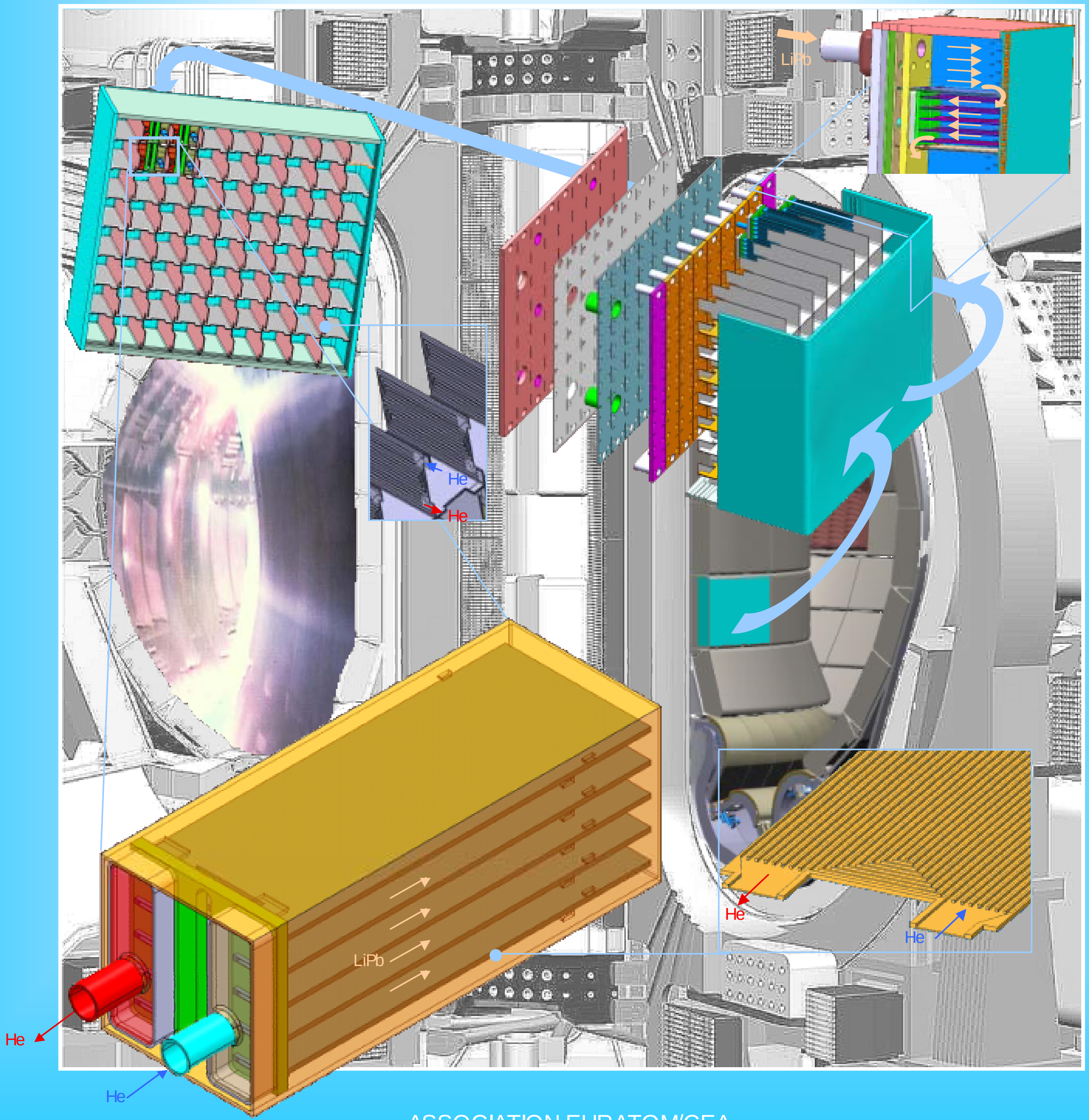
FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA

2003

(full report)

Compiled by : Ph. MAGAUD and F. Le VAGUERES



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Cover : *Exploded view of the Helium Cooled Lithium Lead (HCLL) breeding blanket concept.*

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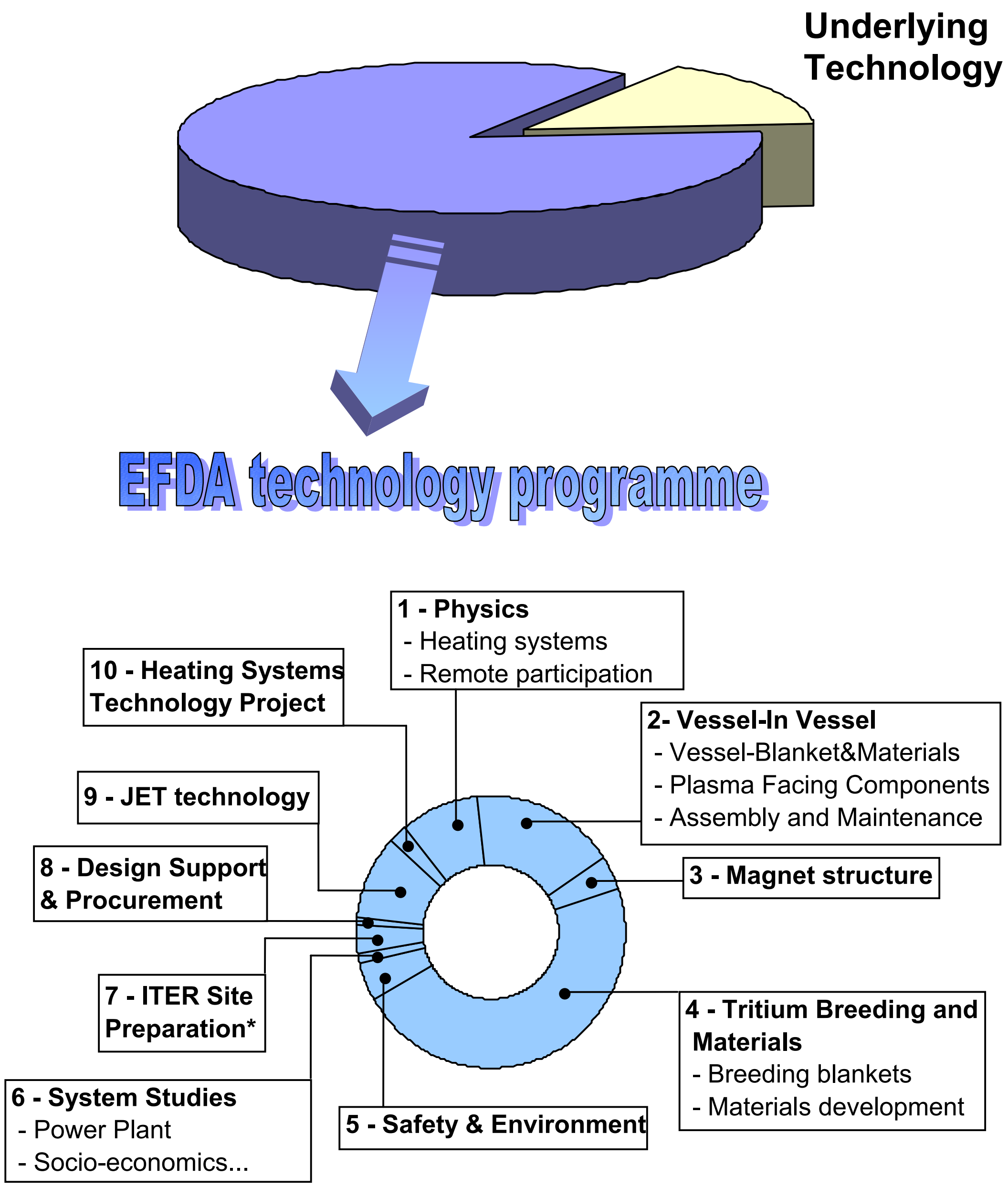

*European ITER Site Study tasks excluded

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 03-1015 to assist the EFDA Close Support Unit 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 include three main activities:

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

2003 ACTIVITIES

DEVELOPMENT OF THE TF COIL HELIUM INLET

This part will be done in 2004.

DEVELOPMENT OF THE CS COIL HELIUM INLET

The CS conductor consists of a Nb_3Sn cable-in-conduit with a central cooling channel, cooled by supercritical helium. The material used for the conductor jacket is stainless steel. The jacket inner diameter is 33.2 mm and the jacket outer square section is 49.9 mm × 49.9 mm. The CS modules are wound as hexa-pancakes (6 pancakes with a single conductor length) and quad-pancakes (4 pancakes with a single conductor length). Helium inlets are at the crossover regions on the inner bore between each double pancake and outlets are at the crossover regions and joints on the outside. The high field region is therefore cooled by the coldest helium. There are three helium inlets for each hexa-pancake and two for each quad-pancake.

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

A Finite Elements Model (FEM) relevant to this proposed design has been built. The mechanical analysis has shown a stress concentration up to 1.45 near the helium inlet reinforced pipe. An optimisation of the design geometry has been done (figure 1) and has led to a reduction of the stress concentration factor from 1.45 to 1.30. This final value corresponds to an overloading up to 12 % with comparison to the maximum regular conductor stress [1].

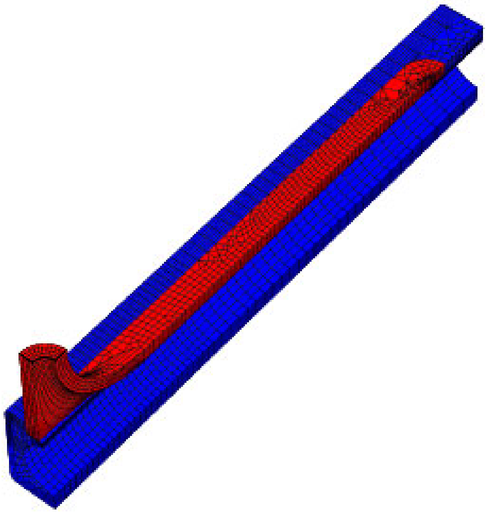

Figure 1 : F.E. Model of CS inlet

DEVELOPMENT OF THE BONDED TAILS OF THE PF COIL WINDINGS

The PF coil conductor consists of a NbTi cable-in-conduit with a central cooling channel, cooled by supercritical helium. The material used for the conductor jacket is stainless steel.

