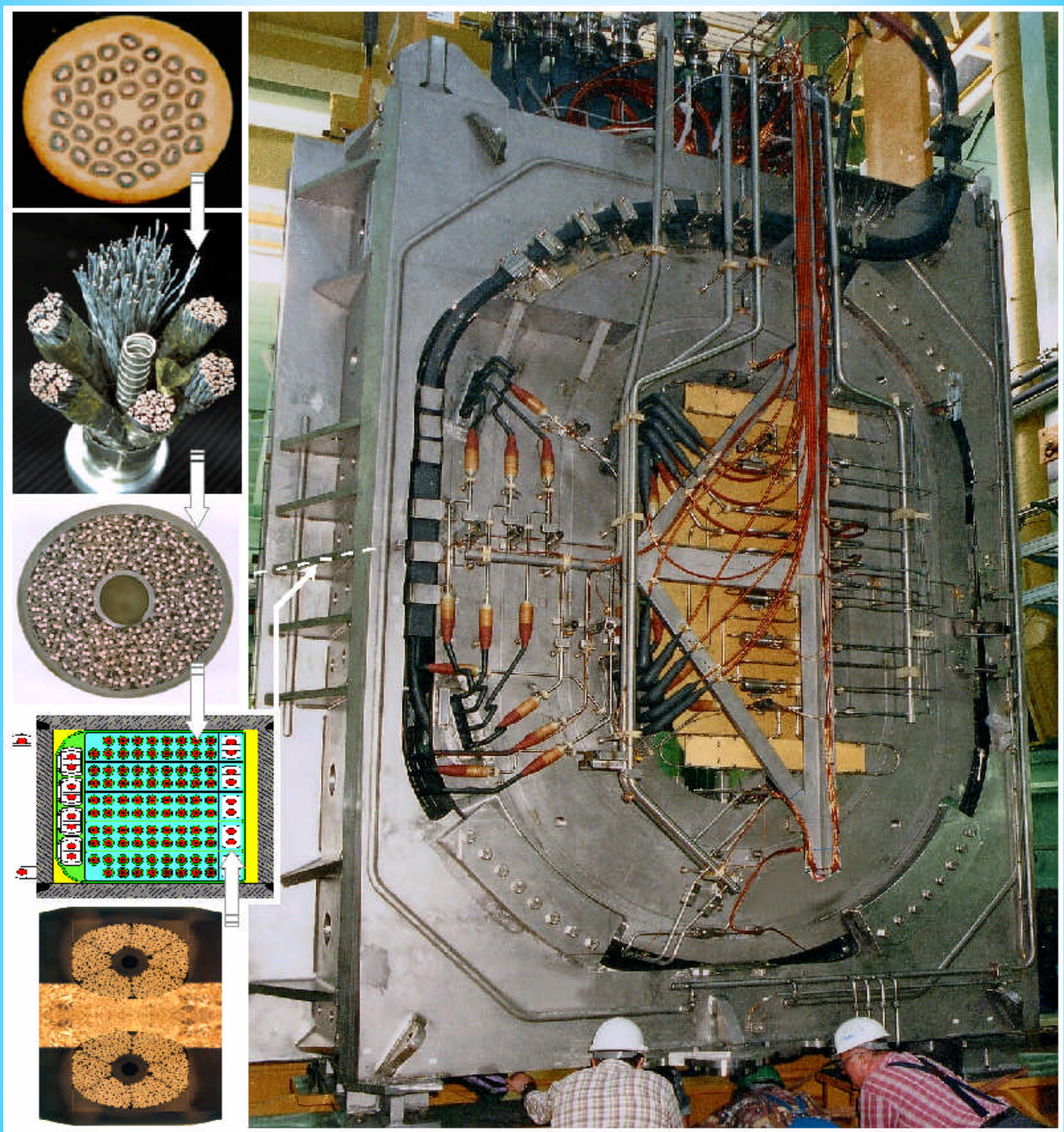
FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA 2001

