fatigue life qualification has to be performed with a number of cycles of 600 000 which is a factor 20 of the ITER TF number of cycles. All the tests were performed under load control since it was not possible to control the strain with acceptable cycling frequency.

The qualification was performed on TF-IN3 and 4 in the FZK 500 kN cycling test facility at 4 K.
TF-IN3 was used first for calibration of the machine and to determine the maximum reachable cycling frequency in order to minimize the test duration. Two sets of local double extensometer were used to check the regular jacket as well as the orbital weld area strain. At the end, the mock-up was submitted to 100 000 cycles under a maximum loading of 38 kN ± 30 kN at a 4 Hz frequency.

The orbital weld strain was observed to have the same behaviour than the regular jacket one. A final loading at twice the nominal value was performed to test the attachment system and has shown some slipping which was identified to come from a bad attachment installation at one end of the mock-up. A final helium test of the mock-up did not show any leak.
The final fatigue test was performed on TF-IN4 mock-up. On this mock-up, a new double extensometer set was used in order to check the global strain of the inlet. The strain of $(11 \pm 3)\times10^{-4}$ was applied by the way of a loading of 45 ± 17 kN at a 7 Hz frequency. Unfortunately, the mock-up broke after 476 117 cycles instead of the 600 000 required. The breakage was located in the jacket near one of the orbital welds in the heat affected zone (figure 3).

Figure 3: Detail of the broken area on TF-IN4 after tests

Hydraulic qualification

The hydraulic qualification was performed on TF-IN5 in the OTHELLO test facility using GN2 at room temperature under relevant Reynolds conditions.

The ITER TF operating point is Qc = 8 g/s, P = 0.5 MPa, T = 5 K in supercritical helium.
Using a Reynolds analogy, the corresponding operating point with nitrogen in our facility was determined to be Qc = 41.7 g/s, P = 0.5 MPa, T = 300 K
The hydraulic path was symmetric as it is on the TF coils with temperature, pressure and flow rate sensors as shown in figure 4. Due to symmetry, the conductor flow rate was recorded at one side only. A specific preparation of each conductor end allows to separate each petal flow rate and to record it using a movable flow-meter. With this facility layout, pressure drop as well as flow repartition among the petals were recorded.

Three tests were performed: the first one with a 2 m conductor length at each inlet side, this length was then reduced to 1 m and finally 0.5 m. With this process, the evolution of the flow rate distribution was checked at different distances from the inlet. The inlet pressure drop as well as the flow rate distribution was compared to reference pressure drop and flow rate distribution gained on a 4 m long TFMC conductor with a gas inlet at one end.

The pressure drop of the inlet was found to be quasi-linear with the conductor flow rate. It was interesting to compare the inlet pressure drop coefficient to the one of the unit length of conductor. However, in ITER type conductors, the hydraulics uses a dual channel with a high Reynolds inside central channel and a low Reynolds in the petals area. Then the conductor characterization is not easy. For simplification, in the particular TFMC conductor geometry, a reduced pressure drop coefficient and a reduced Reynolds number independents of the wetted area Ac and hydraulic diameter Dh can be defined with respect to the global conductor mass flow rate Qc and the measured pressure drop ΔP as follows:

$$K^* = \frac{\rho \Delta P}{Qc^2} \qquad \mathrm{Re}^* = \frac{Qc}{\mu} \qquad \text{with} \quad K^* = \frac{K}{2Ac^2}$$

and $$\mathrm{Re}^* = \frac{\mathrm{Re}\,Ac}{Dh}$$

(ρ, ΔP, Qc, μ, Ac, Dh) in (Kg/m^3, MPa, Kg/s, Pa.s, m^2, m)

The reduced inlet pressure drop coefficient K* was found to have a very low dependency on the reduced Reynolds number Re* in a same way that for the regular conductor but its value was 7.3 times higher than the unit length conductor one (figure 5).

The flow rate distribution among petals was recorded at 2 m, 1 m and 0.5 m from the inlet and compared to the one gained on our reference 4 m long straight conductor. The results at the TF operating point are summarised in table 1. These results show clearly that with this design of helium inlet, the petals helium supply is increased when the distance with the inlet decreases. A maximum flow rate ratio of 14 % was recorded on petal n° 1 which was the one in regard of the helium hole of the distribution grid.

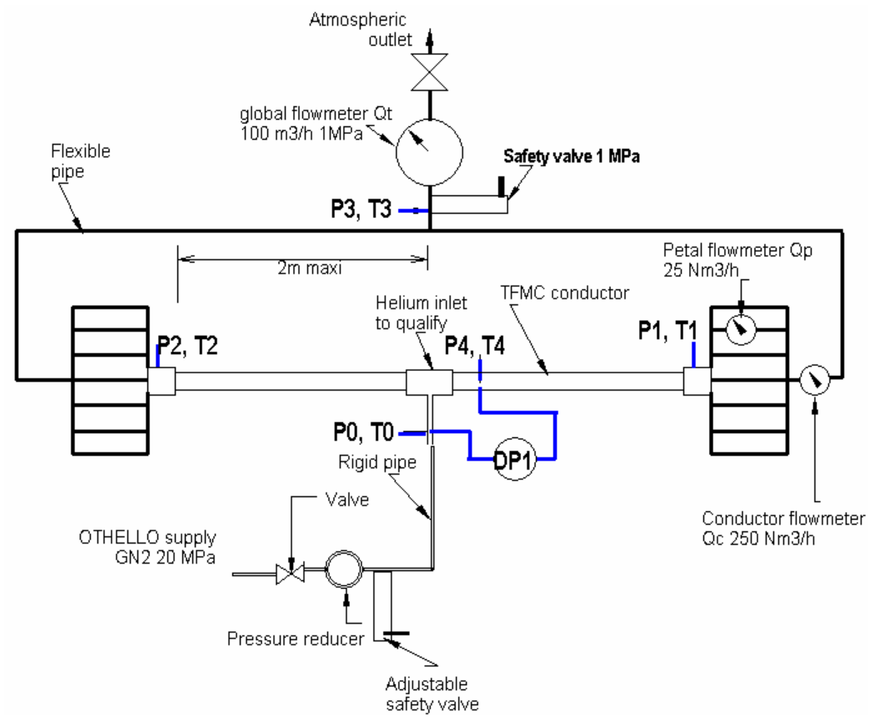


Figure 4: Hydraulic path of the OTHELLO test facility for inlet qualification

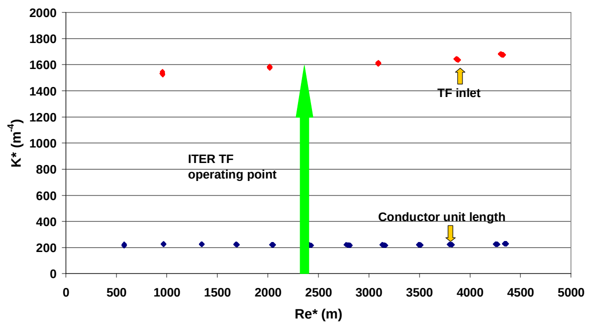


Figure 5: Flow rate ratios for the different studied configurations

Table 1: Flow rate ratios for the different studied configurations

	Petal 1	Petal 2	Petal 3	Petal 4	Petal 5	Petal 6	Annular
At 4 m of direct inlet	5.5 %	5.5 %	5.5 %	5.5 %	5.5 %	5.5 %	33 %
At 2 m of TF inlet	8.5 %	8.5 %	8.5 %	8.5 %	8.5 %	8.5 %	51 %
At 1 m of TF inlet	8.7 %	9.4 %	8.3 %	9.3 %	9.1 %	8.1 %	52.9 %
At 0.5 m of TF inlet	14 %	10.9 %	10 %	11.5 %	10.8 %	10.3 %	67.5 %

DEVELOPMENT OF THE CS COIL HELIUM INLET

Design and analysis

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 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. 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 IT to achieve these requirements. A model of the inlet was built and a F.E.M. analysis has led to a design optimization. In addition, a manufacturing mock-up allowed to validate the feasibility of this kind of inlet which is characterised by a narrow groove of one cable twist pitch long. All this work was performed during year 2004.

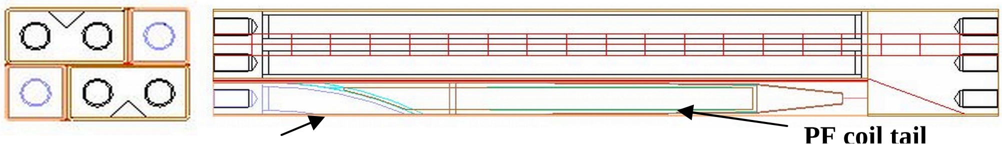


Figure 6: Overall view of the mock-up design

Mock-ups manufacture

Unfortunately, due to development problems, no relevant material for the conductor jacket manufacture was available. It was decided in agreement with EFDA and IT to cancel the mechanical qualification part of the contract. An hydraulic mock-up only was built using a dummy TFMC cable which was jacketed with a square Valinox tube. A final length of 4 m of conductor was produced by ENEA. The helium inlet mock-up called CS-IN5 was manufactured in the middle of this conductor length and will be tested in the beginning of year 2006.

DEVELOPMENT OF THE BONDED TAILS OF THE PF COIL WINDINGS

Design

The ITER PF coils design consists of a stack of double pancakes of cable cable-in in-conduit conductor with a square section jacket and, wound as ‘two in hand’. At each joint and terminals of a double-pancake a structural element is required to transfer the hoop force on from the outmost, most external conductor, to the bulk of the winding winding-pack. The present design envisages a ‘tail’ welded to the terminal conductor jacket, and bonded to the adjacent turns, transferring this force by shear though the interposed insulation. A preliminary design was developed in the framework of contract CEFDA00-541, using as reference PF5 where, in the reference scenario, the highest hoop loads develops with a tensile stress of 150 MPa. The scope of the present contract is to develop the manufacturing and assembly of the ‘PF 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 subjected at fatigue test at LN_2 temperature at ENEA laboratory (Brasimone, Italy).

Manufacturing of mock-up and tests structure

In early 2005 the manufacturing of the coil tails parts and the adjacent steel plates were completed, including the terminal parts with a threaded hole for the bolted connection. The assembly and impregnation of the mock-up was performed successfully by the company Alstom under CEA specifications. The insulation wrapping, according to the ITER design, was made of various layer of glass-fibre coupled to Kapton, half overlapped. Particular attention was paid to the the filler parts which were machined from special high glass density G10 material (Micam®) to limit thermal induced stresses at cool-down. Following the impregnation, performed in auto-clave, the end faces of the mock-up were machined to provide the suitably smooth surface to assemble the bolted flanges for anchoring the mock-up to the test structure. Finally dieletric high voltage tests at 4.5 kV were performed to confirm the integrity of the insulation. In parallel the special bolts M30, in Inconel 717 for anchoring the mock-up to the test structure were procured from the company PS-Superbolt. These were required to overcome the strict space limitations and apply sufficient pre-load (400 kN per bolt).
Also the test structure, required to reverse the compressive force of the test machine into a traction force on the mock-up was manufactured. This consists of two, inner and outer, coaxial tubes and the two end flanges, 100 mm thick, where the mock-up end faces are bolted. The Flanges are made of 5% Ni steel to match the thermal contraction of the Inconel bolts during cool-down.

Figure 7: Coil-tail first insulation wrapping

Figure 8: PF tail mock-up after impregnation and end face maching

Qualification of processes

In parallel to the above activity, samples of the weld performed between the tail and the bent conductor jacket were extracted and subjected to tensile cycled testing at 7 K, at the FZK laboratory. The samples subjected to the test were able to withstand 60000 cycles at an equivalent tensile stress of 400 MPa (average on the sample section) and would fail after 22000 cycles at 500 MPa. The expected result was that the sample would pass the 60000 cycles at 600 MPa. Further investigation showed a not complete penetration of the weld which explains the results. This is not considered satisfactory as a full qualification of the weld to be implemented on the ITER-PF coils and the matter requires to be reviewed.

As similar welds were performed on the coil-tail mock-up parts, the testing procedure and load level for testing the mock-up at ENEA are also under re-consideration. While the testing of the mock-up, at this stage, could not be conducted at twice the nominal load level and therefore it would not meet the requirement of a full qualification of the process. Nonetheless it could certainly be tested at the nominal load and 60000 cycles be able providing an invaluable experience and source of data. Given the limitations of the computing codes in cases where stresses are reacted by bonded surface it could provide an experimental confirmation or otherwise, on the sound basis of the design.

CONCLUSIONS

This task is devoted to design and fabrication of mock-ups for three different items: the TF helium inlets, the CS helium inlets and the PF bonded tails. During the year 2005, the following actions were performed:

For the TF inlets, following the design analysis which was performed during year 2004, five mock-ups were manufactured. Two were used to determine an assembly procedure for the fabrication of the inlets, two were used for fatigue life qualification and one for hydraulic qualification. The fatigue life mock-up broke after 16 times the ITER lifetime, the breakage occurring in the heat affected zone of the jacket. The inlet design was considered to be acceptable but raise the problem of the qualification of the jacket butt welds which were never qualified. The hydraulic behaviour was correct since the pressure drop was found to be equivalent to about 8 m of regular conductor and the petals flow rate was found to be higher than in a regular conductor at every distance from the inlet.