In all PF coils, the winding pack consists of a stack of double pancakes, which are wound two-in-hand. Three types of joints exist in the PF coils. The joints between the two hands of a double pancake, the joints between double pancakes and the terminal joints. All double pancake joints are located in the toroidal direction. Terminal joints are instead in the vertical direction for easy connection to the feeders. At all joints, a structural element is required to transfer the operating hoop load on the conductor. This is provided by conductor tails welded to the conductor jacket and bonded to the adjacent turns of the pancake. The load is therefore transmitted to adjacent turns through shear stresses in the insulation.

The load to be carried by the bonded tails is different for each coil. The highest hoop load on a single conductor occurs in PF Coil 5: the average hoop load on the conductor is about 25 tons, which corresponds to a tensile stress of 144 MPa.

A design was developed using a hollow profiled tail as a result of the stress analysis carried out by CEA Cadarache in the framework of the EFDA Contract 00-541 [3]. The design of the tail arrangement and the winding pack assembly during fabrication can therefore be simplified.

A review of the mock-up design for the tensile fatigue test at ENEA (Brasimone, Italy) was performed to define the most relevant one on the basis of the available cryostat and fatigue machine capacity [2]. A mock-up design using a set of 6 conductors to simulate the winding pack stiffness was selected. The final design of this mock-up, including its supporting structure which allows operation of the press in compressive mode to provide tension in the mock-up will be available in early 2004.

CONCLUSION

This task is devoted to design and fabrication of mock-ups for three different items: the TF helium inlet, the CS helium inlets and the PF bonded tails. During the year 2003, a FEM analysis of the CS helium inlet was performed and an optimisation of the geometry has led to a reduction of the maximum stress concentration level from 1.45 to 1.30. For the PF bonded tails, several mock-up designs have considered and one selected as the most relevant. The manufacture of the mock-ups will be performed during year 2004.

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M50

Task Title: CONDUCTOR R&D - DEVELOPMENT OF NbTi CONDUCTORS FOR ITER PF COILS

INTRODUCTION

The development of NbTi conductors for ITER PF coils has to address several questions:

- Characterisation of NbTi strands in a range of temperature between 4 K and 7 K and in magnetic field up to 10 T.
- Control of the conductance between strands by strand surface coating or by a CuNi internal barrier at the proper level in the range 10^7 $(\Omega m)^{-1}$. The solution has to take into account the temperature of the curing step.
- Connections: design and fabrication procedures have to be confirmed and tested on subsize conductors in the connection test facility JOSEFA. The strand-copper sole contact cannot be treated as for Nb_3Sn due to the absence of high temperature heat treatment.
- The removal of the coating if any has to be specifically addressed.
- The impregnation heat treatment occurring after the connection fabrication of real coils and the final joint soldering has to be considered.
- Conductor behaviour : The operation margin can be assessed on subsize conductors in JOSEFA and the final conductor and joint check can be performed on a full size joint sample in the SULTAN facility at Villigen.

The development can be led on cable and jacket dimensions compatible with the existing fabrication tools (cabling + jacketing) and the existing test facilities. This activity is performed in collaboration with ENEA.

2003 ACTIVITIES

CRITICAL PROPERTIES CHARACTERISATION OF THE TWO CANDIDATE STRANDS FOR THE ITER PF COILS [1]

Work terminated in 2002.

MANUFACTURE AND TEST OF TWO SUBSIZE CONNECTIONS AND CONDUCTORS RELE-VANT TO PF OPERATION [2]

From the two selected strands: Europa Metalli (EM) Ni coated strand and Alstom strand with CuNi barrier, two subsize joint samples (respectively PF1 and PF2) were manufactured in 2001 using the 108 strands conductor lengths.

In 2002 the Joint part of each sample was characterized in the JOSEFA facility:

- DC tests : Temperature of current sharing (T_{CS}), quench temperature (T_Q) and Joint Resistance (R_J) at various fields and temperatures.
- AC losses tests : trapezoidal magnetic field variations with various ramp rates.. Time constant were deduced consistently with R_J. Note that the transverse field orientation is here along the worst direction with respect to joint losses and induced currents, thus simulating the radial field component (i.e. the most demanding component) in the ITER PF coils.
- Stability tests : trapezoidal B pulse at different current, temperature and mass flow rate.

The tests of the subsize samples conductor parts were analyzed. Despite difficulties encountered due to temperature gradients, they showed a better stability for the PF2 (Alstom) sample than for the PF1 (EM) sample, consistently with what was found on the PF-FSJS sample tested in 2002.

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

The facility was upgraded in 1999. The tests of the first subsize NbTi joint sample were performed within year 2001 at various temperature under magnetic field up to 3.4 T and with a transport current through the samples up to 10 kA. The first tests started in the joint position (upper position) in 2001 were successfully completed by tests in the lower position for conductor test during year 2002. The new control command of the test facility was used for the test of both samples. An upgrading of the sample heating system was implemented to avoid temperature oscillations in the beginning of year 2003.

Some actions to reduce the thermal gradient which occurs during the tests along the sample were engaged. Investigations were led to understand the origin of the thermal gradient. The thermal conduction through the supporting tie rods as well as a bad cooling of the sample housing which insure the mechanical containment of the sample were discovered. A thermal insulation of the sample housing from the conduction through the tie rods as well as a thermalization of the housing against the magnet helium bath will be performed at the beginning of year 2004.

The adaptation of the regulation parameters for temperature control will be performed at the end. These modifications will be fully operationnal for the TW3-TMSC-ELRES task devoted for study of controled joint defects during year 2004.

MANUFACTURE OF THE PF FULL SIZE JOINT SAMPLE [4]

The sample was delivered to CRPP for tests on July 10, 2002.

TESTS OF THE PF FULL SIZE JOINT SAMPLE

The PF-FSJS was extensively tested in the SULTAN facility in summer 2002 on the basis of a CEA testing program [5]. CEA and ENEA both participate in the tests of the sample at CRPP (Villigen, Switzerland).

The hypothesis of uneven current distribution in the Left leg (EM) found in 2002 using Rogowski coils signals [6] was cross-checked by performing DC tests simulation with an electromagnetic code (ENSIC) developed by CEA. The result on a chosen run can be seen in figure 1.

Uniform Geometrical Model (UGM) is a model that only take into account the strands orientation in the field while Current Distribution Model (CDM) also include voltage due to current redistribution between petals.

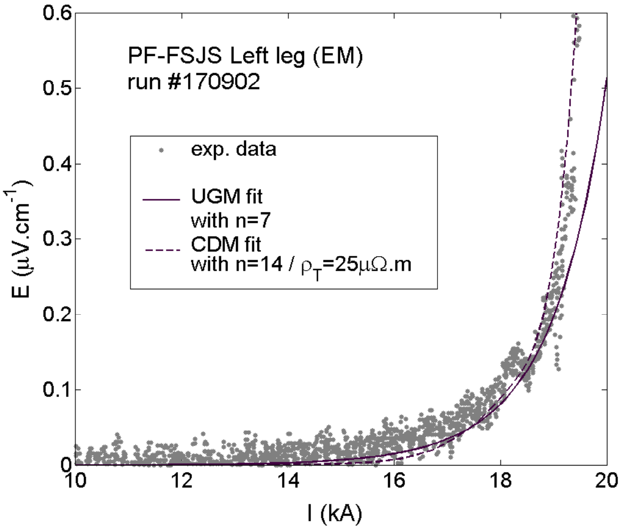

Figure 1 : E(I) curve comparison between experimental and calculated values.
In the CDM calculations, the current distribution found in 2002 using Rogowski coils signal was assumed.

Finally this study assessed the imbalance current distribution between petals in the left leg and a barely homogeneous situation in the right leg (see [7]), likely to be due to an incomplete Ni removal in the joint part.

As a consequence on the ITER PF joints manufacture, the Ni removal operation should be considered with particular care.

CEA analyses on conductor AC losses, joint DC performances and AC losses, as well as on thermosiphon effect between annular and central channels, were presented at the CRPP Workshop in Gstaad [8, 9, 10]. A general overview of the PF-FSJS test results was exposed in an oral presentation at the 6th EUCAS Conference (Sorrento) [11]. A related paper has been accepted for publication in SUST [12].

CONCLUSIONS

The M50 task has been terminated during year 2003. The tests on two subsize conductor samples, each of them using one of the previously selected strands were performed in the JOSEFA test facility. Some extra analyses were performed on the PF-FSJS sample and were found consistent with the work achieved in 2002. A final upgrading of the JOSEFA test facility was engaged to reduce the thermal gradient along the sample and to implement the temperature regulation for the next joint development task ELRES which should be completed within year 2004.

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TW1-TMC-CODES

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

INTRODUCTION

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

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

2003 ACTIVITIES

PROCUREMENT OF SPIRALS AND MEASUREMENT OF PRESSURE DROP IN THE OTHELLO FACILITY

To characterise the thermal and hydraulic behaviour of the Cable In Conduit Conductor (CICC), the friction factor for the channel have to be determined, specially for the central channel in order to define a useful correlation and predict pressure drop as well as heat exchange coefficient influence.

From previous work and tests performed on the Toroidal Field Model Coil central spirals provided by Showa and Cortaillod [1], some spirals were defined to determine the influence of the design parameters. Three different hydraulic (external) diameter were defined (7.6, 8 and 10 mm) as well as the gap length (near 3 mm (S), 5.6 mm (C) and 6.3 mm (I)) for a given turn length of 6.5 mm (twist pitch length varying between 9.1 and 13.5 m, figure 1).