Compiled by : Ph. MAGAUD and F. Le VAGUERES



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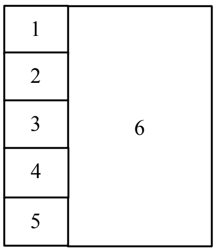

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CEFDA00-517

Task Title : DESIGN OF CRYOGENIC TRANSFER LINES AND RING MANIFOLDS FOR ITER-FEAT

INTRODUCTION

ITER-FEAT installation requires a large cryoplant for distributing, all around the tokamak, the helium liquefaction and refrigeration needed by the magnets and the structures at 4.5 K and 80 K (about 60 kW at 4.5 K and 800 kW at 80 K for normal operation mode).

For such a large plant, it is important the widest possible experience is used in the design and the cost estimate.

The role of the European working group was to provide technical analysis and study. Both were based on CEA and CERN available experiences, respectively design and operation of the TORE SUPRA tokamak and large scale cryoplants and cryolines for the LEP and LHC particle accelerators.

Each of these installations are supplied by European firms (AIR LIQUIDE or LINDE).

Due to this relevant experience, ITER Joint Central Team (JCT) has requested support from European home team to get technical design for ITER-FEAT cryogenic lines and ring manifolds.

2001 ACTIVITIES

Technical assistance to ITER JCT in 2001 followed previous works about ITER-FDR cryoplant design evaluation and complete 2000 activities *(see reference [1] / Annual Report of Technofusion 2000 for Stage 1 and Stage 2)* about conceptual design for ITER cryodistribution system and comparative study for Stainless Steel or INVAR cryogenic manifold design solution.

This work was divided in two parts (Stage 3 and Stage 4) as presented hereafter.

DETAIL DESIGN, ASSEMBLY STRATEGY AND PRELIMINARY COST ESTIMATE FOR MANIFOLDS AND CRYOLINES OF MAGNET SYSTEM

Following conclusions of 2000 activities (*see reference [1]*) and based on ITER-FEAT requirements (*see reference [2] / Cost Procurement Packages)*, detailed studies were performed to define the **cryogenic transfer lines of magnet system** *(see for details : Stage 3 report / Note SBT/CT/01-13).*

This part was a complete study of the following two typical cryogenic transfer lines required by the magnet system :

- Detailed **stainless steel design for TF cryolines and manifolds** including thermal and mechanical calculations, vacuum analysis, strategy assembly and preliminary cost estimate for stainless steel design solution **as reference design for magnet system cryogenic lines inside tokamak building** (PF, CS, TF, cryopumps)

- Detailed **stainless steel design for ACB common manifold** including thermal and mechanical calculations, vacuum analysis, strategy assembly and preliminary cost estimate for stainless steel design solution **as more complicated manifold** due to high number and large diameters of internal tubes (6 internal tubes inside an outer diameter of about 1 m in diameter).