For the CS inlet, after the detailed design and analysis, a specific relevant fatigue life mock up design was produced but it was agreed to stop the mechanical qualification at this step due to the lack of relevant material for conductor manufacture. An hydraulic qualification mock-up was only manufactured using a TFMC type cable with square steel jacket specially produced in industry. The hydraulic tests should be completed in 2006.

For the PF tail, the manufacture of the PF tail mock-up was performed, including assembly of its components, impregnation of the insulation and assembly with the structure for testing. The assembled mock-up was delivered to ENEA for testing. Unfortunately, the results of the qualification tests of the welds of the tail to the conductor, carried out at FZK, showed a reduced fatigue life, which was further explained by a lack of penetration of the weld.

This defect makes compulsory the manufacture of a new mock-up to complete the qualification of the PF tail design, since failure of the present mock-up is likely to occur prematurely in the conductor-tail welds.

REPORTS AND PUBLICATIONS

[1] P. Decool, H. Cloez, EFDA contract 03-1015 - Deliverable 1: Intermediate report on TF cooling inlet design and manufacture, Note AIM/NTT/2005.014, 15/06/2005.

TASK LEADER

Patrick DECOOL

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

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

e-mail : decool@drfccad.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 devoted to the development of Nb_3Sn conductors which will be used in the ITER TF and CS Coils. The models built in the framework of the ITER EDA phase (CSMC, CSIC, TFMC, TFCI) have shown reduced performances compared to those expected, which led to a revision of the conductor design relying on the use of advanced Nb_3Sn strands. Consequently a specific EU R&D action was launched to procure from industrial companies advanced Nb_3Sn strands meeting specifications adapted to the ITER TF Coils system, i.e. for the most important ones:

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

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

In the framework of the ASTEST task, six European laboratories have to perform crossed measurements of the properties of these advanced strands, procured from the European companies. CEA was asked to test three strands, produced respectively by Oxford Instruments (OST), Outokumpu Finland (OKSC) and Outokumpu Italy (OCSI). The tests involve:

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

In 2004, the benchmarking step and a partial characterization of the strand provided by Oxford Instruments (OST) were performed (see 2004 activities report). In 2005, the remaining parts of the program were completed, which are namely:

- geometrical, AC magnetic losses and RRR characterizations of OST strand
- a complete characterization of strands fabricated by Outokumpu Finland (OKSC) and Outokumpu Italy (OCSI).

Finally all experimental results were compared to the initial specifications provided by EFDA and the agreement of each strand commented.

2005 ACTIVITIES

OST STRAND

Geometrical tests

All studies were achieved in collaboration with the DTN/STPA service at CEA-Cadarache. The characterizations were performed through an image analysis obtained with BEM facility. A strand cross section is visible in figure 1.

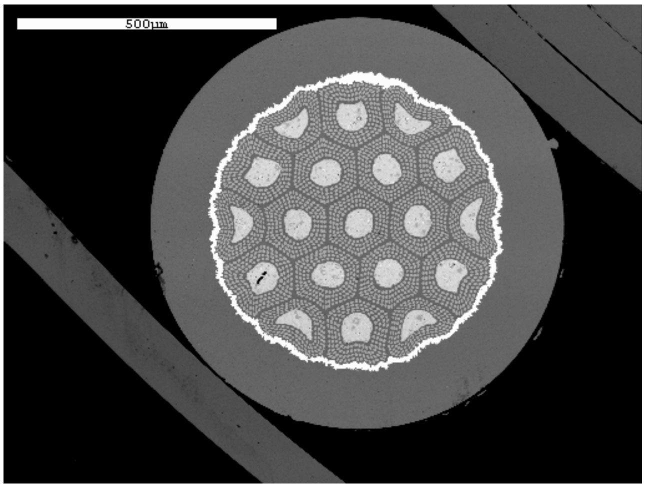


Figure 1: Micrographic view of the SMI strand cross-section.

The Cu/nonCu ratio was evaluated by image analysis and checked by weighting method. The experimental values are found in good agreement and the ratio retained is 1 ±0.08. The overall strand diameter is also measured with a three-points method, and found as high as 815 ±5 µm. The Cr plating thickness is 2 ±0.5 µm.
All those values are in good agreement with EFDA specifications.

The filamentary twist pitch (TP) is also measured by imaging, using an innovative preparation method based on a 0.5 mm lamination of strand and an acid etching of the flat surface supposed to enable the vision of filaments trajectory despite of the Ta barrier. The resulting image is shown in figure 2.
As a result, a value of 14.7± 1 mm is found, satisfactorily cross-checked with longitudinal sections views. This value is close to the manufacturer specifications (15 mm).

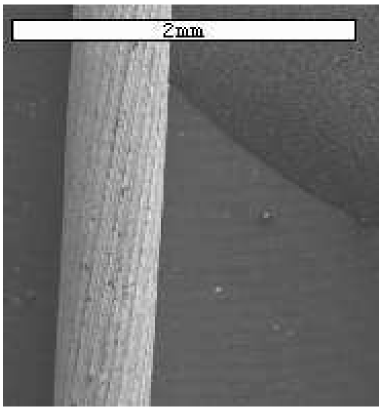


Figure 2: OST strand longitudinal external view after preparation for TP evaluation.

Magnetic AC losses

The hysteresis losses Q_{hyst} are extracted from a signal generated in a two pick-up compensated system, which is used in the SUSI facility at CEA-Cadarache. Dedicated geometrical coefficients are applied in order to deduce the absolute value of the energy density dissipated through hysteresis magnetic losses. The experimental curve relevant to AC losses evaluation is given in figure 3. The coupling losses were also given even if not specified in the EFDA contract.
The values of Q_{hyst} and $n\tau$ found are respectively of 448 mJ.cm^{-3} (overall strand volume) and 7.1 ms.
The value of OST strand Q_{hyst} is found below the previously mentioned EFDA specification of 500 mJ.cm^{-3}.

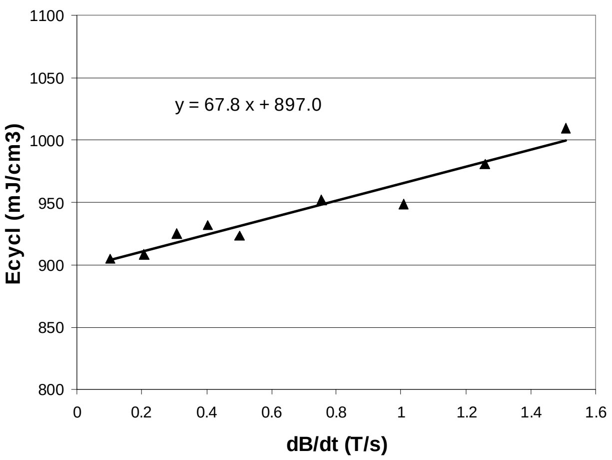


Figure 3: OST strand magnetic energy density variation with B ramp rate.

RRR

The RRR found is 118±10, which is in agreement with ITER requirements (>100).

OKSC strand

Geometrical tests

A similar method was applied to the OKSC strand for geometrical characterization, resulting in the following experimental values:

- strand diameter: 815 ±3 µm.
- Cu/nonCu ratio: 1.02 ±0.05
- filament TP: 13.9± 1 mm

finally all OKSC strand geometrical parameters were found to meet the EFDA specifications.

Electrical tests

the I_C was evaluated in the CETACES facility
located at DAPNIA/SACM service in CEA-Saclay. The results are illustrated in figure 4.

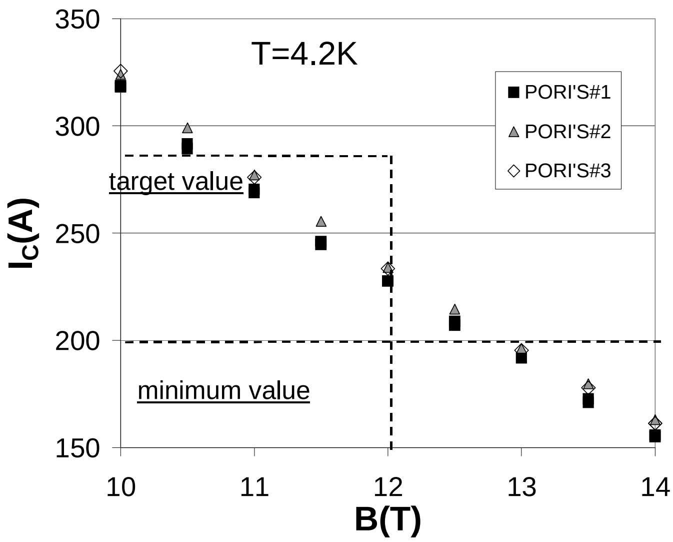


Figure 4: OKSC strand critical current variations with magnetic field (3 samples tested).

As a result, the I_C(4.2 K, 12 T) value of 230 A is found, in-between the minimum value and the target value.
Besides, n-value is found around 18, slightly lower than the specified limit of 20.
A value of RRR of 130±3 is found, meeting the EFDA requirements.

Magnetic AC losses

Here we obtained Q_{hyst}=630 mJ.cm^{-3}, that overcomes by nearly 20% the EFDA specification. This significant deviation from requirements is thought to be due to anomalies that occurred in the heat treatment (HT) sequence, leading to an unexpected increasing of the filaments effective diameter. This point is supported by the I_C values, found 10 to 20% lower than in other EU laboratories. The checking of this point is in progress in the CRPP (CH) laboratory.

OCSI strand

Geometrical tests

Following experimental values are found:

- strand diameter: 815 ±5 µm.
- Cu/nonCu ratio: 1.44 ±0.15
- filament TP: 14.9± 1 mm

Electrical tests

An average I_C(4.2 K, 12 T) value of 197 A is found, failing to meet the EFDA requirements by a few percents. Nevertheless, this strand experienced the same HT as the OKSC one, possibly causing the same impact on the performances. As a matter of fact, experimental differences with EU laboratories were also observed. Moreover if related to the nonCu section, a J_C(4.2 K, 12 T) of 937 A.mm^{-1} is observed, consistent with ITER TF requirement of 800 A.mm^{-1}.
The average n-value of 21 found meets the specifications.
A value of RRR of 95±5 is found, slightly below the limit of 100.

Magnetic AC losses

For this strand we obtained Q_{hyst}=437 mJ.cm^{-3}, that satisfactorily meets the EFDA specification. However, as the Cu/nonCu ratio is significantly higher than for the two other strands, the Q_h^{nonCu} is found slightly higher than the ITER TF specification of 1000 mJ.cm^{-3}.

CONCLUSIONS

During the year 2005 the task ASTEST was completed, including the following actions:

- the OST strand characterization remaining steps (geometry, AC losses, RRR)
- the OKSC and OCSI strands were fully characterized

After comparison with EFDA specifications, the only OST strand was found to meet the totality of EFDA specifications. The OKSC strand deviation from specifications was found in the AC losses (+25%), but this could be due to an anomaly of HT. For the OCSI strand a slight deviation was found for I_C, but transport properties still remain in agreement with ITER specifications in terms of critical current density.

TASK LEADER

Louis ZANI

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

Tel. : 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 SUBSIZE SAMPLES

INTRODUCTION

The tests of the ITER TF model coil in 2001 – 2002 have shown that the performance of the conductor was lower than expected. 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, regarding the critical properties. This will be done by ordering and manufacturing subsize samples in the industry and then by participating to the tests at FZK (Germany) in the FBI test facility.

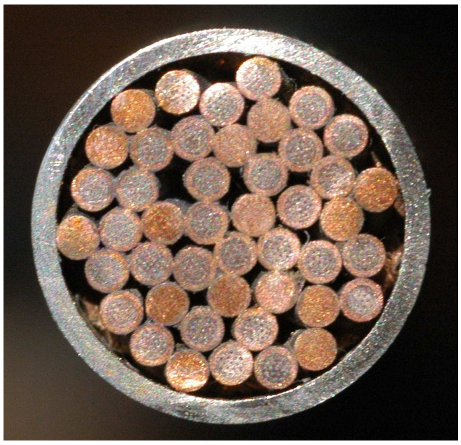


Figure 1: Example of sample 3x3x5

2005 ACTIVITIES

DESIGN OF THE SUBSIZE SAMPLES

As part of the EFDA contract TW4-TMSC-SAMAN1, CEA/DRFC is responsible for the production of about fifty sub-size Nb_3Sn conductor samples. The samples are of three different sizes corresponding to various stages of the cabling pattern of a ITER TF conductor petal. In particular the samples to be produced, by increasing size are of the type (3x3), (3x3x5), (3x3x5x4). The contract is staged in two phases: (a) batch 1 samples where the parameters vary (void fraction, cabling pitch, ratio of superconductor strands relative to copper strands) in order to study the changes in performances, (b) batch 2 samples which are of the same type, but using superconducting strands produced by 5 different manufacturers, in order to compare them. All superconducting strands are delivered by EFDA and have a diameter of 0.81 mm.