The company Mécaressorts was selected to provide us with the central spiral samples. These spirals were installed into specific tubes to allow the proper measurement of their hydraulic characteristics (except the I7.6 spiral).

These samples were tested with pressurised nitrogen, in the Othello Test Facility, at Cadarache at the beginning of year 2003. By measuring the corresponding pressure drop, the results of the friction factor could be presented in function of the Reynolds number, as in figure 2, and compared with the previously tested spirals (Showa and Cortaillod).

An important result is that the friction factors of the spiral with hydraulic diameter of 8 mm (near 0.35), is near two times higher than those of the spirals with 10 mm hydraulic diameter (f = 0.2) and more than three times higher than Showa and Cortaillod spirals (with hydraulic diameter = 12 mm, and f = 0.11 for Reynolds = 10^5).

As the ITER design for the central spirals has recently changed and could lead to an hydraulic diameter of 9 mm, for some of the coils, three more representative spirals (with this diameter) have been procured and will be characterised (specially here also the friction factors).

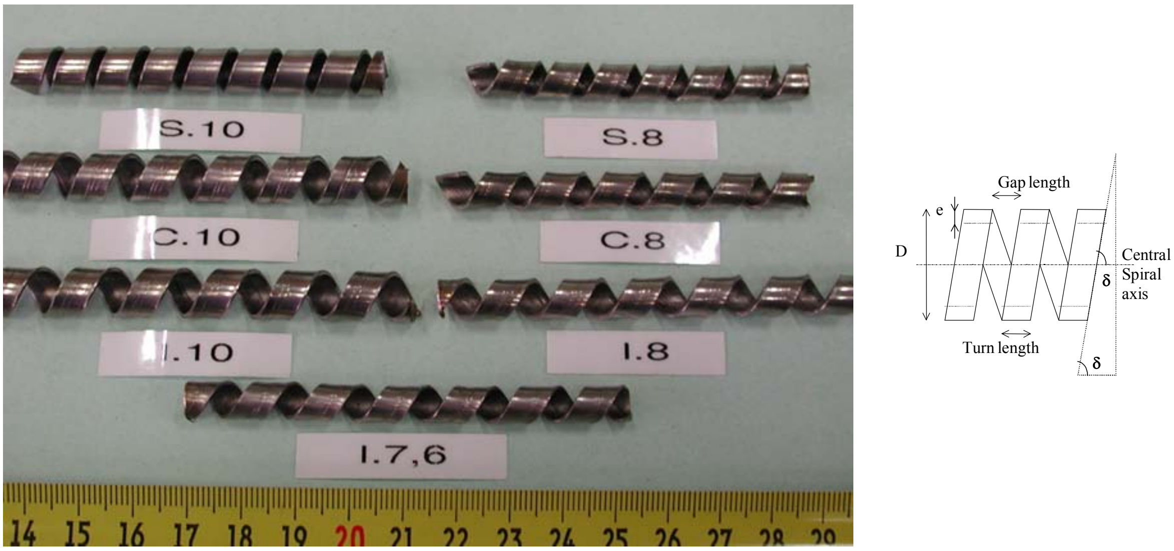

Figure 1 : Central spiral samples

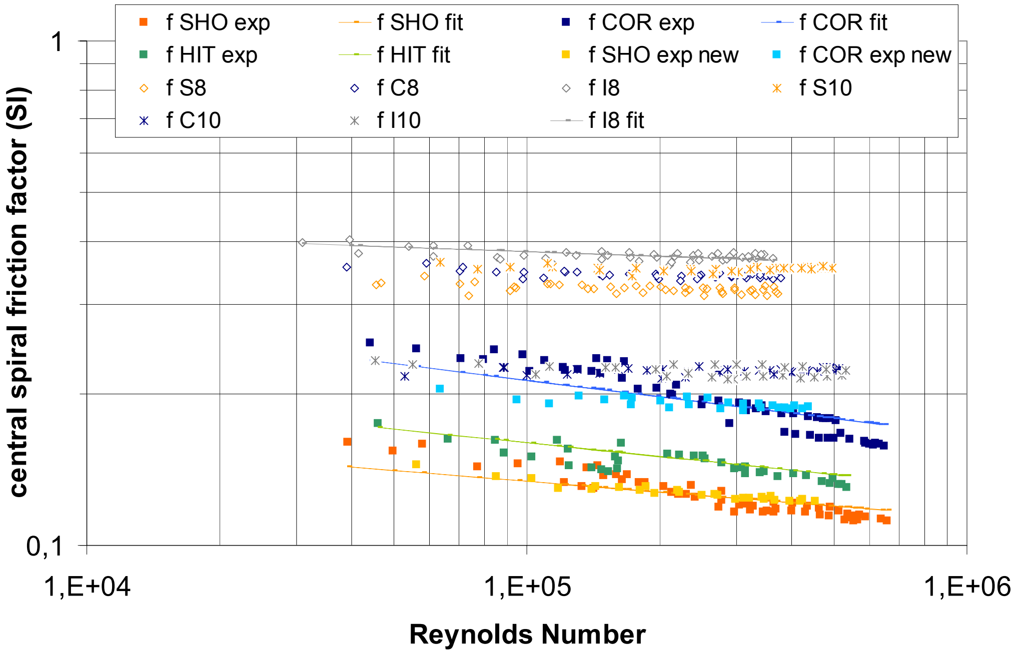

Figure 2 : Central spiral samples friction factor as function of Reynolds number

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

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

- The heat transfer coefficient between the two parallel channels.

- The fluid velocity in each channel.

A numerical and analytical model was developed to predict the temperature evolution along a CICC after a temperature step at the inlet. This model relies on the heat transfer coefficient between the two parallel channels Hai, but also the heat transfer coefficient Haj between the jacket and the water. To evaluate this heat transfer coefficient , an experimental facility operating in relevant Reynolds number at 100°C in pressurised water was defined [2].

A call for tender has shown that the cost of a such installation was not compatible with the allowable budget. A review of the project with reasonable limitations especially on the range of the reachable Reynolds number has led to a new test facility definition operating only at 60°C [3].

The loop named HECOL was manufactured and installed at the beginning of year 2003.

The loop allows a circulation of water at 50°C at nominal Reynolds number. Thanks to the 100 liters tank pre-heated up to 60°C and the 3 way valve, a temperature step is imposed through the conductor sample.

The temperature variations recorded at the inlet and at the outlet allows to derive the conductor heat transfer coefficient. A prediction of the foreseen results with the CEA model was performed [4].

The starting tests performed in july 2003 have checked the correct operating range of the facility and its instrumentation [5].

A test campain was performed in July in collaboration with POLITO institute and first results were obtained. For instance, for a total mass flow rate of 1.5 kg/s and an initial temperature of 60°C, we determined experimentally the evolution of the temperature at the outlet of the conductor (L = 8 m) following a step of -17°C of the inlet temperature (test n° 220703-3). By comparing the resulting evolution of the outlet temperature measured in the two channels (in the annular channel and in the central channel) in combinaison with that obtained by a validated model, we were thus able to assess the average value of these heat transfer coefficients Haj and Hai for a set of thermal-hydraulic conditions.

Figure 3 shows a comparison of the evolution of the outlet temperature in the two channels (in the annular channel and in the central channel) obtained in the experiment (green and blue curves) with that obtained by the model (red and dark blue curves). The best fit is obtained for the following values of the two heat transfer coefficients:

$$\text{Hai} \approx 42000 \text{ W/m}^2\text{.K}$$
$$\text{Haj} \approx 3200 \text{ W/m}^2\text{.K}$$

An upgrading of the facility in order to allow the active recooling after each temperature step and the permanent heating tests was performed. The addition of temperature measurements along the conductor in the annular channel was also decided.

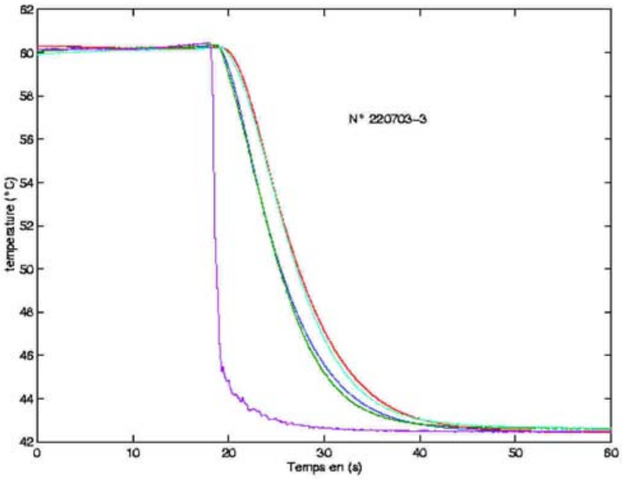

Figure 3 : Comparison of the evolution of the outlet temperature in the two channels (in the annular channel and in the central channel) obtained in the experiment (green and blue curves) with that obtained by the model (red and dark blue curves).
The violet curve is the inlet temperature.

An adaptation of the facility in order to be able to test for cross-checking the spiral samples previously tested in the OTHELLO facility in water with relevant Reynolds conditions. A facility sketch is shown in figure 4.

A new join test campain between POLITO and CEA was performed on the upgraded facility in november. Some unexplainable temperature evolutions along the conductor were measured.

A check of the temperature sensors calibration as well as their location inside the annular area was engaged. A new version of the DAS programmation is also foreseen to increase the measurement accuracy. Complementary tests are planned in 2004.

CONCLUSION

During the year 2003, seven spirals relevant to ITER type conductors with different geometrical parameters were tested in GN2 at room temperature in the OTHELLO test facility. A cross checking of these results is foreseen on the HECOL facility using water during year 2004. These pressure drop measurements should lead to a model of the central channel of ITER type conductors.