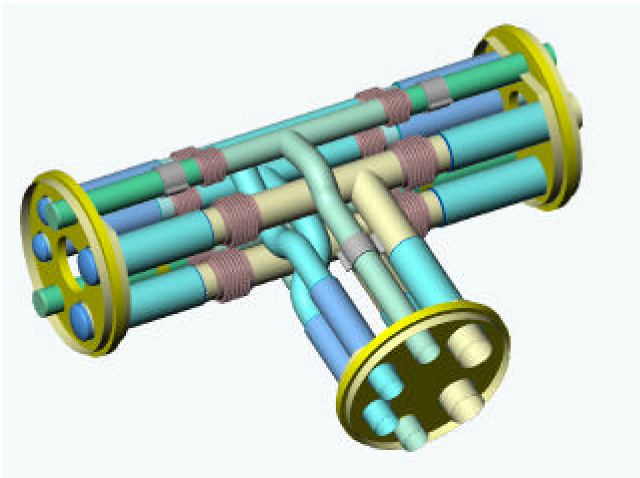

Figure 1 : ACB Common Manifold connection module details

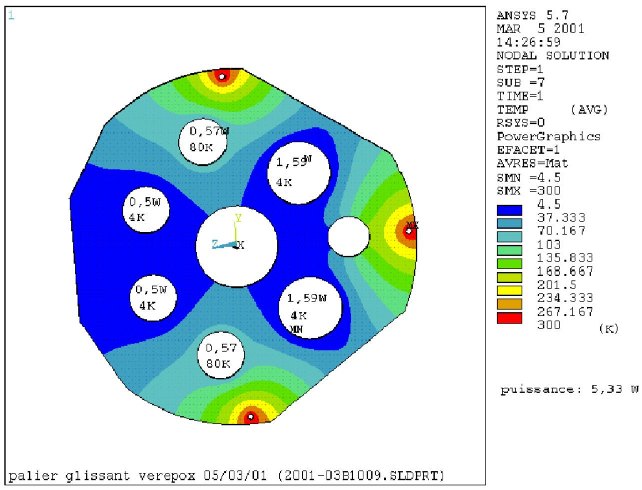

Figure 2 : ACB Common Manifold thermal calculations for fibre glass supports

DETAIL DESIGN, ASSEMBLY STRATEGY AND PRELIMINARY COST ESTIMATE FOR TOKAMAK - CRYOPLANT CRYOLINES

Following conclusions of 2000 activities (*see reference [1]*) and based on ITER-FEAT requirements (*see reference [3]*), similar studies of Stage 3 were performed to define the **cryogenic transfer lines between tokamak and cryoplant buildings** *(see for details : Stage 4 report / Note SBT/CT/01-30).*

This part was a complete study of the following cryogenic transfer lines :

- Detailed **stainless steel design for Tokamak-Cryoplant cryolines** including thermal and mechanical calculations, vacuum analysis, strategy assembly and preliminary cost estimate for stainless steel design solution **as longer and larger cryolines** (126 m in length and about 1 m in diameter) due to the total mass flows coming from cryoplant building and going to tokamak building

The main conclusions of these 2001 Stages were :

- **Complete and detailed studies** (design, calculations, drawings, assembly strategy and cost estimate) **of ITER-FEAT cryogenic transfer lines** were performed to obtain a compact, efficient and reliable solution *(see for details : Final Report / Note SBT/CT/01-35)*

- These designs will be introduced as reference design in the next DDD.

CONCLUSIONS

- A general review of existing solutions for cryogenic transfer lines has shown potential improvements in their design for welding, insulation, thermal compensation system, supports or standardisation such as new orbital welding machine for compact solution, superinsulation on tubes for reducing heat inleaks or prefabricated modules.

- The comparison studies between stainless steel and INVAR design solutions for cryogenic transfer lines had lead to choose **stainless steel solution as reference design for ITER-FEAT cryogenic transfer lines**.

- Consequently, detailed studies (including mechanical, thermal, hydraulic, vacuum calculations, drawings and assembly strategy and cost estimate) were performed to obtain a compact, efficient, reliable and low cost stainless steel **design solution for ITER-FEAT cryogenic transfer lines of the magnet system and between tokamak and cryoplant buildings**. These designs will be introduced in the next DDD as reference. Cost Estimate for cryogenic transfer lines was introduced inside European Home Team proposal for ITER-FEAT procurement packages *(see for details : Part 1 Report : Cost Estimate for the Cryoplant / contract FU05-CT2001-00026 / EFDA/00-566)*.

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[1] Annual Report of the Association EURATOM/CEA 2000 - Task title : Design of Cryogenic Transfer lines and Ring Manifolds for ITER-FEAT - page 103 - François MILLET - CEFDA 00-517.

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- Stage 3 Report : Detailed design, assembly strategy and preliminary cost estimate for manifolds and cryolines of magnet system - ITER task agreement N 34 TD 04 FE // EFDA / 00-517 // FU05-CT 2000-00047 - Note SBT/CT/01-13, François MILLET, May 2001.