In February 2005, a contract for the cabling and jacketing of the samples has been awarded to the company Nexans. Prototypes were required to confirm the capability of NEXANS to produce samples according to the CEA specifications. Controls have been performed to confirm that the samples comply with the required specifications.

CONTROLS BY THE CEA ON THREE PROTOTYPES

The samples are made with strands coming from two OST billets: Billet #1 7878/1, Billet #2 7730/1.

Before the series production, 3 prototypes corresponding respectively to sample (3x3), (3x3x5) and (3x3x5x4) have been manufactured and checked by CEA (see figures 1 and 2). A detailed description of the controls made by CEA can be found in [1].

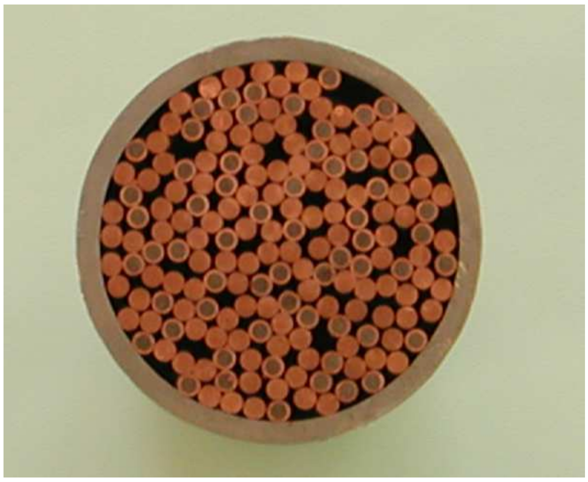


Figure 2: Example of sample 3x3x5x4

During this characterization it was found that the chrome removal of the sample extremities, where electrical connections are made, was not satisfactory. The process by brushing was changed and replaced by a chemical process by chrome etching with acid for the series production.

Dimensional checks have also been performed by CEA and independently by the manufacturing company (Nexans). In table 1, a summary and comparison of measurements performed by CEA-DRFC and Nexans is presented.

Table 1: Dimensional controls performed by Nexans and CEA-DRFC: comparison and summary

	CABLING					JACKETING			
	Stage 1 mm (1)	Stage 2 mm (1)	Stage3 mm (1)	Stage 4 mm (1)	cosθ (2)	Dint mm	Dext mm	Wall Thickness mm	Void fraction (3)
Specification (mm)	45±5	85±5	125±5	160±5	NA	NA	NA	NA	32%
Nexans measures prototype 3X3	43 before jacketing	87 before jacketing	NA	NA	Estimated 0.995	2.95	3.39	0.22	31.84%
CEA measures Prototype 3X3	45 after jacketing	87.2 after jacketing	NA	NA	Measured 0.998	3.01	3.41	0.2 poor accuracy	32.1%
Nexans measures Prototype 3X3X5	43 before jacketing	87 before jacketing	122 before jacketing		Estimated 0.987	7.58	6.65	0.465	32.4%
CEA measures Prototype 3X3X5	44 after jacketing	88 after jacketing	133 after jacketing	NA	Measured 0.988	7.61	6.66	0.475	32.7%
Nexans measures Prototype 3X3X5X4	45 before jacketing	86 before jacketing	123 before jacketing	155 before jacketing	Estimated 0.977	13.25	14.88	0.815	31.10 %
CEA measures Prototype 3X3X5X4	47.5 after jacketing	100 after jacketing	150 after jacketing	165 after jacketing	Measured 0.978	13.2	14.88	0.84	30.7 %

(1) Note that the twist pitch measurements were performed by Nexans on the cable prior the jacketing and by CEA after jacketing, destroying the jacket in the process to expose the cable

(2) Overall equivalent cosθ were estimated prior fabrication and the estimate used by Nexans for the void fraction estimate; the actual cosθ value was measured by CEA and used for the void fraction estimation

(3) CEA Void fraction estimate are based on strand diameter Ø 0,81 and the most reliable/accurate measurement of jacket external diameter and jacket thickness

Apart the sequence of the twist pitches for the 3x3x5x4 which was difficult to control exactly during the production, the controls proved that the specifications of the samples were fulfilled. It can be considered that the quality of the production is acceptable for the scientific program.

STATUS OF THE SAMPLES PRODUCTION

All the subsize samples corresponding to phase (a) have now been manufactured by Nexans, which represents a total of 28 samples for batch 1.
CEA is in charge of the heat treatment of the samples and of the equipment with copper grips and force grips in the extremities.

The two samples (3x3x5 A2) and (3x3) A3 have been heat treated on the 21/06/05 and sent to FZK, without the results of inspection on the two prototypes, to accelerate the testing process.

According to the delivery from Nexans, all the samples have then been treated in two batches:
First batch on the 10/10/05, second batch on the 14/11/05.

They have been partially sent to FZK for being tested. The detailed status of the samples production in January 2006 is presented in table 2.

Up to now 3 samples have been tested at FZK, but sample #2, the first sample to be tested was unfortunately destroyed by an undetected quench before the stretching of the sample. The analysis of the first experimental results is in progress.

Table 2: Status of batch 1 sample production in January 2006

Triplet / n.	Acronym	Cabling	Billet	Delivery by Nexans	Heat Treatment	Sent to FZK	Test FZK	Measurements	Return by FZK to CEA	Remarks
3 Sc										
n.1	A3	3x3	#2	16/06/05	21/06/05	20/07/05	Report 25/11/05	To repeat with n.9	05/01/2006	no sufficient chrome removal
n.9	B3	3x3	#1	05/10/05	10/10/05	07/11/2005				no holes - 1140mm long
n.11	A3	3x3x5	#1	05/10/05	14/11/05	kept as back-up				no holes
n.10	B3	3x3x5	#1	05/10/05	10/10/05	07/11/2005				no holes
1 Cu +2 Sc										
n.2	Prototype	3x3	#2	16/06/05	verified OK	held by CEA				no sufficient chrome removal
n.12	A2	3x3	#1	05/10/05	14/11/05	To be sent				no holes
n.13	B2	3x3	#1	05/10/05	10/10/05	kept as back-up				no holes
N.3	Prototype	3x3x5	#2	16/06/05	verified OK	held by CEA				no sufficient chrome removal
n.4	A2	3x3x5	#2	16/06/05	21/06/05	20/07/05	Report13/09/05	Destroied - repeat with n.14	05/01/2006	no sufficient chrome removal
n.14	B2	3x3x5	#1	05/10/05	10/10/05	07/11/2005	Report 09/12/05			no holes
n.5	A225	3x3x5	#2	26/10/05	14/11/05	09/12/2005				
n.15	B225	3x3x5	#1	26/10/05	14/11/05	kept as back-up				
n.6	A245	3x3x5	#2	26/10/05	14/11/05	09/12/2005				
n.16	B245	3x3x5	#1	26/10/05	14/11/05	kept as back-up				
n.25	AS	3x3x5	#1	05/10/05	14/11/05	kept as back-up				no holes - special twist pitch
n.24	BS	3x3x5	#1	05/10/05	10/10/05	07/11/2005				no holes - special twist pitch
n.17	A2	3x3x5x4	#1	26/10/05	14/11/05	09/12/2005				
n.18	B2	3x3x5x4	#1	26/10/05	14/11/05	kept as back-up				
2 Cu+1Sc										
n.20	A1	3x3	#1	05/10/05	14/11/05	09/12/2005				no holes
n.19	B1	3x3	#1	05/10/05	10/10/05	kept as back-up				no holes
n.22	A1	3x3x5	#1	05/10/05	14/11/05	09/12/2005				no holes
n.21	B1	3x3x5	#1	05/10/05	10/10/05	kept as back-up				no holes
n.7	Prototype	3x3x5x4	#2	10/07/05	verified OK	held by CEA				void fract. between 30.7 and 31.1 % chrome removal OK
n.8	A1	3x3x5x4	#1	26/10/05	14/11/05	09/12/2005				
n.23	B1	3x3x5x4	#1	26/10/05	14/11/05	kept as back-up				

As far as phase (b) is concerned, Nexans has delivered 8 samples of batch 2: 4 samples using EAS strands and 4 samples using OCSI strands. The manufacture of the other subsize samples is delayed due to unavailability of the strands.

CONCLUSIONS

The manufacture of samples corresponding to phase (a) is now completed. The manufacture of samples corresponding to phase (b) has been delayed due to late delivery of the strands from the different companies. The unit lengths from different strands are expected to be delivered at Nexans end of march 2006.

REPORTS AND PUBLICATIONS

[1] J.L. Duchateau, N. Dolgetta "EFDA contract TW4-TMSC-SAMAN1**:** First intermediate report on subsize sample manufacture" October 2005 internal report AIM/NTT-2005.026

TASK LEADER

Jean Luc DUCHATEAU

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

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

e-mail : duchat@drfccad.cea.fr

CEFDA04-1134

Task Title: TW4-TMSC-BARBEN: EFFECT OF BENDING STRAIN ON Nb_3Sn 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 are jacketed single strands. For this, 316 L stainless steel (SS) tubes are used for the jacket.

The pure bending strain is imposed by changing curvature radius of the jacketed strand after heat treatment (HT), by transfer on adapted measuring mandrels.

In the task action program, various steps were included:

1- the validation of a newly developed method for applying a pure controlled bending strain on a SS-jacketed Nb_3Sn strand. This was performed through a dedicated test program with a 0.5% maximum bending strain.
2- the application of this method to the same strand but with a lower bending strain (0.25%).
3- an extra cross-checking of SS-jacketed strand IC variations with temperature. This action involved the Variable Temperature Cryostat (VTC) recently improved at CEA-Cadarache.

Practically the parts 1 and 2 of this work have been performed in collaboration with ENEA Frascati (Italy) for jacketed strands IC tests at T=4.2 K and B=12 T that are measured in a dedicated local facility.

Besides, the experimental data were interpreted with both a classical electromechanical model and a newly developed one, that cold be considered as a possible generalization of the latter.

2005 ACTIVITIES

BENDING APPLICATION METHOD (BEAM) DEVELOPMENT AND VALIDATION

Supports and tools description

Basically the BEAM includes the samples preparation and positioning on the HT mandrel and the strand transfer onto the measuring mandrel after HT. The main tool used is a home-made one, shown in figure 1. This tool is used tomaintain the strand during the transfer and soldering stages, requiring a specific caution.

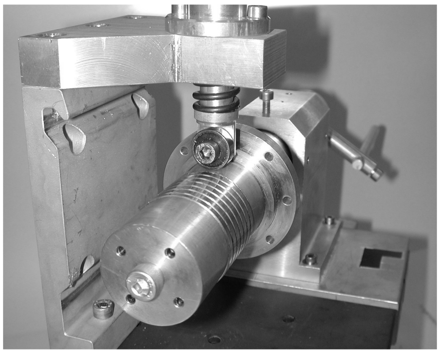


Figure 1: Mechanical tool used in BEAM (COBALT for Controlled Bending Application Loading Table).

Detailed descriptions of the development actions are available in [1].

Tests for BEAM validation

Finally four BEAM candidate methods were defined, each being a unique combination of processes including strand transfer with radius increasing (RI) or decreasing (RD) and ends connections by unjacketting before HT (UB) or after HT (UA). All those were applied to 18 samples (including the unbent ones for reference) with a maximum bending strain of 0.5%. The final method choice is performed through a dedicated comparison campaign. For that 3 samples of each method are tested and comparisons were correlated with a hierarchic list of criteria.

The experimental results were considered in terms of I_C degradation with $\Delta I_C = 100\,(\frac{I_C^{UNBENT} - I_C^{BENT}}{I_C^{UNBENT}})$.

They are illustrated in figure 2.

Finally, the most reliable method chosen was the one implying a radius increase and the unjacketting occurring before HT (RI-UB). The strand (from Oxford Instruments) involved in this validation stage is candidate for ITER TF Coils and consequently can also be considered as tested in relevant conditions to ITER TF operation. For this particular strand, a moderate degradation in I_C due to bending of 5% to 10% is observed.

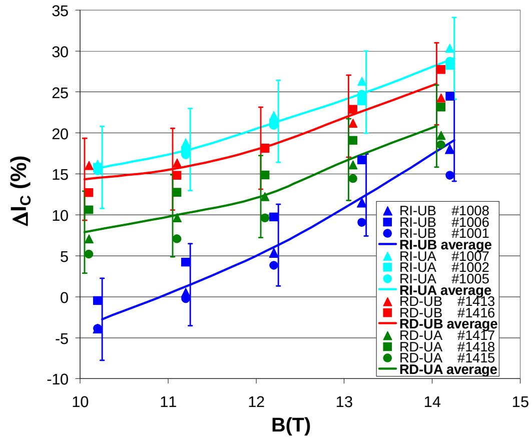


Figure 2: I_C degradation curve for B from 10 T to 14 T for the four candidate methods in BEAM choice.