For the evaluation of the heat transfer coefficient between annular area and central channel of ITER cable-in-conduit conductors, a dedicated experimental facility HECOL which operates in pressurized water at 60°C was installed. The first test results have been compared to a dedicated code and have led to a first evaluation of the heat transfer coefficient.

However, unexplained temperature evolution along the conductor was observed. It was then decided to upgrade the facility as well as its instrumentation in order to increase the measurement accuracy and analysis possibilities. Complementary tests are planned in 2004 to help for explanation of temperature evolution along conductor.

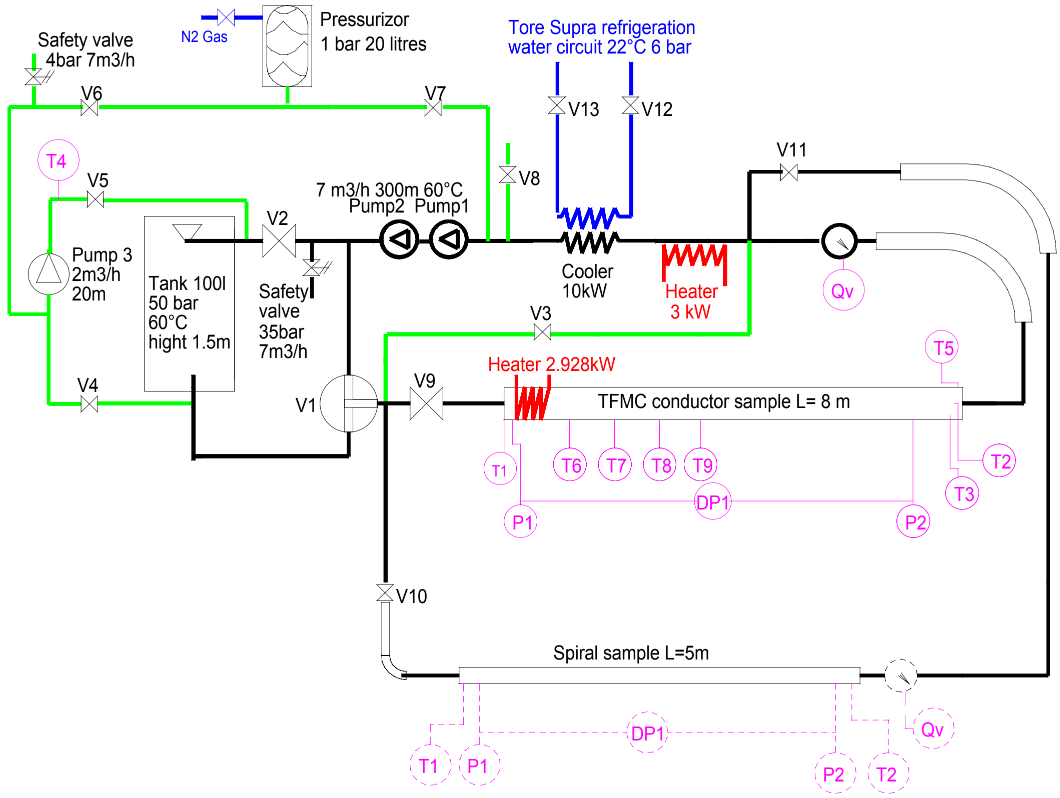

Figure 4 : HECOL facility scheme

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TW1-TMC-SCABLE

Task Title: CABLE AND CONDUCTOR CHARACTERIZATION Determination of critical properties and losses of superconducting strands and cables for fusion application

INTRODUCTION

This task aimed at an extensive characterization of three types of NbTi strands. Those strands being candidate for the ITER PF Coils conductors, a detailed database on their critical properties in the PF coils temperature and magnetic field operating range was needed. One strand was provided by the Bochvar Institute (Russia) and comes from the production used for the Poloidal Field Coil Insert conductor, to be tested in Naka (Japan) in 2005.

The two other strands come from the production used in task M50 for the Poloidal Field Full Size Joint Sample (PF-FSJS) conductor. One was Ni-plated and provided by Europa Metalli and the other had a CuNi internal barrier and was provided by Alstom. Some unexpected results in DC tests [1] led us to extend a previous characterization [2] to only the PF-FSJS operating range. In this goal, the CEA Variable Temperature Cryostat (VTC) facility was used in magnetic field provided by the Grenoble High Magnetic Field Laboratory (GHMFL).

2003 ACTIVITIES

GEOMETRICAL ANALYSIS OF THE BOCHVAR STRAND

A micrography (figure 1) of the strand cross-section has been achieved together with a Cu/nonCu ratio measurement by acid dissolution and weighting (1.46 was found).

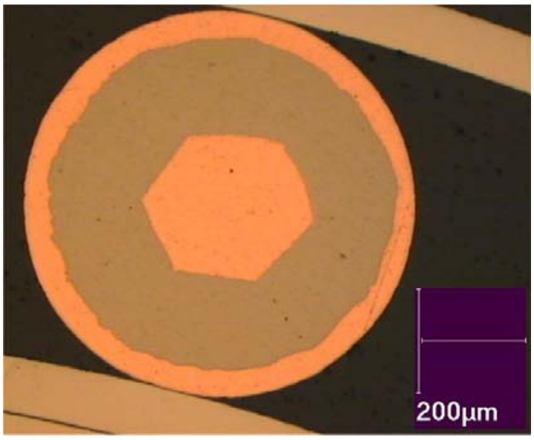

Figure 1 : Micrographic view of the Bochvar strand cross-section

VTC FACILITY UPGRADE AND QUALIFICATION

As it was observed that it was impossible to stabilize and homogenize correctly the strand temperature, an upgrade of the VTC facility turned out to be necessary. This upgrade included modifications of the hydraulic circuit, modification of the strand instrumentation, replacement of the data acquisition system by a National Instruments DAS and was followed by a qualification campaign carried out at Cadarache. Qualification of the testing arrangement was finally achieved with severe temperature criteria regarding stability (20 mK) and gradient along the mandrel (30 mK). All criteria were met in the NbTi temperature range (4.2 K – 7.5 K).

STRANDS CRITICAL PROPERTIES MEASUREMENTS

All three strands were characterized namely:

- in a broad range for Bochvar strand: $T \in [4.2\ K\text{-}7\ K]$; $B \in [3\ T\text{-}10\ T]$; $I_C \in [5\ A\text{-}450\ A]$,
- in the PF-FSJS (rescaled) operating range for EM and Alstom strands: $T \in [4.2\ K\text{-}7\ K]$; $B \in [3\ T\text{-}10\ T]$; $I_C \in [5\ A\text{-}100\ A]$. Moreover T_{CS} measurements were performed for direct comparisons in dedicated conditions corresponding to chosen PF-FSJS DC tests runs (approximately 6 for each sample). This qualified the facility for V(T) curves tests too. Some V(B) curves (so-called B_{CS} tests) were performed too.

An example of $J_C(B)$ curves is shown in figure 2. A consistent fitting was found with the “Bottura’s formula” for all three strands. Comparisons with previous characterization measurements on these strands showed:

- A good agreement with VNIINM tests (Bochvar strand) except at high or low fields. Probably due to scattering between billets properties, error bars should be considered in the future.
- Some discrepancies with 2001 CEA and University of Twente results. As it happens at high temperatures, this is likely to be due to DAS errors in previous temperature measurements.

For the two PF-FSJS strands, a comparison with DC tests performed in SULTAN assessed the crucial role of self-field in the difference between strand and conductor performances.

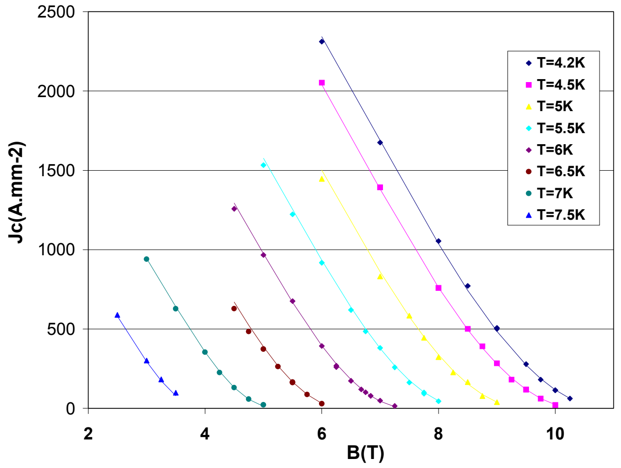

Figure 2 : Bochvar strand critical current density versus magnetic field for dedicated temperatures - Fitting are also shown

Besides, confrontation with ITER PF coils criteria (namely PF1 and PF6 ones) gave the following results :

- all strands met the J_C(4.2 K,5 T) criteria of 2900 mm^{-2},

- none of the three strands met the temperature margin of 1.5 K (all lie between 1.23 and 1.3 K). This is mainly due to the curvature of J_C(T) at low current densities (see figure 3).

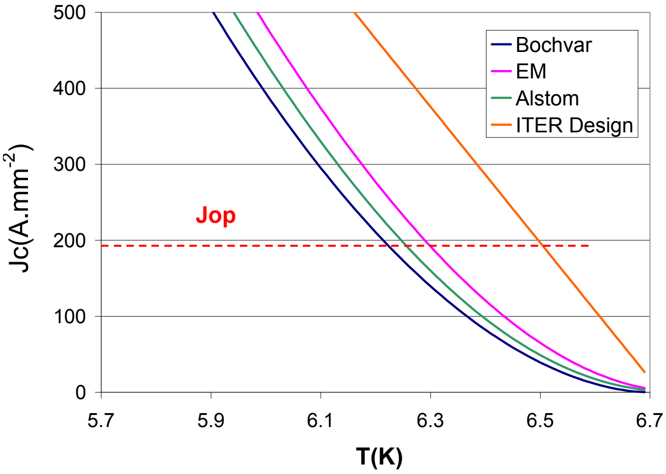

Figure 3 : Comparison of the three strands performances with ITER Design parameters for PF1 and PF6 Design - Operating conditions
($B = 6$ T, $J_{OP} = 196$ A.mm^{-2} and $T = 5$ K)

CONCLUSION

During the year 2003 different operations were achieved in the framework of the SCABLE task:

- An upgrade of the VTC was achieved followed by a qualification of the facility for critical current (V(I) curves) measurements with more severe temperature criteria. Qualification for T_{CS} (V(T) curves) measurements was also achieved in GHMFL.