- Stage 4 Report : Detailed design, assembly strategy and preliminary cost estimate for Tokamak-Cryoplant cryolines - ITER task agreement N 34 TD 04 FE // EFDA / 00-517 // FU05-CT 2000-00047 - Note SBT/CT/01-30, François MILLET, July 2001.

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- Part 1 Report : Cost estimate for the cryoplant - ITER task agreement N 34 TD 06 FE // EFDA / 00-566 // FU05-CT 2001-00026 - Note SBT/CT/00-66, François MILLET, December 2000.

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CEFDA00-566

Task Title : LAYOUT OF THE CRYOPLANT FOR RTO/RC ITER

INTRODUCTION

ITER-FEAT installation (RTO/RC ITER) requires a large cryoplant for producing and distributing, all around the tokamak, the helium liquefaction and refrigeration needed by the magnets and the structures at 4.5 K and 80 K (about 60 kW at 4.5 K and 800 kW at 80 K for normal operation mode).

For such a large plant, it is important the widest possible experience is used in the design and the cost estimate.

The role of the European working group was to provide technical analysis and cost estimate. Both were based on CEA and CERN available experiences, respectively design and operation of the TORE SUPRA tokamak and large scale cryoplants and cryolines for the LEP and LHC particle accelerators. Each of these installations are supplied by European firms (AIR LIQUIDE or LINDE).

Due to this relevant experience, ITER Joint Central Team (JCT) has requested support from European home team to get :

- cost estimate for the complete ITER cryogenic system,
- cryoplant layout rechecking,
- industrial feasibility for a large quench tank.

2001 ACTIVITIES

Technical and cost assistance to ITER JCT in 2001 followed previous works about ITER-FDR cryoplant design evaluation *(see reference [1] / ITER Cryoplant Design Evaluation and reference [2] / DDD 3.4)* and completed the contract EFDA/00517 *(see reference [3] / Design of Cryogenic Transfer Lines and Ring Manifolds for ITER-FEAT).*
This work was divided in three separated Parts as presented hereafter.

COST ESTIMATE FOR ITER CRYOGENIC SYSTEM

The cost estimate for ITER-FEAT cryogenic system (including cryoplant, cryodistribution and cryolines sub-systems) was assessed on the basis of European market (CEA, CERN, AIR LIQUIDE, LINDE) and based on previous experience and existing standard products for large scale cryogenic systems (*see reference [1], reference [5] : AIR LIQUIDE cost estimate, reference [6] : ELFE Conceptual Design Report and reference [7] : LINDE quotation*).

A dedicated report for this cost estimate part *(see for details : Part 1 report / Cost Estimate for the Cryoplant / Note SBT/CT/00-66)* was submitted to allow the general cost review of ITER-FEAT project in beginning of 2001.

CRYOPLANT LAYOUT RECHECKING

ITER cryoplant includes the liquid helium production plant - called LHe cryoplant -, the liquid nitrogen (LN2) production subsystem and the 80 K helium loop – called 80 K cryoplant – and helium purification units *(see for details : Final Report / Layout of the Cryoplant for RTO/RC ITER / note SBT/CT/01-36)*. These sub-systems will be installed in 2 separated buildings : one dedicated to compressors, the other one to cold boxes.

The main conclusions of this cryoplant layout rechecking are the following :

- Basically, the present dimensions for cryoplant components mentioned in JCT documents (*reference [4]*) are correct and similar to existing or expected products required by such large scale cryoplants.
- But some extra areas have to be introduced for final cryoplant building designs such as provisions for truck unloading, local electrical sub-stations especially for warm compressors, spare parts storage, work place, instrument air production, ventilation, ...
- Furthermore, special building designs for doors, removable walls and roofs have to be also discussed with transport, handling and unloading teams to insure easy installations of components inside future buildings.
- Finally the global piping design (water, air instrument, helium, nitrogen, electrical wires, ...) have to be included in the building design to define clearly potential component interference. 3D design including all of the components and utilities should avoid such mistakes.
- Consequently, the present dimensions of cryoplant buildings (about 4800 m² for cold box building and about 5400 m² for compressor building) allow the installation of all of the cryoplant required components or spaces. Indeed, the minimum required surfaces for cryoplant buildings should be at least 2000 m² for cold boxes ones and at least 3000 m² for compressors ones.