BEAM APPLICATION: TESTS ANALYSIS AND MODELLING

Tests at low bending

A maximum bending strain of 0.25% is applied on a new samples batch with same strands. Although some inaccuracies, the results were found in good consistency with the latter ones at 0.5% bending strain. This point also supports the validity of the chosen method for BEAM.

Electromechanical modelling

In first approach a classical model [2] was applied to fit the experimental data, in which roughly two extreme electrical configurations are considered in terms of interfilamentary current redistribution (ICR) capacity. Significant deviations were observed, leading to the development of an alternative possible model, called the Weighted Distribution Model (WDM). In this model we consider all intermediate ICR by mean of a dedicated function H with a parameter λ (see figure 3 for a general presentation).
As a result a better fitting can be observed, compared to the classical model (figure 4). Nevertheless room for improvement still remain for the WDM to be fully relevant to the experimental data obtained. As a matter of fact, parameters such as filamentary matrix magnetoresistance or neutral axis shift could be investigated deeper.

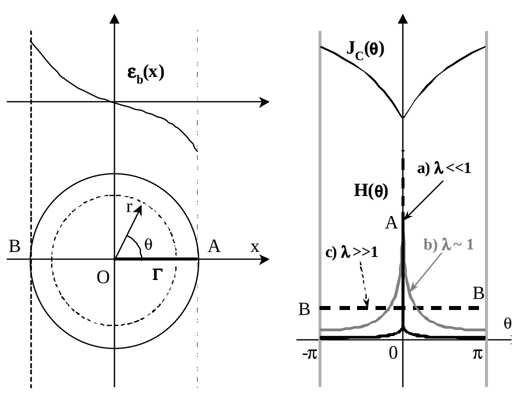


Figure 3: Basic principles of the WDM.
Left: strain variation over the strand cross-section
Right: different H weighting functions for various λ values.

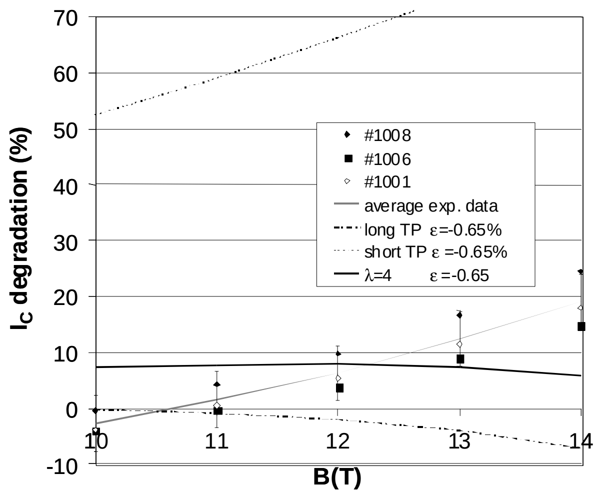


Figure 4: tentative fitting with both classical (long TP and short TP) and WDM (with λ value) models.

TESTS AT VARIABLE TEMPERATURE

The critical properties of the SS-jacketed strand were evaluated using the VTC facility. The experimental value were collected in GHMFL (CNRS, Grenoble) and correlated to the usual fitting for this type of strand. The parameters were found consistent except for the longitudinal intrinsic strain, typically 0.1% higher than expected. This could be due to the preparation conditions.

CONCLUSIONS

During the year 2005 this task BARBEN was completed, including the following actions:

- Definition of the four candidate methods for BEAM and validation of the final choice process for the most reliable one. Here the RI-UB option was chosen in a test with 0.5% maximum bending strain.
- Application of this method in lower bending strain range (0.25% maximum).
- Development of an original electromechanical model (WDM) to analyze the experimental data, provided that the classical one show some deviations. However WDM improvements are in progress.
- Check of the SS-jacketed strand IC variations with temperature, found globally consistent with expectations.

REFERENCES

[2] J W. Ekin, Filamentary A15 Superconductors Ed. New-York Plenum press (1980).

REPORTS AND PUBLICATIONS

[1] Zani L, Cloez H, Tena M, Della Corte A, Muzzi L and Di Zenobio A, *Development of a controlled bending application method for investigating Nb_3Sn jacketed strands,* Supercond. Sci. Technol. 18 S390–S395 (2005)

TASK LEADER

Louis ZANI

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

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

e-mail : louis.zani@cea.fr

CEFDA04-1170

Task Title: TW4-TMSC-RESDEV: DEVELOPMENT AND TESTING ON NEW RESIN SOLUTION

INTRODUCTION

New advanced cyanate ester-based resin materials have been tested and found to have significantly improved radiation resistance as compared to currently used resins. Therefore, it is necessary to stimulate the activity within Europe to gain experience with these new resin systems in close collaboration between the associations and the European companies.

The primary objective of this task is to industrialise the vacuum impregnation technique of new advanced resins with optimized catalyst contents, resin temperatures and times for large magnet systems. To qualify the process, a mock-up with about 50 kg of resin will be manufactured.

2005 ACTIVITIES

The first step was to verify the capability of the resin proposed for the mock-up realization to be used in the industrial process of the coils manufacture.

The cyanate ester/epoxy resin blend (PY 306 : 60 ppw; AroCy 10-L : 40 ppw; Mn-acetyl-acetonate in nonyl-phenole : 1.5 ppw), proposed by Hunstman and tested by ATI appears to be very interesting because of its good mechanical properties after irradiation.

But, after discussions with potential coils manufacturers (Garching - March 05), we have had the confirmation that some properties of this resin (pot life, curing temperature, toxicity) were really not compatible with the vacuum impregnation process of the ITER TF coils in an industrial context.

The conclusion was that the resin has to fulfil the following requirements:

- According to the dimensions of the coils to be impregnated, a pot life of at least 24 hours is required at the impregnation temperature (between 40°C and 70°C): viscosity initially <100 mPa.s and the increase should not exceed a factor of 2 during the life time.

- The safety aspect is important: it could be very difficult, even impossible, to use carcinogenic elements in an industrial context.

- Because of the constitutive elements of the coil, the curing temperature cannot exceed 150 °C.

- The system has to support 3 or 4 curing cycles.

According to this fact, it was decided that the test on the mock-up should be done with the relevant resin and that the next step will be to find a resin which matches the manufacture requirements for the ITER TF coils. The test has been postponed until the new resin is available.

A meeting has been organised the 26th of april by CEA-Saclay in the Hunstman company at Basel (participants: Alstom - Ansaldo – CEA-Saclay –Hunstman - Supratec) to see how the company can adjust the resin composition [1].

Hunstman is working on new formulations and the progresses were regularly followed by mails and phone calls. Several catalyst components have been tested and some encouraging results have been obtained with the cyanate-ester alone. The required viscosity profile has been obtained using a catalyst based on Cobalt (III) acethylacetonate: the resin presents a pot life of 24 h at 70°C, the viscosity increasing from 50 mPas to about 200 mPas, which is suitable for an impregnation.

At this time, Hunstman begins the tests with the epoxy/cyanate-ester blend (60% epoxy, 40% CE), which has been defined as the baseline.

Before the new formulation will be approved, samples will be tested under irradiations by ATI at Vienna (this step will take about 3 or 4 months).

The delay to obtain the 50 kg of resin needed for the mock-up is about 3 months.

REPORTS AND PUBLICATIONS

Report on the meeting by Huntsman (26/04/2005) ref: RESDEV-R-005-05.

TASK LEADER

Françoise RONDEAUX

DSM/DAPNIA/SACM/LEAS
CEA-Saclay
F-91191 Gif-sur-Yvette Cedex

Tel. : 33 1 69 08 64 49
Fax : 33 1 69 08 69 29

e-mail : francoise.rondeaux@cea.fr

CEFDA04-1201

Task Title: TW5-TMS-EDDES: EUROPEAN DIPOLE DESIGN ACCELERATOR TYPE MAGNET

INTRODUCTION

Within the framework of the European Fusion Programme a design activity has been started late 2004 by the EFDA Close Support Unit at Garching (FRG) to design a 12.5 T superconducting dipole magnet. This new magnet shall be hosted in one of the existing cryogenic laboratories in the EU to test, in particular, the full size conductor samples that shall be produced during the ITER magnets procurement.

The objective of the 2005 activity, which covers the full task activity (all the work has been done in 2005), deals with the studies carried out on one of the possible designs: The cos θ coil configuration (saddle coil) commonly used for accelerator magnets. This coil configuration, based on the use of Rutherford-type cables, could lead to less voluminous and less expensive solution compared to that using cable-in-conduit conductor.

2005 ACTIVITIES

After having finalized the requirements for the magnet and the design criteria, two possible magnetic configurations have been determined, using two superconducting cables made of strands which should be available in 2005.
For each of these two magnetic configurations, the following aspects have been studied:

- Dynamic losses (when the magnet is pulsed)
- Magnet protection
- Mechanics
- Rough cost estimate

REQUIREMENTS AND DESIGN CRITERIA:

The requirements are as follow:

- Bore field: Use 12.5 T as minimum guaranteed + 10% as target
- Clear cold bore diameter : 130 mm
- Current density in superconducting material: use Nb_3Sn strands available in 2005 (i.e. with a current density in non copper @ 4.2 K @ 12 T of about 2000 A/mm^2) Magnetic field homogeneity : 1% at 20 mm from the free cold wall (i.e. ∅ 90 mm)
- Magnet length: such that B >= 12.5 T over 1500 mm Magnet cycling: +/- 0.5 T at 4 or 10 T with dB/dt = 0.01 T/s (meeting at CERN) or 0.18 T/s (annex of contract)

And the design criteria are:

- Mechanics: As Nb3Sn superconducting strands show significant degradation (current density) when submitted to stress higher than 150 MPa, this value must not be exceeded, especially if the margin on the load line is low.
- Protection: Two aspects have to be considered:
    - o Maximum temperature in case of quench: It is commonly admitted that this temperature should not exceed the room temperature, 300 K.
    - o Voltage: The electrical installation has to be tested to verify that it can resist to the voltage induced by a quench. The rules to determine the voltage tests are 2U+1000 or U+2000. A voltage in case of quench of 750 volts can then be admitted, even if we consider that 500 volts would be better.

SUPERCONDUCTING STRANDS

After having chosen the coil inner diameter (145 mm), two strand with slightly different characteristics where chosen:

Characteristics of the 2 strands:

	OST Strand	Alstom Strand
J_{cnonCu} (12T, 4.2K) (A/mm^2)	2167*	2000
J_{cnonCu} (14T, 4.2K) (A/mm^2)	1289*	
Strand diameter (mm)	0.7	0.825
Cu/nonCu ratio	1	1

* measured on non cabled strand [2]

All calculations have been carried out with the two strands, but we will report here only with the one which gives the best results

MAGNETIC STRUCTURE:

The classical cos θ structure is shown in figure 1

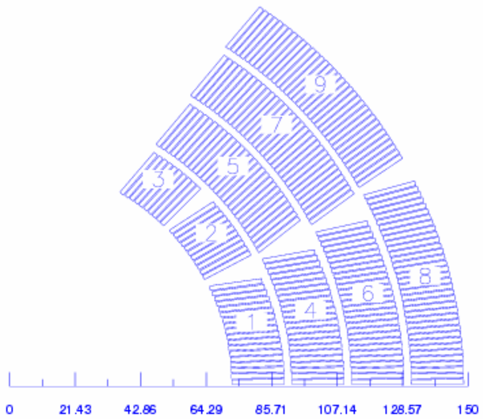


Figure 1: ¼ of the magnetic structure

Main characteristics

	Without yoke	With yoke
Current in each block (A)	9472	7590
Peak field (T)	13.69	13.41
L (mH/m)	87.2	114.8
E (kJ/m)	3912	3309
Quench margin (%)	3.3	7.4
Temperature margin (K)	-	2.3

LOSSES DURING MAGNET CYCLING

Two cycles have been considered: +/- 1 T around 4.5 T and +/- 1 T around 10.5 T. For each of these two cases, 2 ramp rate have been studied: 0.01 T/ s and 0.18 T/s
Results are as follow:

Cycle	3.5 T->4.5 T->3.5 T		9.5 T->10.5 T->9.5 T	
Ramp rate	0.01 T/s	0.18 T/s	0.01 T/s	0.18 T/s
Pc (R_c =10^{-4} Ohms)	0.06	19.26	0.05	17.23
Pa (R_a=10^{-6} Ohms)	0.08	24.27	0.07	21.74
Pif	0.03	9.37	0.03	9.09
P_{hyst}	19.98	359.64	6.34	114.12

This table shows that the losses due to the magnetization of the filaments are predominant.
More generally, the level of the losses in the conductors should be manageable at a ramp rate of 0.01 T/s but it becomes problematic at a ramp rate of 0.18 T/s.