- An extensive critical properties characterization campaign for three ITER PF coils candidate strands in dedicated [B,T,I_C] ranges was undertaken. The one used in PFCI showed consistent behaviour with a good agreement with VNIINM tests. EM and Alstom strands showed the central role of self-field in the PF-FSJS conductor behaviour.

- A discussion on ITER Design criteria pointed out that all strands meet the J_C(4.2 T,5 T) criterion and none the ΔT_{MARGIN} of 1.5 K (PF1 and PF6 coils). This is mainly due to the non-linear J_C variations with temperature.

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TW1-TMS-PFCITE

Task Title: POLOIDAL FIELD CONDUCTOR INSERT (PFCI)

INTRODUCTION

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

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

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

CEA has been deeply involved in the design and analysis of the ITER PF coils through EFDA task M50 [1] and contract 00/541 [2]. The work of CEA within task PFCI covers the following items :

- Participation to definition and review of the test procedure.
- Participation to operational campaigns of the PFCI and reporting of the results.
- Analysis of the results, including thermo-hydraulic, electro-magnetic, and structural simulations of the real operating conditions of the coil.
- Analysis of impact of results on ITER PF coils design.

The NbTi cable for the PFCI was delivered to Ansaldo in August 2002 from the Russian Federation, the jacketing was completed at Ansaldo in June 2003. Fabrication of the coil at Tesla (UK) is expected to be completed by June 2004. Final acceptance and shipment to the CSMC test facility are foreseen in July 2004, and assembly in the Naka facility during September-November 2004. Testing programme at JAERI should start in February 2005.

2003 ACTIVITIES

For 2003, our activities were first to collect updated informations on the conductor and coil designs, as well as on the preliminary proposals for the testing programme (PFCI Morioka meeting, 22 Oct. 2003). Since the coil tests were planned not earlier than 2005, the definition of the final testing programme could be postponed to 2004, while the coil instrumentation had to be finalized on early 2004.

We participated actively to the discussion on the coil instrumentation, calling for the use of two orthogonal pick-up coils to measure the full joint magnetization, which has now been retained by the Test Group Leader in his January 20, 2004 memo (see figure 1). We also proposed to use coil discharges with different time constants in order to help discriminating the losses due to the radial field component from those due to the vertical field component. We proposed to modify the location of the voltage taps used to measure the joint resistance. All these proposals were sustained by the work already performed by CEA within task M50 on sub-size and full-size NbTi conductor and joint tests [1], as well as within contract 00/541 on analysis of the ITER PF coils [2].

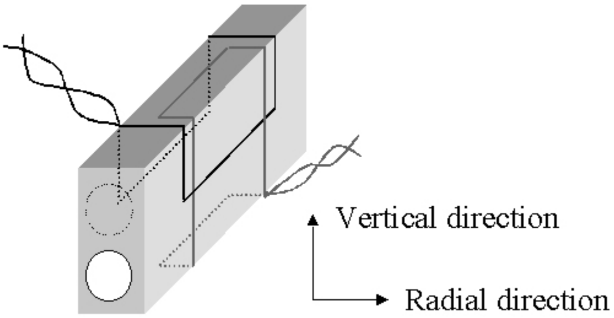

Figure 1 : Location of magnetization pick-up coils on the PFCI intermediate joint (directions refer to coil)

We have improved the model developed in contract 00/541 for the ITER PF coil joints, in order to identify the critical operating conditions of these joints. This model calculates the joint AC losses and the associated temperature increase during an ITER scenario. Particularly of concern is the total current carried by the conductor sub-cables when the loop current (produced by the variations of the radial magnetic field component) adds to the transport current to overload sub-cables.

The temperature margin (with regard to current sharing temperature) is then a good tool to estimate the operating margin of the subcables in the joint. The results of these analyses were provided to the European representative to the PFCI Test Group for a presentation at the Morioka meeting. This work has shown that the situation of the PF6 joints looks acceptable (i.e. the temperature margin remains above the ITER nominal value of 1.5 K, see figure 2), while it becomes critical for the PF2 joints when considering the addictive effect of the loop current to the transport current, which reduces the temperature margin below 0.5 K (see figure 3).

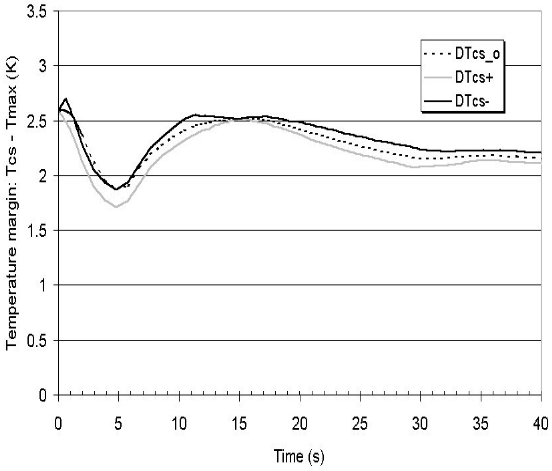

Figure 2 : Computed evolution of temperature margin in ITER PF6 bottom joint during the first 40 s of plasma scenario #2 (copper RRR = 6) : with transport current only (DT_{cs_o}), with adding or subtracting algebraically the loop current (DT_{cs+} and DT_{cs-} , respectively)

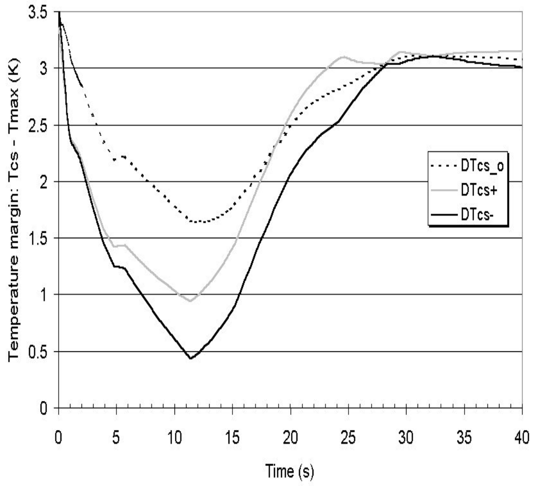

Figure 3 : Computed evolution of temperature margin in ITER PF2 top joint during the first 40 s of plasma scenario #2 (copper RRR = 6). See Fig. 2 for legend

This model will help to define a relevant testing programme with regard to the PFCI intermediate joint, by reproducing the most critical operating conditions of the ITER PF joints (i.e. the associated variations of magnetic field).

Although the conductor of the PFCI is relevant only to the PF1 & PF6 coils and not to the PF2 coil (which conductor contains a much lower NbTi area), extrapolations to the PFCI could be envisaged.

CONCLUSIONS

The Poloidal Field Conductor Insert is under fabrication in industry and should be tested in the CSMC facility (Naka, Japan) in February-April 2005. CEA is participating in the definitions of both the PFCI instrumentation and the testing programme.

The model used for the analysis of the ITER PF joint behaviours has been improved to take into account the effect of the loop current induced by the variation of the radial magnetic field. This model will be a useful tool for the assessment of the testing programme as well as for the PFCI test analysis.

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TW2-TMST-TOSKA

Task Title: TFMC TESTING WITH THE LCT COIL

INTRODUCTION

In the framework of the TOSKA Task, CEA was asked by EFDA to participate to the testing of the ITER Toroidal Field Model Coil (TFMC) in the TOSKA facility at FZK in Karlsruhe and to the testing of the ITER Poloidal Field Conductor Insert Full Size Joint sample (PFCI-FSJS) in the SULTAN facility at CRPP in Villigen. The TFMC was tested in 2001 and 2002 but an important activity still took place in 2003 in particular to evaluate the critical properties of the conductor, aiming at final decisions for the ITER conductors of the TF system and of the CS system as well.

2003 ACTIVITIES

TESTS OF THE ITER TFMC

Analyses of the phase II tests

The analyses of the measurements performed during the phase II tests of the ITER TFMC, carried out in 2002, have been completed. The main conclusions of these analyses were presented at the 17th TFMC Test and Analysis meeting, organized by CEA at Cadarache on 4 and 5 February 2003 and attended by 27 participants, mainly from the EU laboratories. The representatives from CEA made 9 presentations dealing with:

1. Thermohydraulics

1.1 Heat exchange in the joint and in the conductor

The mass flow fraction circulating in the bundle regions between which the heat exchange take place in the TFMC joints, is only 25 %. This is the reason why the power which can be exchanged between two TFMC joints is small. Typically for 100 W in one of the circuits, only 20 % can be transferred to the other circuit. This has been observed recently during the PF_FSJS experiment and checked again during a Tcs preparation experiment in TFMC phase II.

1.2 Thermohydraulic model of the ripple losses at very low current (4 kA)

In the TFMC, due to the 600 Hz power supply voltage ripple, the plates constitutes a secondary whose primary is the TFMC winding. It was difficult to electromagnetically model this ripple because the 600 Hz voltage component of the power supply is difficult to estimate, and because the model is based on the leakage inductance between plates and winding which is impossible to evaluate with precision.

The thermohydraulic manifestation of the ripple was observed in particular during a long run at very low current (4 kA) to eliminate any contribution from the joints.