Addition studies should occur during the next year to prepare cryoplant building layout and associated galleries taking into account present conclusions.

INDUSTRIAL FEASIBILITY OF A LARGE QUENCH TANK

Design studies and industrial inquiry were performed to define a solution for ITER-FEAT quench tank *(see for details : Final Report / Layout of the Cryoplant for RTO/RC ITER / note SBT/CT/01-36)*. Indeed, such tank has to be designed to accept all of the expelled helium (6700 kg) from magnet system at fast energy discharge and also to be able to store it until re-liquefaction and re-filling of magnets (some days to some weeks).

For such purposes, 2 design options are available with their corresponding requirements :

- Cold quench tank with an active cooling system with 80 K Gas Helium (GHe) and special insulation design. The corresponding volume should be at least 570 m^3 for storage temperature of 80 K and operating pressure of 2.0 MPa (density 11.6 kg/m^3).

- Warm quench tank operating at room temperature. The corresponding volume should be at least 2100 m^3 for storage temperature of 300 K and operating pressure of 2.0 MPa (density 3.2 kg/m^3).

The main conclusions are the following :

- The feasibility of ITER quench recovery tank is proven.

- Such tank operating at 2.0 MPa could be a cold one with 80 K GHe active cooling system (2 units for about 600 m^3) or a warm one at room temperature (5 units for about 2100 m^3).

- Cold quench tank solution is the preferred design for the following reasons :

  . Low stress in vessel due to the lowest dilatation and gradient solicitation during quench (50 K helium in 80 K tank).

  . Reduced sizes and furthermore low cost.

  . Rapidity for helium re-liquefaction.

- However such cold tank requires an <u>active</u> cooling system with 80 K GHe and its regulation system for extracting about 20 kW of heat loads on each cold vessel unit.

CONCLUSIONS

All technical discussions and studies performed with the support of the Grenoble group in the frame of European Community support have been introduced in the final documents written at the end of the ITER EDA and will prepare the next ITER CTA phase.

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[1] Annual Report of the Association EURATOM/CEA 1998 - Task title : ITER Cryoplant Design Evaluation - page 71 – Gérard CLAUDET – CENT 96-409.

[2] Design Description Document DDD 3.4 : Cryoplant and Cryodistribution System - N 34 DDD 7 98-06-15 W 4, Vladimir KALININ, June 1998.

[3] Annual Report of the Association EURATOM/CEA 2000 - Task title : Design of Cryogenic Transfer lines and Ring Manifolds for ITER-FEAT - page 103 – François MILLET – CEFDA 00-517.

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[5] Estimation de prix pour la réfrigération du projet ITER - AIR LIQUIDE document DTA/CRYG/PD/ DS/01.003, P.DAUGUET, January 2001.

[6] ELFE Cryogenics / Part of ELFE at CERN Conceptual design report - CERN-NuPECC document, CERN99-10, S.CLAUDET, August 1999.

[7] Technical proposal and quotation for quench tanks - LINDE document : quotation no.0841 1610, Gerald HECHT, May 2001.

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- Final Report : Layout of the Cryoplant for RTO/RC ITER - ITER task agreement N 34 TD 06 FE // EFDA / 00-566 // FU05-CT 2001-00026 - Note SBT/CT/01-36, François MILLET, July 2001.

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CEFDA00-541

Task Title : MAGNET DESIGN ON PF AND CORRECTION COILS : CONCEPTUAL DESIGN AND ANALYSIS

INTRODUCTION

CEA is requested to assist the EFDA Close Support Unit of Garching in the detailed design of the Poloidal Field Coils of the ITER machine, the design of the Central Solenoid cooling inlets and the development of some conductor analysis tools.

2001 ACTIVITIES

PF COIL CONDUCTOR ANALYSIS

Introduction

The 6 PF coils of ITER FEAT Reactor are manufactured in double pancakes of a thick-wall stainless steel square conductor, which provides the main structural material (figure 1).