MAGNET PROTECTION

This study has shown that the protection of the magnet is a critical issue: quench heaters are needed on each coil layer and even with these heaters, the temperature and the voltage stay at the limit of what is acceptable:

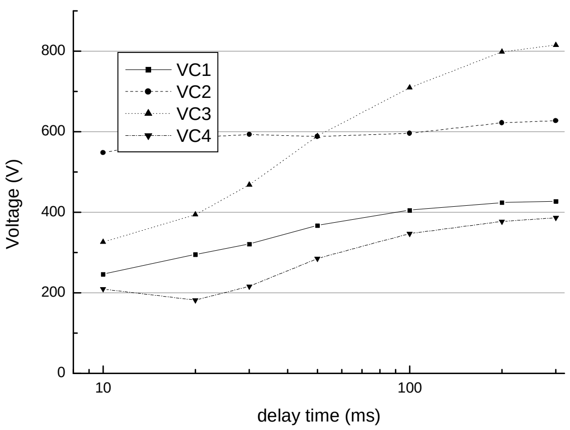
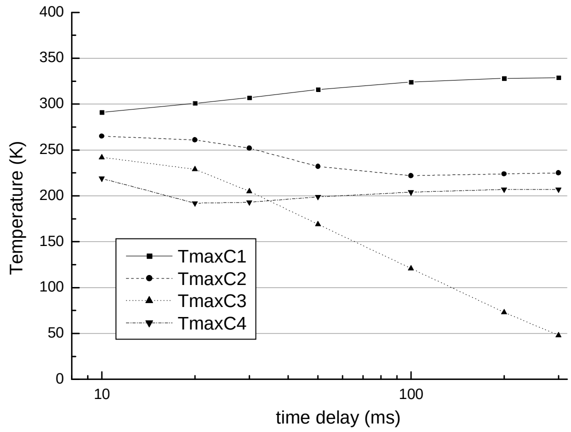


Figure 2: Voltage at the terminals of each layer vs delay time with quench heaters on the external and second layers



Temperature of the hot point of each layer vs delay time with quench heaters on the external and second layers

MECHANICS

This study has shown that mechanics is the main issue: The mechanical stress reaches 231 MPa in the coils during magnet energization. This value is well above the limit of 150 MPa.

This shoes that magnets with such high magnetic field and large aperture will require new mechanical structure, demanding for long studies, before to be useable for either particle accelerators or other applications

	Welding + Cool down		Energization	
Coils				
Stress (MPa)	σ_θ	σ_r	σ_θ	σ_r
Average over coil	-157	-52	-160	-78
Average over midplane	-142		-178	
Average over pole plane	-177		-112	
Minimum over pole plane	-23		-10	
Point A	-182		-231	
Point B	-75		-103	
Point C	-188		-35	
Point D	-23		-10	
Displacement (mm)	Δ_θ	Δ_r	Δ_θ	Δ_r
Average over midplane		-0.696		-0.582
Average over pole plane	-0.144	-0.775	-0.190	-0.779
Collars				
Peak Von Mises stress	1292		1236	

ROUGH COST ESTIMATE

The total estimated cost for this magnet is about 2 100 k€ for the dipole magnet and 21 full time equivalent for human resources.

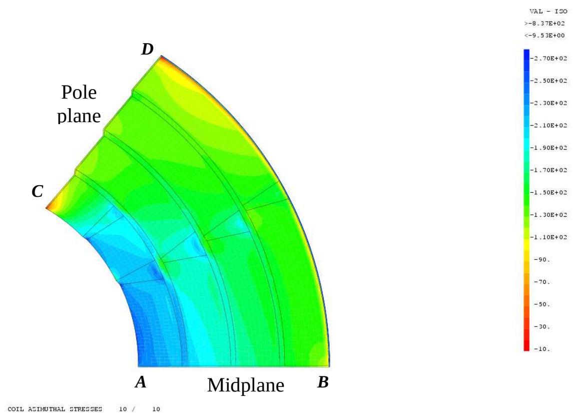


Figure 4

CONCLUSIONS

The purpose of our study was to verify that a dipole magnet for the ITER test facility can be an "accelerator type" magnet and to give the basic parameters of such a magnet for a future possible detailed study.
It appears that on several aspects, such a magnet is near or beyond the limits for a safe design:

- The needed field quality doesn't allow a design where the peak field in coils is fully optimized. In other words, the margin on the load line could be increased up to 10%, (which is still a rather low value) but only if the needed field quality is relaxed.
- The magnetic design of the magnet can be achieved with two different superconducting strands but the criterion for voltage has to be increased from 500 to 750 Volts.
- On the mechanical part, we have shown that the maximum stress in the coils is higher than 200 MPa, well beyond the one judged to be acceptable (150 MPa). Mechanics appears to be the most critical aspect of this design.
- During magnet cycling, losses are acceptable. This aspect is not a big issue.

This magnet would be built using the usual technology of Nb_3Sn "cos θ" magnets working in a 4.2 K helium bath. The structure of the cryostat could then be rather simple.

The price of such a magnet is rather low with respect to the price of a "Cable In Conduit" design. We estimate the material to cost about 2.1 MEuros, and the manpower needed to build it to about 21 FTE. However, a lot of R&D has to be made and such a magnet could probably not be realized in less than 4 years from now.

In summary, our study shows that, for a free cold area of 130 mm in diameter and 12.5 T, the "cos θ" design is above the norm in terms of the mechanical behaviours (B^2R, which is representative of mechanical stress, should be decreased by about 35% to stay in the norms). A safer design of such a magnet, with an alternative mechanical structure would demand for time consuming developments, especially for the mechanical aspect.

REFERENCES

A. Devred at al., "Status of the Next European Dipole (NED) Activity of the Collaborated Research in Europe (CARE) Project", Proc. of ASC 2004 conference
Private communication (Dan Dietderich, Lawrence Berkeley National Laboratory)

R. Scanlan, "The USA experience on Nb3Sn and Bi-based superconductors and future plans". HEHIHB-AMT WAMS (Workshop on Accelerator Magnet Superconductors), 22-24 March 2004, Archamps, France

S. Russenschuck, "ROXIE: Routine for the optimization of magnet X-sections, inverse field calculation and coil end design". Proceedings of the first international Roxie users meeting and workshop, 16-18 March 1998, CERN, Switzerland

A. P. Verweij, "Electrodynamics of superconducting cables in accelerator magnets". PHD Thesis, Twente University, The Nederlands, 1995

L.T. Summers *et al.*, "A model of prediction of Nb_3Sn critical current as a function of field, temperature, strain and radiation damage", IEEE Trans. Mag., Vol. 27 N°2, pp2041-20044, 1991

D. Leroy and O. Vincent-Viry," Preliminary Magnetic Designs for Large - Bore and High - Field Dipole Magnets", Report CERN/EDMS Nr 555826 December 2004.

J. E. Kaugerts *et al.*, « Design of a 6T, 1T/s Fast-Ramping Synchrotron Magnet for GSI's planned SIS 300 Accelerator », proceedings of ASC 2004.

R. Otmani, "Etude de câbles Nb_3Sn pour quadrupôles supraconducteurs", PHD Thesis, CEA/DAPNIA/STCM 99-1001, 1999 (in French).

P. Verpeaux, T. Charras et A. Millard, "CASTEM 2000 une approche moderne du calcul des structures, Calcul des structures et intelligence artificielle", Pluralis, 1988, p. 261-271.

P. Vedrine et al., "Measurement of the thermo-Mechanical Properties of NbTi Windings for Accelerator Magnets", IEEE Trans. Appl. Supercond., Vol. 9, No. 2, pp. 336-239, 1999.

M. Durante, "Essais de compression sur empilements droits et autres échantillons", Rapport technique interne n°5-2650N--2300 004 00, 2000.

M. Durante, "Mesure de retreint thermique d'empilements droits et d'autres échantillons", Rapport technique interne n°5-2650N--2300 005 00, 2000.

M. N. Wilson, "Superconducting Magnets", Oxford Science Publication

REPORTS AND PUBLICATIONS

H. Félice, P. Fazilleau, A. Payn, J.M. Rifflet, L. Quettier, M. Segreti, “EFDA Dipole conceptual Design; Accelerator type magnet; EFDA contract CEFDA01-1201”, Final report for this task

A. Portone, E. Salpietro, L. Bottura, P. Bruzzone, W. Fietz, R. Heller, J-M. Rifflet, J. Lucas, F. Toral, S. Raff, P. Testoni, “Conceptuel Design of the 12.5 T Superconducting EFDA Dipole, Magnet Technology Conference 19, Genoa, September 2005

TASK LEADER

Jean-Michel RIFFLET

DSM/DAPNIA/SACM/LEAS
CEA-Saclay
F-91191 Gif-sur-Yvette Cedex

Tel. : 33 1 69 08 49 16
Fax : 33 1 69 08 69 29

e mail : jean-michel.rifflet@cea.fr

CEFDA04-1215

Task Title: TW4-TMSC-CRYOLA: CRYOGENIC TESTS ON ITER MAGNET STRUCTURAL MATERIALS

INTRODUCTION

The main objective of this contract for CEA/DRFMC/SBT service is to perform cryogenic tests at 4 K to characterize the ITER magnet structural materials and to prepare European laboratories for the large number of tests necessary during the ITER magnet procurement action.

This task is performed in collaboration with FzK for the definition of the standard procedures to be followed during cryogenic tests at 4 K, 77 K and room temperature.

Air Liquide / DTA and SBT have been collaborated for several years. Air Liquide / DTA is in charge of mechanical tests (Young modulus, tensile test, compression test, materials fatigue …) thermal tests are performed at SBT (thermal expansion, thermal conductivity …).

From a technical point of view, the work is separated in two parts, the first one concerns the upgrade of the tests bench to increase the quality of the measurement and to standardize the measurement procedure.
In the second part, the same tests have been carried out at FzK laboratory and SBT or Air Liquide / DTA then the results have been compared.

This task started at the beginning of 2005 and will finish at the end of 2006.

2005 ACTIVITIES

In 2005, activities concerned mechanical and thermal tests. All the thermal tests have been performed; the mechanical tests will be finished in 2006. The Instron tensile machine is presented in figure 1.

Figure 1: Instron tensile machine for mechanical testing

MECHANICAL TESTS

This activity is separated in several items; the goal is to prepare the test bench to realize a large amount of tests with some quality aspect (reliability, reproductibility, precision…).

Background

Air Liquide owns several machine types that permit to perform mechanical test like tensile tests, compressive tests, resilience test or materials fatigue. The range of temperature varies from room temperature to 4.2 K with different liquid baths. The major advantage of the use of a liquid phase is that gives an accurate and stable temperature along the measurements.

Improvement of the tensile machines

To be able to answer to the ITER requirements different modifications have been made on the tensile machines.
Load direction: An easy modification of the load direction has been implemented during the tests to perform specific fatigue tests.
Voltage reduction for extensiometers: To reduce the production of bubble on the helium bath the voltage of the extensiometers has been reduced from 5V to 2V. The consequence is a higher stability of the temperature of the sample.
Raw data storage: Such system has been installed on the machine for easier calculation and recording aspects. Two extensiometers: A second extensiometer has been installed for the tensile test to improve the young modulus measurement. The figure 2 presents this new arrangement.

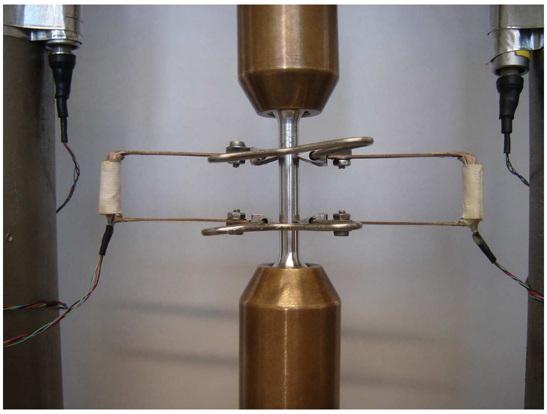


Figure 2: Specimen installed in the machine and equipped with extensiometers

Characterization of the machine

After improvement of the machine, different sensors (load cell, extensiometer) were characterized and calibrated so that their noise at room temperature (RT) and 4 K was estimated. The following table indicates the results.

Sensors	Temperature	Noise (% of full range)
Load cell	RT	0.3
Extensiometer	RT	0.2
Extensiometer	4 K	0.25

These values are lower than the ITER requirement (0.5 % of the full range) which validate the test facility.

Mechanical tests

After the characterization of the test bench, some tests have been carried out with different samples and at different temperatures. The figure 3 shows the results for a stainless steel specimen (304 L) at 4 K.