It mainly consists in a global load of 40 W on the plates. There was no common agreement about extrapolation to ITER and how much cold losses can be awaited from this phenomenon.

2. TFMC thermal behaviour during fast discharges [1], [2]

The heat diffusion from plates to conductor during a fast discharge is now correctly modelled by gandalf.

This process is driven by the conductor insulation conductivity. The observed heat transfer to helium is slower than expected due to insulation thermal conductivity lower by a factor 6 from the epoxy thermal conductivity.

This is not well understood and can be due to the multi layer arrangement of the insulation; this has important consequences for ITER especially the fast discharge and deserves an experimental crosschecking on short samples.

3. TFMC joint resistances

No evolution of TFMC inner joint resistances was observed between Phase I and Phase II experiments at 80 kA in TFMC without current in LCT. The slight increases of the TFMC inner joint resistance with current in LCT follow the expected magneto-resistance effects.

4. TFMC mechanics [3]

In the phase II tests, the TFMC, operated simultaneously with the LCT coil, was submitted both to in-plane and out-of-plane loading, whereas in Phase I tests it had been submitted to in-plane loading only. The coil behaviour was found to be fairly well predicted by the FEM model of the test configuration, initially built by industry and further developed by FZK, as well in the single coil tests as in the two coil tests. The accuracy of the displacement predictions was within 15 % for most displacement transducers and within 20 % for the equivalent stresses, measured with rosettes strain gauges. Stresses relevant to that which will arise in the ITER coils could be applied without any noticeable damage to the coil.

5. TFMC conductor performances [4]

During the TFMC tests, it was discovered that the strain sensitivity of Nb_3Sn in large Cable in Conduit Conductors (see figure 1) was larger than expected. Moreover this strain was found to be a quasi linear function of the Laplace force per meter applied to the conductor.

The critical current density of Nb_3Sn is a function of this strain. Three presentations were done by CEA about this crucial point using different models and in particular the code ENSIC developed at CEA. During this meeting a global quantitative agreement was found between the participants about this effect which is presented in figure 2.

Whereas before TFMC experiment, the equivalent thermal strain was estimated at –0.61 %, the ITER TFMC tests show that for a Laplace force relevant to the ITER TF coil conditions, the equivalent thermal strain in the conductor will be in the range from -0.76 to -0.79 %. Overall because also due to a too pessimistic estimation of the effective field on the conductor, the degradation of the conductor is equivalent to a loss of 0.3 K in temperature margin.

At the end of the meeting, Jean-Luc Duchateau was nominated TFMC Testing Group Leader due to the retirement of Albert Ulbricht from FZK with the objective to organize the publication in a journal, collecting all the TFMC results and teachings.

Figure 1 : TFMC conductor (Φ = 40.7 mm)

In 2003 the 10 chapters composing the publication have been written and internally reviewed. It is expected that the draft publication be sent to the Fusion Engineering and Design journal in March 2004 and include about one hundred pages.

TESTS OF THE PFCI-FSJS

Unfortunately, the tests of the PFCI-FSJS could not be performed in 2003, since the manufacture of this prototype sample by Tesla (UK) was delayed, although the contract had been placed by EFDA in late 2002.

The delivery of the sample in Villigen has been achieved in February 2004 and the tests are now scheduled to start in March 2004.

CONCLUSION

The tests of the ITER TF model coil were very fruitful, due to a strong involvement of the EU Associations, demonstrating that this coil design relies on sound concepts, suitable for the ITER TF coils.

Nevertheless, these tests pointed out a decrease of the achievable current density when increasing the Laplace force applied to the conductor, which calls for a revision of the design of the ITER Nb_3Sn conductors. The previous criteria were in some cases too optimistic and in some other cases too pessimistic in a range which can overall correspond to a decrease of the temperature margin by 0.3 K to 0.4 K. This decrease can be easily compensated, keeping the same size of conductor and a stainless steel jacket, by taking benefit of the progress in superconducting materials critical properties during these last ten years. On the other hand, the manufacture of the PFCI-FSJS was delayed, postponing the tests in 2004.

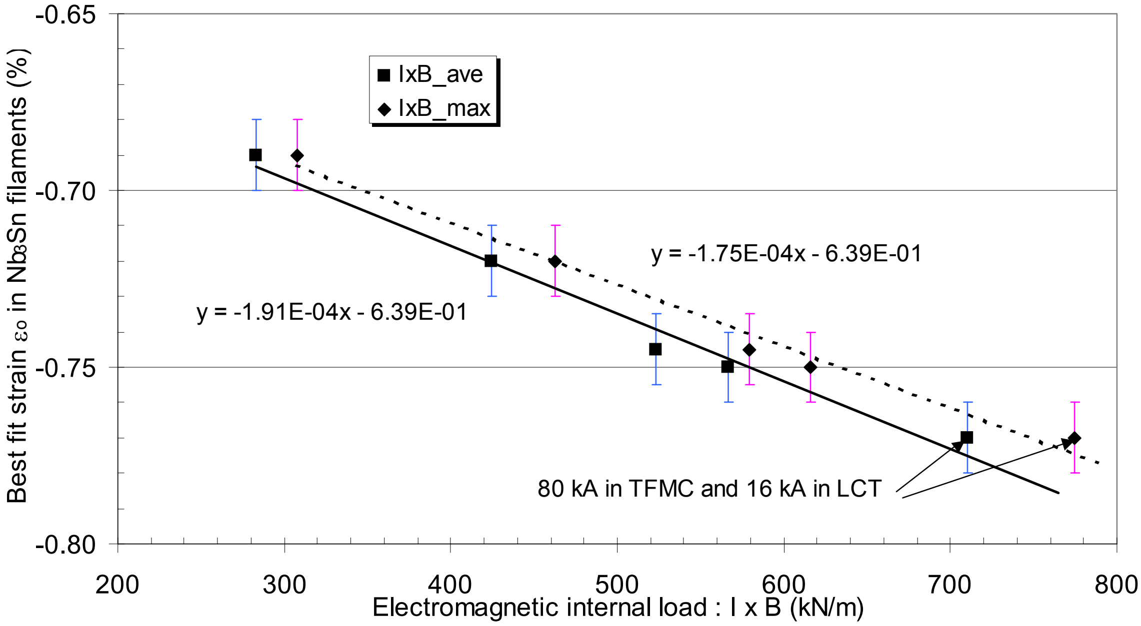

Figure 2 : Influence of Laplace forces on ε_0 in TFMC experiment

REPORTS

[1] S. Nicollet, J.L Duchateau, H. Fillunger, S.H Park, G. Zahn. Experimental behaviour of the toroidal field model coil: application to ITER transient regimes. Presented at Conference CEC (Anchorage, USA, September 2003). To be published.

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[3] P. Libeyre et al Mechanical Tests of the ITER Toroidal Field Model Coil. Presented at MT18 Conference (Morioka, Japan ,October 2003) To be published.

[4] J.L Duchateau et al Exploring the limits of a very large Nb_3Sn conductor: the 80 kA conductor of the ITER Toroidal Field Model Coil. Presented at Conference EUCAS 2003. (Sorrento, Italy, September 2003). To be published.

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TW3-TMSC-ELRES

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

INTRODUCTION

Task ELRES aims at investigating experimentally the effect of the joint-to-strands resistance values and of different percentages of joint-to-strand connections on the possible variation of the "global" V-I characteristic of a NbTi ITER-type cable, limited at the last but one stage. The samples will have different joint resistances and different fraction of directly connected strands. This activity also investigates the effect of the strand-to-strand transverse resistances, which have been shown to change considerably with cycling and to affect the values of critical current and "n" parameter of s/c cables. Five joint samples have to be fabricated and tested, each sample contains two different legs which leads to test in fact 10 different legs. The first three joint samples are fabricated using already existing conductor lengths remaining from task M50. Extra conductor lengths (with a different cable void fraction) are fabricated in industry using already existing NbTi strands. The last two joint samples are fabricated using this new conductor. The samples will be tested (V-I or V-T characteristics) in the JOSEFA facility at Cadarache. Complementary tests will be carried out to measure conductor interstrand resistances.

The task activities can then be summarized as follows:

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

2003 ACTIVITIES

DEFINITION OF SAMPLES AND OF TESTING PROCEDURE

We had first to write a document to define the sample designs as well as the testing procedure, this document was agreed by the EFDA-CSU [1].

For the sake of simplification, it was decided to use the same overall design as the one of task M50 samples (see figure 1), except in task ELRES each sample is made of two different conductor legs: one leg makes use of the M50 Alstom NbTi strand (with an internal CuNi barrier), while the other leg makes use of the M50 Europa Metalli NbTi strand (with Ni plating). This choice allows to test two different conductors (i.e. having different interstrand resistances) with only one sample.

Figure 1 : Picture of a M50 sample showing the conductor joint on left and the bolt sample terminals on right (a pen is put for scale)

The joint also is fabricated similarly as in task M50, according to the CEA twin-box concept, using copper-steel joint boxes in which the cable is compacted down to a void fraction of about 25 % (see figure 2). The unconnected area of strands in the joint corresponds to a defined unconnected length of cable, which is referred to the last cabling twist pitch of the cable as follows : 0 % (reference), 25 % (serious degradation), 50 % (major degradation).