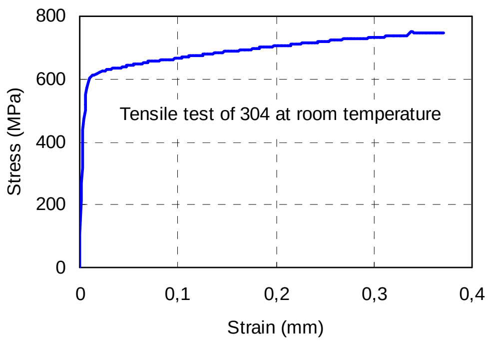


Figure 3: results of tensile test for 304 L 55 steel at 4 K

THERMAL TESTS

Two types of thermal tests are carried out in this contract: thermal expansion and thermal conductivity. These tests are performed from room temperature to 4 K. They are done twice: SBT lab and FzK. The purpose is to qualify CEA lab for these types of tests for the ITER project. After the measurements, results are compared; a good agreement between the two labs has been obtained. figure 4 and figure 5 present the conductivity cell and a measurement result.

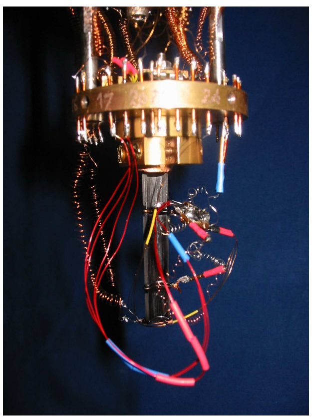


Figure 4: View of the thermal conductivity measurement cell

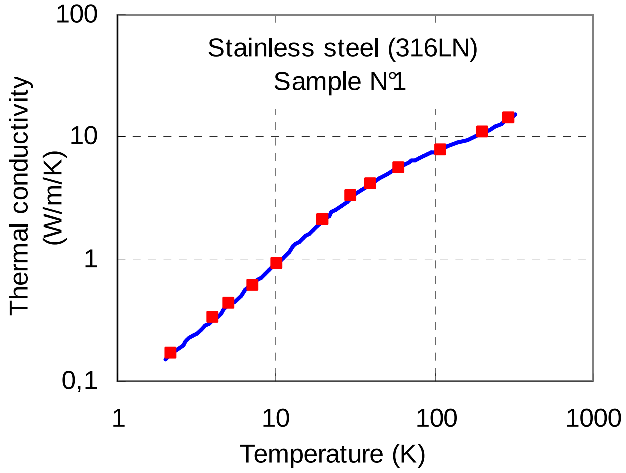


Figure 5: Thermal conductivity measurement of the stainless steel (316 LN) between 4 K and room temperature at CEA

CONCLUSIONS

CEA / SBT and Air Liquide / DTA have a long experience on thermal and mechanical tests on materials for a range of temperature between 4 K and room temperature. An agreement exists between these two entities: CEA / SBT is in charge of the thermal tests and Air Liquide / DTA is in charge of the mechanical ones.
Due to the large amount of tests to be done for ITER and due to new mechanical tests requests for the project some improvements were necessary and have been completed in 2005.
Concerning the thermal measurements, all the specified tests have been achieved (thermal conductivity and thermal expansion at 4 K and room temperature).
In 2006, two subtasks will remain: the end of the mechanical measurements and new modification proposal for the test bench in order to improve productivity.

TASK LEADER

Alain GIRARD

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

Tel. : 33 4 38 78 43 65
Fax : 33 4 38 78 51 71

e-mail : alain.girard@cea.fr

CEFDA04-1219

Task title: TW4-TMSC-SAMFSS: MANUFACTURE OF TWO FULL SIZE SAMPLES OF Nb_3Sn STRANDS

INTRODUCTION

Following the revision of the design of the ITER TF conductor in 2003, relying on the use of advanced Nb_3Sn strands, EFDA launched an R&D programme in 2004 to procure advanced strands from industry. The final advanced Nb_3Sn strand qualification will be done by the testing of two full size conductor samples. This task covers the manufacturing of the samples according to the requirements of the SULTAN facility. The work includes the joint fabrication, sample assembly and instrumentation. The manufacture of the conductor lengths is performed by ENEA and the heat treatment is performed at CRPP. The zero field joint resistance will be less than 2 nΩ, in order not to interfere with the conductor measurements. The same applies to the upper terminations, which will meet the SULTAN requirements. The two full-size samples (corresponding to four legs) will be made using different types of advanced strand.

2005 ACTIVITIES

SAMPLE DESIGN

The main guideline for the design of the two full size samples was to test the candidate of advanced strands produced by industry in a real conductor configuration. In order to be able to check the performance upgrade due to the strand itself, it was proposed to use a cable layout identical as the one of the previous TFMC Full Size Joint Sample (FSJS) which was the conductor used in the TF Model Coil. A conceptual design of the full size sample was produced on the basis of the use of a TFMC type conductor with thin circular steel jacket and with a joint using the twin box concept previously developed by CEA. The main basis was the PF-FSJS design drawings which were adapted to the use of a circular conductor. The sample is 3.50 m long hair pin type constituted by two parallel conductors joined at the bottom by a joint and connected at the top by the way of two upper terminations to the test facility busbars (figure 1).
The sample is devoted to be tested in the CRPP SULTAN test facility for conductor test which means that the transverse high field will be applied on a reduced length (i.e. 450 mm) of the conductor only. The cooling of the sample is insured by circulation of supercritical helium from the top to the bottom in parallel for each of the two legs. In order not to heat the flow through the upper joints, an intermediate inlet piece is inserted at the bottom of the upper terminations to inject helium from this point through the circumferential cable area. In this way, a thermal gradient is produced between the upper joints and the inlet. A sample ohmic heater is installed below the inlet on each leg to control the temperature inside the conductor at the high field region.

The instrumentation was defined in order to carry the critical current and current sharing temperature measurements with voltage taps and temperature sensors. Additional instrumentation was implemented in order to investigate the current repartition among sub-cables with hall probes as well as to study the thermo hydraulics with temperature sensors along the sample legs. A complete conceptual drawing set including an instrumentation drawing was produced using CATIA v5.
A technical specification document was issued and used for a call for tender [1]. The manufacturer was chosen to be Ansaldo Superconduttori in Genoa (Italy).

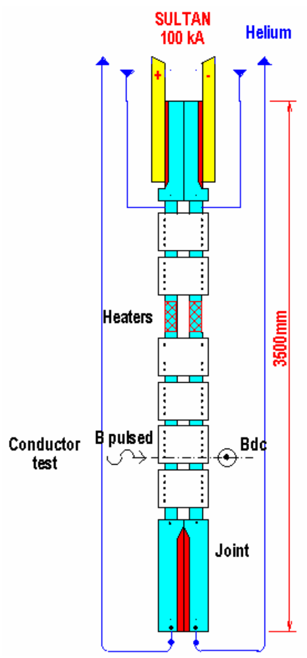


Figure 1: Sketch of a Full Size Sample

CONDUCTORS

Four conductor lengths were used for the manufacture of the two full size samples. Each leg of each sample being manufactured using one candidate advanced strand for TF coils. In this way, four different conductors will be tested separately. The layout of all these conductors is the same as the TFMC conductors. Table 1 summarises the main characteristics of each of these conductors. The first two conductors using EAS and OST strands were delivered by ENEA to A.S. on may 2005. They were used for the manufacture of the first sample called EU-TFAS1. The second conductor pair using OKCS and OCSI strands were delivered in september 2005.

Table 1: Main characteristics of the four conductors

Conducto rName	EAS	OST	OKSC	OCSI
Jacket	AISI 316 LN, o.d. 40.4 mm, 1.6 mm thick			
Cabling layout	3x3x4x5x6 (1080 strands)			
Central spiral	10 x 12 mm			
Number of s.c. strands	1080	720	720	1080
Number of Cu strands	0	360	360	0
Strand diameter	0.81 mm			
Manufacture way	Bronze route	Internal tin	Internal tin	Internal tin
Cu/ non Cu ratio	0.92	1	1	1.4
Manufacturer	European Advanced Superconductors	Oxford Instruments	Outokumpu Finland	Outokumpu Italy

EU-TFAS1 MANUFACTURE

The manufacture of the first sample started in may 2005. The conceptual drawings produced by CEA were converted in manufacture drawings by A.S. after agreement on the manufacture techniques. The samples joint using the twin box concept, the remaining part of the copper-steel plate bonded by explosion used for the PF-FSJS manufacture was delivered by ENEA to A.S. After machining of the main components as the termination boxes and associated covers, the two legs were prepared for terminations assembly according the following way: The jacket was removed at each conductor end, the cable wrapping was removed, the central spiral was locally cut and replaced by a 3 mm thick plain tube. After re-forming of the cable twist pitch, the sub-cables wraps were locally cut and the strands chrome plating was removed by mechanical brushing. The cable was then inserted into the termination box and was compacted through the cover down to a 25 % void fraction. A force of about 2 MN was needed for each of these compactions. The termination was completed by TIG welding of the cover on to the box and of the termination on to the jacket with respect to the alignment.

Note that despite the new terminations design with a lateral and smaller weld between cover and box, a banana effect of about 2 mm was observed on all the terminations. This unexpected deformation which was higher than in the previous PF-FSJS manufactured by Alstom was probably due to the use by A.S. of the manufacturing process of the TFMC terminations for which this problem was already raised.

After completion of each leg in the same way, an helium test was performed to check the tightness. The legs were then sent to CRPP in august 2005 in order to perform the heat treatment for Nb_3Sn reaction.

After heat treatment, the legs were sent back to A.S. in september. The lower terminations were machined to recover the copper soles flatness and to allow joint clamping. The joint was then soldered using the soldering procedure previously used for TFMC inner joints. The joint quality was checked by gamma ray inspection.

Voltage taps were then installed along the joint on the copper sole as well as on the cover in order to check the contact resistance between the strands and the copper sole. The corresponding wiring was connected since no access to this part will be possible after joint clamping. The steel clamping was the TIG welded on the joint to ensure its mechanical stiffness.

The conductor insulation was then performed by bonding of several turns of 0.5 mm epoxy tape on the conductor jacket at the clamps locations in order to reach the target insulation thickness of 2 mm.

After final assembly of the clamps, the upper terminations were machined to recover the flatness of the copper soles needed for connection to the test facility current leads. The final operations were the piping installation, final tightness check and installation of the instrumentation as voltage taps, temperature sensors and ohmic heaters along the conductors. A specific epoxy support including a set of 4 Hall probes was installed on each conductor just after the high field region, before the joint. The corresponding instrumentation wiring was connected to the sensors and equipped with the required connectors. A protection epoxy nose at the bottom of the sample and four epoxy corners surrounding the sample were installed and a final geometrical check has allowed to control the sample geometry to fit into the SULTAN specifications. The sample was sent to CRPP on november 17th 2005 (figure 2).

EU-TFAS2 MANUFACTURE

The manufacture of the sample started in september 2005, this sample uses the OKSC and OCSI conductors.

The preparation of the two legs was done in the same way as described for the first sample. After completion of the legs manufacture, the terminations deformations were in the same range as previously observed on the first sample legs. This result was foreseeable since no modification of the welding procedures was done by A.S.

The two legs were sent for heat treatment to CRPP in november 2005 and sent back to A.S. in december 2005 for final sample assembly.

Figure 2: EU-TFAS1 ready to be sent for test at CRPP

CONCLUSIONS

This task is devoted to the manufacture of two full size samples to be tested in the CRPP test facility. These samples were designed with a TFMC type conductor using circular steel jacket. Each sample uses two conductor lengths each of them using one candidate advanced strand proposed by the industry. Four different strands will then be tested in the same cable configuration and the results will be compared to the previous results gained on the TFMC full size joint sample. After production of conceptual drawings, the manufacture was performed by Ansaldo Superconduttori (Italy) and started in may 2005. The first sample was manufactured with EAS and OST strands. After the heat treatment at CRPP in august, the assembly including instrumentation was completed during summer. The sample was finally delivered to CRPP for test in november 2005. In the same time, the second sample manufacture was started after delivery of the conductors using OCSI and OKSC strands in september. After preparation of the two sample legs, the heat treatment was performed by CRPP in december 2005 and the legs sent back to A. S. in december 2005 for final assembly.

REFERENCES

[1] N. Dolgetta, Specifications for the manufacturing of two TF full size conductor test samples, Note AIM/CCH-2005.003, 07/02/2005.

TASK LEADER

Patrick DECOOL

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

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

e-mail : decool@drfccad.cea.fr

TW1-TMS-PFCITE

Task Title: POLOIDAL FIELD CONDUCTOR INSERT (PFCI)

INTRODUCTION

Within the framework of the ITER project, the EU Project Team 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 2006.

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 Superconduttori in august 2002 from the Russian Federation, the jacketing was completed at Ansaldo Superconduttori in june 2003. Fabrication of the coil is running at Tesla (UK) under monitoring by EFDA/CSU Garching. Unfortunately, the PFCI secondary impregnation in december 2005 failed partially. In order to correct the situation an additional impregnation needs to be carried out. Tesla informed EFDA/CSU about the new revised schedule, which indicates one month delay compared to the latest schedule, i.e. the revised shipping date is expected to be at the end of march 2006.

2005 ACTIVITIES

For 2005, our activities were reduced because of the delay taken in the fabrication of the PFCI at Tesla (UK). An action was launched in order to build a model of the PFCI with the Vincenta code. Vincenta is a thermohydraulic code developed by the Efremov Institute, in St Petersburg (Russian Federation), dedicated to cryogenic calculations, specially for CICC and associated loops.

A first work was to get some experience with Vincenta and to prepare models for the future analysis of PFCI experiments at JAERI. This work was performed in three steps: first pressure drop calculations, second steady state simulation and comparison with results given by other models, last a pulsed current scenario simulation.

PRESSURE DROP CALCULATIONS

In order to perform any thermohydraulic analysis on a CICC, it is essential to calculate with a good accuracy the pressure drop as well as the mass flow repartition between annular (bundle) and central (hole) channels.

Thus, pressure drop and mass flow repartition in the PFCI winding circuit (~ 43 m long) have been computed with Vincenta, and then compared on the one hand to analytical results, and on the other hand to simulations with Gandalf (Gandalf is another cryogenic code dedicated to CICC calculations, developed by L. Bottura and diffused by Cryosoft).

Results obtained with these three tools (at T = 4.5 K) show very good agreement as illustrated in figure 1 and figure 2.

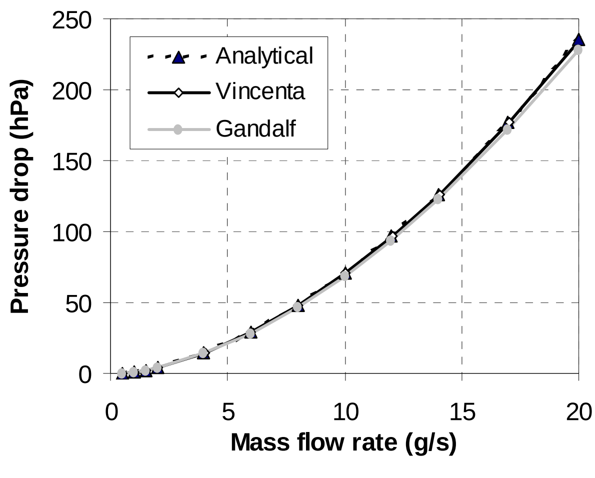


Figure 1: Pressure drop vs. mass flow rate in PFCI conductor.

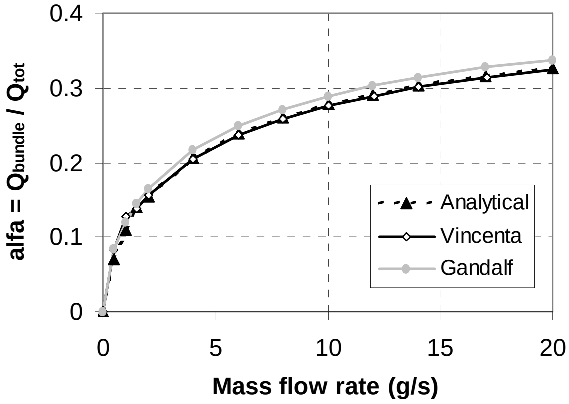


Figure 2: Mass flow rate in bundle channel vs. mass flow rate in PFCI conductor.

STEADY STATE HEATING CALCULATIONS

In order to run Vincenta under steady state conditions, it has been decided to simulate the permanent heating of the PF-FSJS (Poloidal Field Full Size Joint Sample). As a matter of a fact, experimental data have been obtained when testing the PF-FSJS in the Sultan test facility at CRPP (Villigen, Switzerland), and in a previous work, Gandalf simulations as well as a dedicated analytical model have shown good agreement with experimental results.

Thus, Vincenta results under steady state conditions can be validated by comparison with those given by Gandalf and by the analytical model. Only one leg of the PF-FSJS has been modeled. This leg is a 2.2 m long CICC, submitted to a permanent heating of 30 W/m applied over 0.4 m on the jacket, at the entrance of the sample. Inlet conditions are a 8 g/s flow rate of supercritical helium at 4.5 K and a pressure of 1.02 MPa.

Vincenta calculations have shown important sensitivity to mesh size and to a numerical parameter called AH. This parameter, adjustable by the user, is applied to the energy balance in the code, in order to improve the calculation stability.

To get a correct enthalpy balance with Vincenta (30 W/m × 0.4 m = 12 W to the helium flow), one must check that both mesh size and AH values are well adapted to the conditions of calculation. Then, using the same heat exchange correlation in all the tools, Vincenta results are close to those obtained with Gandalf and the analytical model, as shown on the annular (bundle) and central (hole) temperature profiles given in figure 3. Note that the central channel is at a lower temperature since only the annular channel is first heated through the conductor jacket.

PULSED SCENARIO SIMULATION

The PFCI will be tested inside the CSMC at JAERI where both coils will be able to operate in pulse mode (pulsed currents). It has been decided to simulate a scenario of simultaneous current ramp up and ramp down in PFCI and CSMC. Coil currents vs. time are given in figure 4.

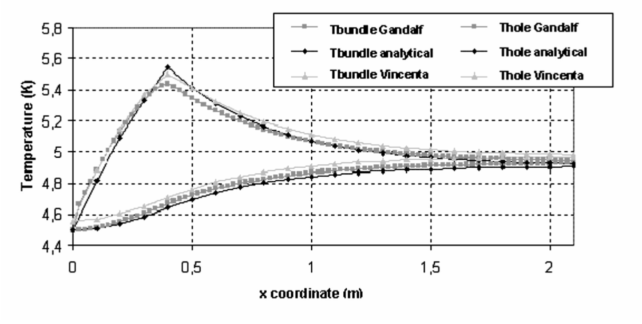


Figure 3: Temperature profiles along PF-FSJS (heating over the first 0.4 m).

After calculations of the heat load in the PFCI, in space and in time, it has been necessary to develop a tool to check the energy balance in Vincenta, in order to choose correct values for both the numerical parameter AH and the mesh size. This tool checks the energy balance in the PFCI between two time steps (PFCI is here an open system under transient conditions). Then, Vincenta calculation has been performed, as well as Gandalf calculation, with of course the same heat loads. Results obtained with both codes are very close, as shown in figure 5 on PFCI winding outlet temperature vs. time (figure 5).

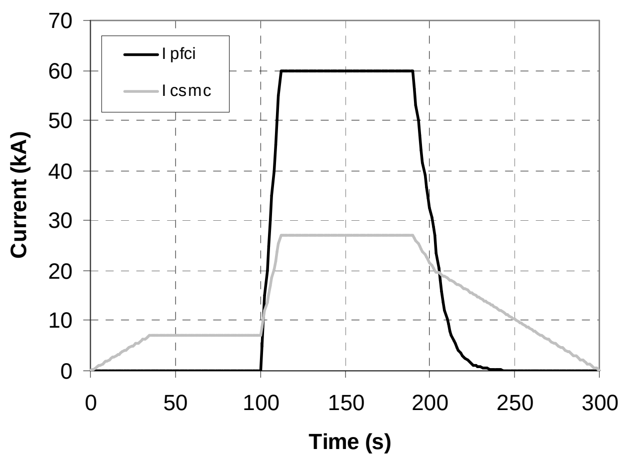


Figure 4: CSMC and PFCI currents vs. time

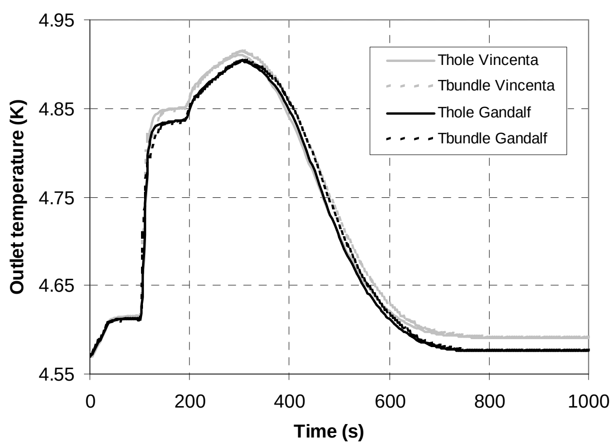


Figure 5: PFCI winding outlet temperature in hole and bundle vs. time

Figure 5 shows negligible temperature difference between annular (bundle) and central (hole) channels. This was expected, since these temperatures are computed at the end of the winding (more precisely at the intermediate joint outlet) so at helium outlet. For easier calculations, joints (lower terminal and intermediate) have been replaced by regular conductor lengths.

Finally, we can consider that Vincenta models (permanent and transient) are reliable, as in good agreement with analytical and Gandalf models. Besides, in the future, it will be useful to precise a methodology to choose mesh size and/or AH value adapted to each calculation.

CONCLUSIONS

The Poloidal Field Conductor Insert is under fabrication in industry and should be tested in the CSMC facility (Naka, Japan) by the end of 2006. CEA is participating in the definitions of both the PFCI instrumentation and the testing programme. In order to model the thermohydraulic behaviour of PFCI, an action has been developed to build a model using the Vincenta code. A first step was to validate this code against analytical model and the Gandalf code under steady state and transient operating conditions.

TASK LEADER

Daniel CIAZYNSKI

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

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

e-mail : daniel.ciazynski@cea.fr

TW5-TMSF-HTSMAG

Task Title: SCOPING STUDIES OF HTS FUSION MAGNETS

INTRODUCTION

The construction of DEMO, a demonstration fusion reactor, is scheduled to start twenty years hence.
Will the superconducting system of DEMO be simply an extrapolation of the superconducting system of ITER, or is it necessary to prepare for a complete technology mutation?
This has to be considered as a function of the objectives of DEMO which are up to now not completely defined.
This mutation could deal with the superconducting material if A15 materials cannot sustain the magnetic field of DEMO. But even if A15 materials are still on the stage, it is not sure that the major components or choices of ITER should be adequate for DEMO as well: plates, conductor shape, mode of cooling etc...
The final report (september 2004) of the Power Plant Conceptual Study (PPCS), an important study carried out in Europe to prepare for the future, did not dedicate much to the magnet system.
Precious indications are however given in the PPCS report on the magnetic field level which is considered. These indications can usefully guide our approach, it is however important that future activity in this field to be carried out in tight connection with the community of the magnet system. The HTSMAG task is dedicated to the investigation of the possible use of HTS superconductors in the future fusion reactors.

2005 ACTIVITIES

INFLUENCE OF THE MAGNETIC TOROIDAL FIELD ON THE DESIGN OF MAGNET SYSTEMS FOR FUTURE FUSION REACTORS [1]

Regarding DEMO, our investigation has been carried out using the design of the European Power Plant Conceptual Study (EPPCS) model C. It is a tokamak the major radius of which is 7.5 m, compared to the ITER major radius of 6.2 m and a toroidal field of 6.5 T compared to the ITER toroidal field of 5.3 T. In figure 1 is presented a scheme of the radial stack which governs the tokamak main dimensions:

- plasma minor radius
- a distance Δ_{int} integrating the first wall, blanket, neutron shield and TF thermal shield
- the TF radial extension
- the CS radial extension

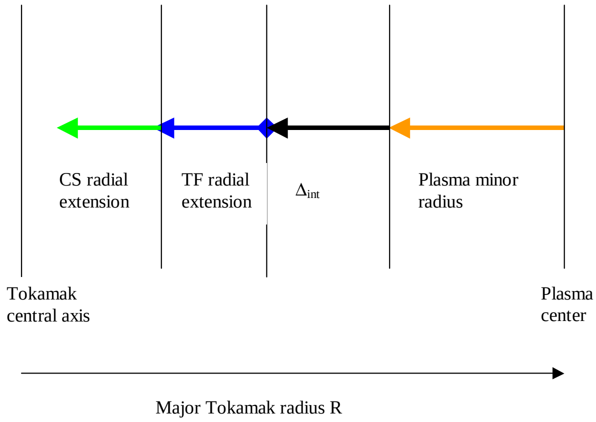


Figure 1: Composition of the tokamak major radius

It is possible to estimate the TF radial extension as a function of the superconducting strand performances. The mechanical properties of the structures are assumed to be the same as in ITER. The maximum magnetic field B_{max} on the conductor is in the range of 13.6 T. From figure 2, it is confirmed that above a non copper current density in the range of 150 A/mm^2, the TF inner leg radial extension is not substantially affected, which means that 150 A/mm^2 is sufficient. Both the Sumitomo Nb_3Al strand and the Oxford Nb_3Sn strand developed in the framework of ITER program, meet this objective but they are at the limit of their capability.