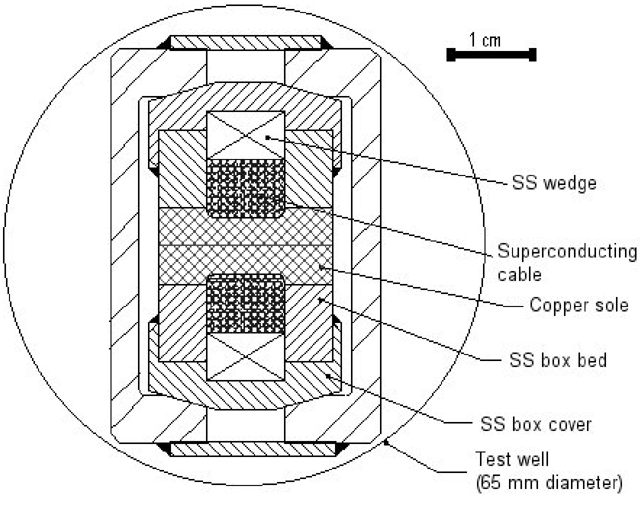

Figure 2 : Sketch of the conductor joint cross section

Measurements of critical current and current sharing temperatures (i.e. V-I curves or V-T curves, respectively) are planned at various levels of magnetic field (1.4 T, 2.4 T, and 3.4 T) and of transport current (from 2 to 6 kA). Effect of mass flow rate (nominal 0.2 g/s) is included. The testing program can be adapted to either virgin or cycled samples. This issue will be resolved by preliminary AC losses tests on M50 cycled samples [1]. Separate measurements of interstrand resistances will be required to fully characterize the tested samples.

PRELIMINARY QUALIFICATION OF FABRICATION PROCESSES

In the case of the EM strands, the nickel plating must be first removed to recover a pure copper external surface. In task M50 subsize samples as in the PF-FSJS, this operation was performed mechanically (using a metallic brush), while it was intended here to use an electrochemical process (i.e. a reverse electrolyse) in order to ensure a better uniformity of contact resistances. However, qualification trials by CEA showed unsatisfactory results with this new process (eventually associated with a mechanical brushing) as concerns the scattering of the contact resistances (see table 1) [2]. Therefore the "old" mechanical abrasion was finally retained for the ELRES sample preparation.

Table 1 : Experimental single strand-copper sole contact resistances (Ni plated strand)

Strand contact preparation (number of samples)	Copper sole preparation	Initial DC resistance (average – scattering)	DC resistance after HT (210°C x 1h) (average – scattering)
Brushed + silver plated (5)*	Silver plated	85 nΩ - 71 %	42 nΩ - 96 %
Brushed + silver plated (2)	Silver plated	181 nΩ - 54 %	67 nΩ - 84 %
Brushed + electrolytic Ni removal + silver plated (3)	Silver plated	140 nΩ - 33 %	31 nΩ - 100 %

(*) Old M50 samples.

In order to get a well controlled degradation of the joints, a real electrical insulation between strands and copper sole was retained. Qualification trials by CEA have led to place two thin (75 μm) insulating Kapton foils in between the cable and the copper sole inside the joint box (see figure 2), to ensure a perfect insulation after a heat treatment (HT) simulating the joint soldering process, and after a LN2 thermal shocking (at 80 K). The only drawback of this method is the decrease of the cable void fraction in the insulated area down to 21 % [2].

FABRICATION OF NEW CONDUCTORS

Using remaining NbTi (Alstom and EM) strands from task M50, new conductor lengths (about 2 x 10 m) have to be fabricated to complete task ELRES. This fabrication includes the multi-stage cabling of 108 strands as well as the compaction of the cable inside a 316L steel jacket. The specifications for this fabrication have been written by CEA [3]. The final void fraction of the cable has been fixed to 32 % (slightly lower than the 36 % of the M50 conductors) in agreement with the EFDA-CSU, so as to introduce a variation in the interstrand resistances. Following a call for tender launched in Europe, the contract for the manufacture of the conductor lengths was signed with the NEXANS company.

STATUS OF THE TASK AT THE END OF 2003

The fabrication of the samples using existing M50 conductors had to be stopped due to cracks detected in the welds between the steel parts (joint box–joint cover, conductor jacket–joint box). After analysis, it turned out that this phenomenon, not seen so far on the M50 samples, could be due to the use of a wrong filler by the welder. The repair of all the samples will then require a local machining of the polluted welds and a new welding.

The fabrication of the new conductors by NEXANS was slowed down due to difficulties they encountered to realize on spare NbTi strands the twist pitch lengths specified for the different cabling stages, although first trials with copper strands were correct. The analysis of the problem led them to slightly modify the cabling machine as well as to increase the pulling force ; last trials looked promising.

The modification of the JOSEFA facility (use of an independent heater on each sample leg) turned out to be not so simple, particularly temperature oscillations were found at low mass flow rates (below 0.4 g/s), also some heat leaks were observed. The cryogenic part of the facility had then to be modified or repaired. In addition, tests with the Variable Temperature Cryostat (see task SCABLE) showed that the data acquisition system (DAS) used in JOSEFA was not accurate enough for critical current measurements (see task M50 [1]). Therefore, it was decided to install a new DAS on JOSEFA, based on a 16-bit National Instruments system controlled with Labview. This system was delivered at the end of 2003.

CONCLUSIONS

Although the sample design was completed and accepted mid March 2003, no sample could be fully fabricated by the end of 2003. The delay was due to the need to first qualify specific fabrication processes such as the Ni removal and the insulation of the strand-copper interface, a delay in the fabrication of the mechanical components of the samples in industry, and last problems encountered with the welds of the steel parts of the samples.

In the meantime, the first tests of the JOSEFA facility called for an improvement of the cryogenic system as well as for a full change of the data acquisition system, which were both initiated in 2003. The fabrication of the new conductors by NEXANS also led to difficulties in the cabling which prevented them to deliver the ordered lengths of conductor in 2003.

In the beginning of 2004, the already fabricated samples should be repaired and instrumented, the JOSEFA facility should be improved and tested, and the new conductors should be delivered, so that the task should be completed by the end of 2004.

REPORTS AND PUBLICATIONS

[1] D. CIAZYNSKI and P. DECOOL, "Task TW3-TMSC-ELRES : Milestone #1 : Definition of Samples and of Test Procedure," CEA Note DRFC/STEP, AIM/NTT-2003.007, 13 March 2003.

[2] P. DECOOL, H. CLOEZ, " Task ELRES : Qualification of Nickel Removal and Insulation Processes," CEA Note DRFC/STEP, AIM/NTT-2003.051, 10 Dec. 2003.

[3] P. DECOOL, "Task ELRES : 108 Strand NbTi Conductor Specification," CEA Note DRFC/STEP, AIM/NTT-2003.021, 28 April 2003.

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CEFDA02-663

Task Title: ITER CRYOPLANT AND CRYO-DISTRIBUTION DESIGN

INTRODUCTION

The main objective of this task (EFDA 02-663) is to provide input information for establishing the final dimension details of the main tokamak complex and the cryoplant buildings, which are time-critical buildings for ITER construction and to develop further details for the cryoplant design.

The task was broken down as follows (*see Report 1*).

- Establishing the design of the cryolines and Cold Valve Boxes (CVBs) for the distribution of the cryogenic fluids to 10 Torus cryopumps.
- Development of a wide range of working characteristics of the LHe plant in order to study its reliable operation over the full range of plasma scenarios, including cool-down after fast energy discharge from the TF coils.

2003 ACTIVITIES

The work of this task was performed with an alternation of working period and progress - review meetings between le Service des Basses Températures (SBT) at CEA-Grenoble (France) and Cryogenic Group from ITER-IT, located in Naka (Japan) and followed by the EFDA/CSU responsible officer from Garching (Germany).

DESIGN OF CRYOLINES AND COLD VALVE BOXES

Conceptual designs for cryolines and CVBs answer to ITER requirements and are based on classical and proven technology.

The cryoline report (*see Report 2*) summarises the conceptual design and the assembling procedure of the Torus cryopump cryolines and manifolds which will be composed by 46 fully prefabricated modules classified in 4 main categories : T-section, curved, elbow and straight line. The compensation system for thermal contraction (300 – 4 K) is adapted to the module design with axial compensation mainly done by external working pressure bellow and radial compensation done by flexible hoses for elbows or standard bellows for T-section. Each module contains 6 internal tubes and one 80 K thermal shield inside a vacuum jacket of about 500 mm in diameter.

The CVB report (*see Report 3*) summarises the conceptual design and the assembling procedure of the CVBs.

Each CVB within a vacuum enclosure of about 1200 mm, contains several internal piping with tube bend design (avoiding the use of bellows wherever possible), one 80 K thermal shield, MLI (multi layer insulation) and a dedicated number of valves, safety valves, sensors to control the supply and return helium cooling flow for the cryopumps.

For both cryolines and CVB design, the thermo-mechanical calculations have given the corresponding heat loads and have validated the mechanical design mainly based on the CODAP or CODETI French codes.

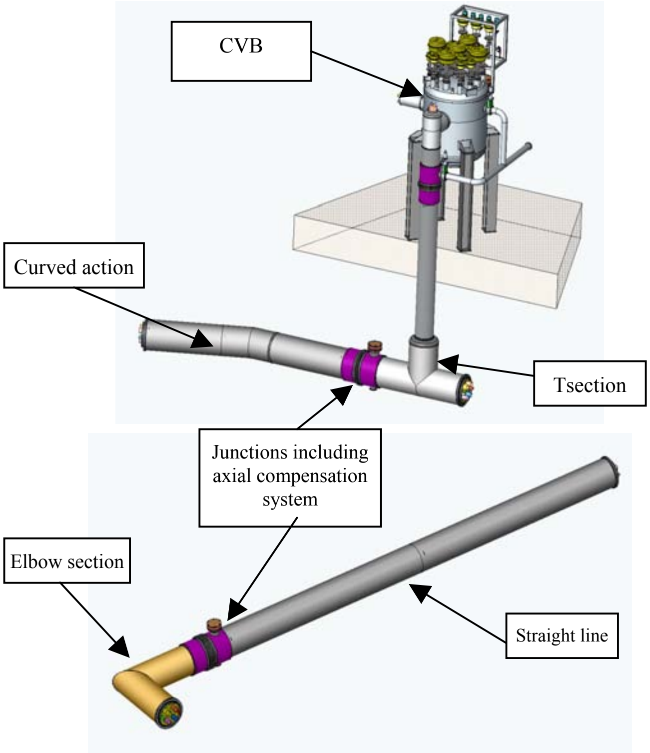

Figure 1 : Torus cryopump cryolines (500 mm in diam.) and CVBs (1200 mm in diam.)