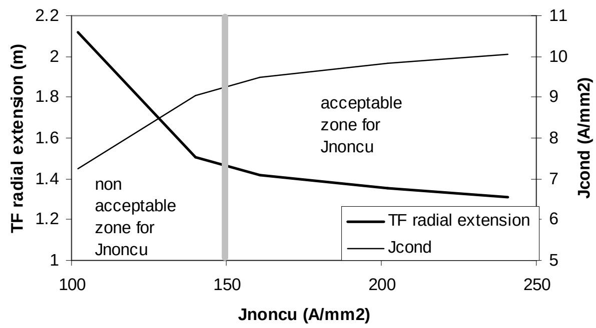


Figure 2: Influence of non copper current density on radial extension in DEMO TF inner leg

In conclusion, for the TF systems of future fusion reactors, the average current density is in the range of 10 A/mm^2 and is driven by the large amount of structures necessary to resist the Lorentz forces. Thereby it is possible to accept superconducting strands with low non copper current density down to 150 A/mm^2, without substantially affecting the TF radial extension of the system. Due to the combined effect of differential thermal contraction and transverse forces arising in large fusion conductors, Nb_3Sn strands developed in the framework of ITER program or Nb_3Al strands are at the limit of their capability at 13.6 T, the envisaged maximum field on the conductor. The conductor concept can certainly be improved to mitigate the effect of the transverse magnetic field on the conductor degradation and even allow higher magnetic field for a demonstration reactor if needed. The improvement in J_{noncu} will be beneficial to the cost by allowing a decrease of the total weight of the superconducting material. Other solutions (Bi-2212 or Nb_3Sn at 1.8 K) can be envisaged but have still to prove their economical profitability.

ESTIMATION OF RECYCLED POWER ASSOCIATED WITH CRYOGENIC REFRIGERATION POWER OF A FUSION REACTOR BASED ON TORE SUPRA EXPERIMENT AND ITER DESIGN [2]

Estimation of power at 4.5 K

The different sources of heat loads are presented in table 1 for both ITER and a steady state fusion reactor. It is assumed that an extrapolation from ITER to the fusion reactor can be done with some confidence if extrapolation rules exist and are sufficiently clear.

It can be considered that P_{st} (steady state losses), for a given plasma elongation, is proportional to the surface of the torus plasma and therefore proportional to Rr, R being the major plasma radius and r the minor plasma radius. P_{st} mainly takes place in the TF system. The thermal radiation component is associated with the surface extension of the TF system. Thermal conduction is associated with the weight of the TF system which is a hollow object, the weight is also related to the surface.

Rr = 12.4 for ITER   Rr=24.65 model B of EPPCS

P_{circ} (due to helium circulating pumps) is proportional to P_{st} in a fusion reactor, which translates that the circulating power is linked to the cryogenic power to be removed by helium circulation. In ITER P_{circ} is proportional to (P_{st}+P_{pl}) (Pl pulsed load). By chance, this term in ITER has the same order of magnitude as the steady state cryogenic power in a fusion reactor. This is the reason why the circulating power will be taken in the fusion reactor at approximately the same level as for ITER.

The heat load on the cold compressors P_{cc} is assumed not to exist in the fusion reactor, supposing that the progress in low Tc superconductors is sufficient to operate the magnets using a liquid He bath at 4.5 K and not at 4.3 K as in ITER.

The power associated with cryopumps dedicated to torus and neutral beam injection (NBI) will be considered in a first approach as proportional to the plasma volume and therefore proportional to Rr^2. As this part is substantial in the 4.5 K balance, it means that for the reactor, more economical means of pumping have to be developed. In ITER the liquefaction power associated for this part has been estimated, taking into account the usual refrigeration capacity of 100 W for 1 g/s liquid.

Rr^2 = 24.8 for ITER Rr^2 =70.7 model B of EPPCS

A 70 kA high temperature superconductor current lead demonstrator for the ITER magnet system has been recently tested. According to the experimental results it is possible to estimate the reduction of the refrigerator power consumption brought by this technology in different operating conditions. In the case of permanent current in the leads which is representative of a fusion reactor and should certainly be available, the reduction factor is 3.7.

Table 1: Steady state 4.5 K heat load compared between ITER and a fusion reactor

	ITER	Extrapolated to fusion reactor
1. Pulsed loads P_{pl}	10.7 kW	≈0
2. Steady state heat load P_{st}	11.9 kW	25 kW
3. Heat load of the He circulating pumps P_{circ}	11.4 kW	15 kW
4. Heat load of the cold compressors P_{cc}	4.5 kW	0
5. Torus and neutral beam injection cryopumps P_{cp}	5.5 kW + 30 g/s (equiv. To 3 kW) total: 8.5 kW	30 kW
6. Liquefaction to cool the current leads P_{cl}	130 g/s equiv. To 13 kW	4 kW
Total	60 kW	74 kW

Estimation of power at 80 K: P_{N2}

The cold power at this level is estimated to 1000 kW in ITER with about 2/3 for thermal shields and 1/3 for the precooling of the LHe plant.

It is assumed that most of the power associated with the thermal shields is dominated by the thermal radiation power, neglecting the conduction through the supports. Both ITER thermal shield systems, the vacuum vessel thermal shield and the cryostat thermal shield, fit the TF system shape. The thermal radiation surface is proportional, at given plasma elongation, to Rr.

Therefore 700 kW is linked to the plasma surface and has to be linearly extrapolated with Rr. Consistently with the following section and the 4.5 K factor of merit, only this part will be taken into account for fusion reactor extrapolation, which gives P_{N2} =1400 kW.

Electrical power for cryogenic refrigeration

P_{st}, P_{circ} ,P_{cc} ,P_{cp} ,P_{cl} and P_{N2} will require a large electrical power at the level of the warm compressor station. This electrical power can be classically evaluated from the cold power using the factor of merit based on an efficiency factor and depending of course of the temperature value at which the cold power is dissipated.

For a cold temperature T_2 and a warm temperature T_1, the Carnot efficiency is:

$$\eta= T_2/(T_1-T_2)$$

In a first approximation the refrigerator global efficiency r is linked to the Carnot efficiency by:

$$r= f\eta \text{ with } f\approx 0.25.$$

A value r=1/250 for the 4.5 K cold power and r=1/10 for the 80 K cold power is assumed based on recent construction of large cryoplants of comparable size.

The resulting electrical power is presented in table 2.

Table 2: From cryogenic power to electrical power in a fusion reactor

Temperature level for cryogenic heat load	4.5 K	80 K
Cold Power	74 kW	1400 kW
Electrical power	19 MW	14 MW

This gives an estimation of 33 MW for the electrical power needed for the refrigerator of a fusion reactor.

CONCLUSIONS [3]

HTS materials can be considered with regard to their higher current density potentiality, which can induce a gain through a decrease of the total weight of the superconducting material. They can be also considered in case the magnetic value of DEMO goes above 14 T.
By extrapolation from ITER cryoplant, a first estimation of the cryogenic power required at 4.5 K for the superconducting system of a steady state fusion reactor is 11 MW, a low value which does not substantially affect the efficiency of the reactor.
Investigations will continue during the second year of activity to estimate the economical impact of a cryoplant operating at a higher temperature than 4.5 K. The operating temperature will be chosen as a function of the HTS (Bi 2212) critical properties in field a temperature.
Design criteria for HTS fusion conductor dimensioning will be explored with a preliminary concept for the conductor.

REPORTS AND PUBLICATIONS

[1] J.L Duchateau, J.Y. Journeaux, F. Millet "Estimation of recycled power associated with cryogenic refrigeration power of a fusion reactor based on TORE SUPRA experiment and ITER design" Nucl. Fusion 46 (2006) S94-S99.

[2] J.L Duchateau "Influence of the toroidal magnetic field on the design of magnet systems for future fusion reactors" Presented at the 15 th International Toki Conference (december 2005, Toki, Japan) To be published in Fusion Engineering and design.

[3] J.L Duchateau et al. January 2006 "task TW5-TMS-HTSMAG first intermediate report Internal report" AIM/NTT-2006.004

TASK LEADER

Jean Luc DUCHATEAU

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

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

e-mail : duchat@drfccad.cea.fr

In close collaboration with DAPNIA and DRFCM departments.

TW5-TMSF-HTSPER

Task Title: HTS MATERIALS FOR FUSION MAGNETS

INTRODUCTION

High Tc superconductors are just coming out of the R&D stage. Long term work will be needed until the availability of such conductors for fusion plant. Among the potential superconducting HTS materials Bi2212 seems the most advanced in term of industrial production as well as suitability for large superconducting magnets. This high Tc superconducting material will be studied in order to identify its engineering performance and the parameters limiting its use. Emphasis will be given in electrical properties with the aim to provide data for the TMSF-HTSMAG program.

The first part of the work will be devoted to the manufacturing of a cryostat insert allowing the critical current to be measured up to 40K. This device will then be used to measure samples having different winding geometries and at different temperatures. The study will be done in tight coordination with the supplier of superconducting material to optimize the reaction cycle of the superconducting phase to produce high magnetic field.

2005 ACTIVITIES

STATE OF THE ART IN Bi2212 SUPERCONDUCTOR PRODUCTION

We have decided to focus our study on the Bi2212 material ($Bi_2Sr_2CaCu_2O_{8-x}$) as it actually provides higher performances than Bi 2223 ($Bi_2Sr_2Ca_2Cu_3O_{10-x}$) under high magnetic field.

The most advanced development in high magnetic field using Bi2212 superconductors has been made between the National High Magnetic Field Laboratory (NHMFL, Florida, USA) and Oxford Superconducting Technology. They have realised a 4 T insert in Bi2212 placed in a compound resistive/Nb_3Sn magnet producing 21.1 T. The conductor used is a round wire. Altogether 2.4 km of wire have been produced. The production has been made in 51 batches of wire, the critical current of which varies from 340 A to 870 A. This shows that the drawing process still needs to be optimized to gain in reliability to produce high performance products. It should be noted that the Oxford Superconducting Technology Company uses Nexans precursors for his production.

The Nexans Company has been working since several years on a 800 kJ SMES (Superconducting Magnetic Energy Storage) operating at 20 K and with a local maximum field of 7 T. The conductor produced by Nexans in length up to 1000 m and contains 85 superconducting filaments in a silver matrix. The outer shell of this matrix is made of AgMg alloy as a strengthening element. The section of this conductor is 4 x 0.25 mm². Its current transport property reaches up to 500 A/mm² at 4.2 K and 20 T as maximum value but the mean value is between 100 and 150 A/mm² at 4.2 K and 20 T.

This is the conductor we will test in our test station once it will be upgraded to allow critical current measurement between 4.2 K and 60 K. Hundred meters of this conductor were delivered free of charge to us by the Nexans company for this purpose.

TEST STATION UPGRADE

The CétacéS test station is dedicated to critical current measurement under high field. Samples of superconducting wires can be tested up to 3000 A in a magnetic field up to 16 T. A thermal regulation allowing measurements between 1.8 and 4.2 K has already been developed. Tested samples are usually Nb_3Sn wires used in VAMAS samples.

A new sample holder has been developed allowing critical current measurement in the 5 K to 60 K range. This special insert is based on a helium gas thermal regulation. Special attention has been paid to limit the thermal gradient in the sample area. The sample temperature is regulated by the mean of two independent systems. The first is a phase separator used to eliminate the liquid helium and adjust roughly the temperature of the gaseous helium. The helium gas is then injected in the sample holder of the test station where it flows trough a heat exchanger for fine temperature adjustment. To limit the thermal losses in the sample area the 500 A current feed trough are made of superconducting ribbons. Extensive simulations have been required to make a satisfactory design and limit the thermal gradient around the sample.

The design study and orders of these equipments have been made in 2005 and will be delivered in 2006. They will be assembled and instrumented in may 2006 and tested in june 2006.

TEST SAMPLE DEVELOPMENT

In parallel to the development of the test station, new types of samples have been designed. A VAMAS like sample holder will be used to measure the critical current of the HTc ribbons. In order to study the influence of residual stresses in the superconducting material these VAMAS like sample holder will be realised in different materials: titanium alloy, aluminium alloy, stainless steel, glass fibre epoxy composite and natural ceramic. A natural ceramic has been selected, called STUMATITE, and preliminary tests took place in order to check that it can be used in a wind and react process. The tests were positive and the ceramic withstand the heat treatment in pure oxygen and does not affect the superconducting material.
A second type of sample has been developed to increase the magnetic field. It is a small double pancake having the same external diameter as the VAMAS. It may produce around 0.25 T and will need to use react and wind technique using ceramic mandrels.

CONCLUSIONS

The main technological developments associated with the task have started and are progressing well. Scientific activities and measurements will start in 2006.

TASK LEADER

Jean-Michel REY

DSM/DAPNIA/SACM/LEAS
CEA-Saclay
F-91191 Gif-sur-Yvette Cedex

Tel. : 33 1 69 08 66 85
Fax : 33 1 69 08 69 29

e-mail : jmrey@dapnia.cea.fr

In collaboration with DRFCM departments.