WORKING CHARACTERISTICS OF THE LHE PLANT

Based on ITER requirements for the LHe cryoplant and assuming four identical modules working in parallel, one REFERENCE DESIGN MODE for one 4.5 K module (magnet ACB operating at 4.3 K) was defined using relevant industrial components and design rules (*see Report 4*).

This Design mode updates the previous CEA proposal for 4.5 K modules for the LHe modules. It also confirms the compatibility of this detailed design proposal with the 2001 cryoplant building layout which was designed with the LHC 4.5 K refrigerators dimensions.

Based on the Design mode (heat exchangers and turbines frozen), the flexible operation for different plasma scenario has been studied from 4.2 K to 4.5 K with no significant limits (*see Report 5*). Thanks to the cold compressors, the 4.5 K module accepts the different operating conditions of the magnets. However the available removable heat loads from magnets are function of their operating temperature (from 8.17 kW at 4.2 K to 9.28 kW at 4.5 K). Finally, the curve Refrigeration versus Liquefaction defines the capacity limits of the LHe plant (from 17 kW to 100 g/s) especially for transient modes such as cooldown and filling of magnets.

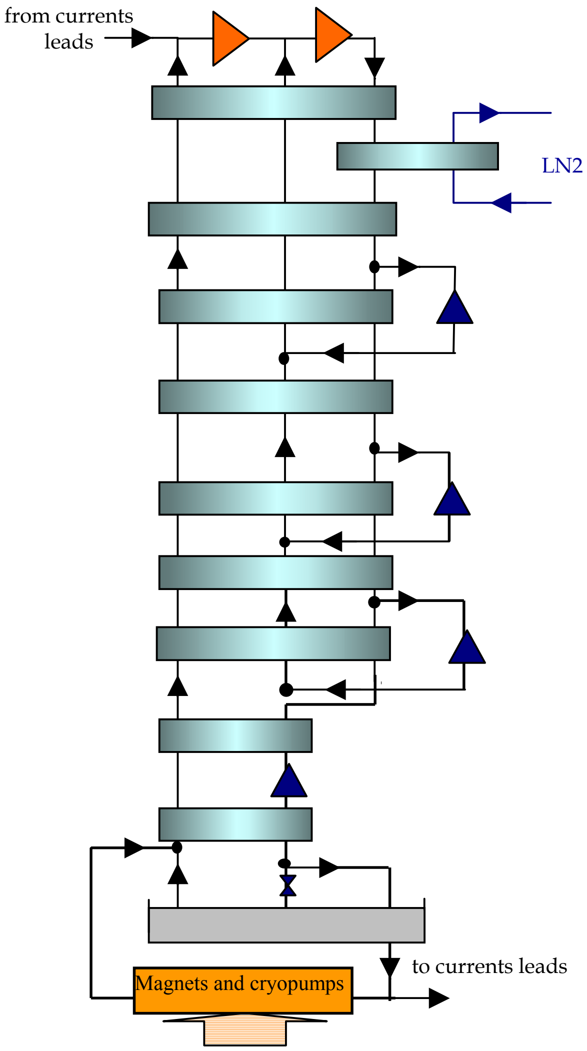

Figure 2 : Reference design mode for one 4.5 K module of the ITER LHe plant

CONCLUSIONS

The proposed design for cryolines and CVBs is a typical design and dimensions or routing should be adapted to the latest ITER requirements such as ITER safety requirements for 4.5 K SHe cooling loops. One can note that such compact design for CVB is risky for any maintenance or reparation during the lifetime of ITER.

Additional works on the distribution subsystem will be performed in the coming years to include the new requirements for pellet injection system or for the 470 K regeneration of the Torus Cryopumps. Some component and instrumentation qualification campaigns have also to be planned to define ITER potential components and instrumentation for at least the ITER cryogenic system and also magnet cryogenic loops.

Some improvements to increase the cycle efficiency of the LHe plant (Factor of Merit around 300 W/W to be compare with 240 W/W already achieved at CERN) are foreseen such as to increase the number of turbines or to develop a warm centrifugal compressor for reducing the electrical power consumption and then the Factor of Merit.

As a conclusion, one should keep in mind that the control strategy of four 4.5 K modules working in parallel is not yet defined or validated and should require specific studies including a deep analysis of the control strategy and the size for the 4.5 K modules and also some experimental measurements.

Finally, the main results of this task are presented in two papers at the Cryogenic Engineering Conference at Anchorage in Sept. 2003 (*see Publications 6 - 7*).

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1. Final Report EFDA/02-663: ITER Cryoplant and Cryosdistribution Design, Note SBT/CT/03-60, François MILLET, September 2003.

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3. Conceptual Design of CVB for ITER Torus Cryopumps, Note SBT/CT/03-57, François MILLET, August 2003.

4. ITER helium refrigerator – Phase 1 – Process calculation note, Note DTA/CRYG/PB/NT03.020(3), Pierre BRIEND, June 2003.

5. ITER helium refrigerator – Phase 2 – Process calculation note, Note DTA/CRYG/03.49(3), Simon CRISPEL, October 2003.

6. Cryogenic subsystem to provide for nominal operation and fast regeneration of the ITER primary cryo-sorption vacuum pumps, publication presented at CEC 2003 – Anchorage (USA), Vladimir KALININE et al., September 2003.

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CEFDA02-684

Task Title: TW2-TDC-MAGSPEC2: SUPPORT TO PROCUREMENT SPECIFICATIONS FOR MAGNET SYSTEM

INTRODUCTION

The ITER International Team is in charge of the development of the technical specifications for the ITER magnet procurement.

In this particular contract, EFDA, acting as the European Participant Team to ITER, request the Magnet Group of the CEA Cadarache laboratory to provide technical support to the writing of the procurement specifications for the Toroidal Field (TF) and Poloidal Field (PF) coil winding packs, plus some support to the specifications for Conductors and Joints. Drafting of the technical specifications for ITER is being coordinated by ad-hoc Working Groups, which have been set up for each Procurement Package.

These Working Groups include members of the ITER Team and Participant Teams from Canada, Europe, Japan and Russia. Two representatives from CEA participated to the meetings of these Working Groups, organized by the ITER Team at Naka in April and November 2002 and at Garching in July 2002.

2003 ACTIVITIES

The specifications for ITER cable characterization have been issued [1] and the contribution of the CEA representatives to the November 2002 Naka meeting [2] and to the TF winding specifications [3] reported.

This contribution included:

- an inventory of the samples and tests to perform for qualification of the revised TF conductor, using the advanced Nb_3Sn strands, with high current density,
- a survey of the European companies capacity to meet the Nb_3Sn strand specification,
- a summary of the lessons drawn from the TF model coil programme,
- a proposal for the attachment of the conductor ends of the PF coils,
- an assessment of the cooling inlet design proposed by CEA for the Central Solenoid coils and which could be used for the PF coils.

PARTICIPATION TO THE MAGNET MEETING OF GARCHING

A magnet meeting was organized by the ITER International Team in Garching on the 6, 7, 8 and 9 May 2003 with participants coming from the Participant Teams from Europe, Japan, Russia and USA, with the aim of taking decisions about the ITER conductor design based on the model coils experience. Two representatives from CEA participated to this meeting. During this meeting CEA reported the TFMC results and assessed the consequences for the ITER TF conductor design. It was emphasized that the TFMC tests and especially the exploration of the limits of the conductor was very helpful for ITER.

On table 1, the evolution of the ITER conductor design before and after the TFMC test has been made visible.

Table 1 : Evolution of ITER TF conductor design after the tests of the TFMC

	ITER TF conductor design in 2000	ITER TF conductor design in 2003 (one possible option)
Jacket material	316 LN	316 LN
I_{op} (kA)	68	68
Bmax- Bmin (T)	11.8 (Bmax)	11.8-10.5 ($B_{effective}$=11.3 T)
ε_{op} (%)	0.1	0.065
ε_0 (%)	-0.6	[-0.75, -0.79] TFMC
$\varepsilon_{effective}$	-0.5	-0.769
Top (K)	5	5
J_{noncu} (A/mm^2) @ 12T, 4.2 K, -0.25 %	650	800
Cable diameter (mm)	40.2	40.2

It can be seen that:

The specifications on field changed to 11.3 T representative of a kind of average field across the conductor instead of the maximum field 11.8 T which was too pessimistic. The specification on strain on the contrary was too optimistic and changed from –0.5 % to –0.77 %. As recommended by Europe, it was decided at the end of the meeting by the ITER Team, in agreement with the Participant Teams, to revise the design of the TF and CS conductor by using for both conductors advanced Nb_3Sn strands with high current density and an A316 LN stainless steel jacket. A draft complementary R&D programme was established to demonstrate by testing subsize and full-size conductor samples the qualification of the new conductor design.

CONCLUSIONS

The participation to magnet meetings and to the writing of the specifications has been reported.

The design of the TF and CS conductors has been revised, following the recommendations from Europe and CEA, using high current density Nb_3Sn strands and a stainless steel jacket.

REPORTS AND PUBLICATIONS

[1] J. L. Duchateau, P. Decool, Specifications for ITER cable characterization, CEA report DRFC/AIM/NTT-2003.009, 24/03/03.

[2] P. Libeyre, P. Decool, J.L. Duchateau, CEA contribution to ITER Meetings on specifications at Naka in November 2002, CEA report DRFC/AIM/NTT-2003.041, 18/09/03.

[3] P. Decool, CEA contribution to TF winding specifications and annexes, CEA report DRFC/AIM/NTT-2003.037, 02/09/03.

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