Figure 1 : Square Cable In Conduit Conductor

The PF coils are subject to pulsed loads with large variations of field within each machine cycle and they have to withstand safely all operational conditions, including plasma disruptions and fast discharges. The PF coils are designed based on a redundancy philosophy which allows the PF coil to operate with full current in case of a failure of one of the double pancakes. The PF coils are wound in separate modules and two-in-hand from a 45 kA NbTi Cable-In-Conduit Conductor with 6 sub-cables arranged around a central cooling channel.

Simulation model and conditions

In the following, main attention has been paid to coil PF6 which experiences the highest field and therefore takes advantage of NbTi at its limits.

The scenario taken into account is referenced as No2 scenario and was transmitted to us by ITER JCT.

The Thermal-Hydraulic Simulation Model and the External Cooling Circuit Model

The complexity of the real thermal-hydraulic circuit is such that we have chosen to model and simulate only one flow path in detail by a flow simulator (GANDALF, FLOWER): one of the two-in-hand conductor chosen as the representative winding. The 1-D model consists of a maximum of four independent components at different thermodynamic states : the strands, the conduit, the bundle helium and the hole helium.

The detailed time and space distributions of all the losses are used as input. The magnetic field distribution and operating electric current are defined by the chosen test scenario. The heat exchange between pancakes and between adjacent conductors of the same pancake is not taken into account.

NbTi Choice for the PF Coils

By using NbTi superconductor, cooled by supercritical helium, a substantial cost compared to Nb_3Sn is saved and the elimination of a reaction heat treatment greatly simplifies the insulation of such large diameter coils. In the framework of the PF Coils design and R&D activity, current density variations with magnetic field and temperature were investigated [2] for two candidate strands (Alstom and Europa Metalli) and correlated to the classical NbTi scaling laws.

For this study, the following general formula for Jc was taken :

$$J_C(B,T)=\frac{C_0}{B}\left(1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right)^{\gamma}\left(\frac{B}{B_{C2}(T)}\right)^{\alpha}\left(1-\frac{B}{B_{C2}(T)}\right)^{\beta} \quad (1)$$

$$\text{with} \quad B_{C2}(T)=B_{C20}\left(1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right)^{\gamma} \quad (2)$$

α, β, γ T_{C0}, B_{C20} and C_0 are parameters dependent only on the composite material. According to the strands measured in [2], the values taken for these parameters in this study are :

α = 0.9
β = 1.2
γ = 1.94
T_{c0} = 8.7 K
B_{c20} = 14.93 T
C_0 = 12.09 10^{10}

Heat conduction between turns

Helium is injected at the inner turn of these coils. For each double pancake there are two helium inlets related respectively to the two independent hydraulic circuit of the double pancake, which is wound two in hand.

Due to that arrangement, it can be demonstrated that the inner turn of the upper pancake is in thermal contact with the inner turn of the lower pancake and their temperatures are different.

In these two hydraulic circuits, helium is circulating in counterflow.

This heat exchanger effect can introduce an additional temperature gradient over a turn of magnet. This effect can be evaluated analytically in a first approach.

$$T_{max}=T_0+\Delta T\frac{(1+\beta)^2}{4\beta}$$

If â < 1 there is no additional gradient due to that effect. â is driven by the series conduction between two conductors due to the stainless steel jacket and the insulation. A numerical application leads to â = 026. No additional gradient is therefore awaited due to that effect.

Effect of non uniform current distribution

Due to the joint, the current is not uniformly distributed among the strands of one petal. This effect has been studied on the PF6 coil mid pancake, which offers the most demanding operating conditions.

The results of the calculations with the CEA DC model are given in table 1. These values concern the most loaded strands (overloading factor J_{max}/J_{ave}). It can be concluded that there is no current redistribution among strands because no significant voltage drop is created along the most loaded strands which remain at a very low level of electric field (below 10^{-25} V/m), and are still operating at a low proportion (< 20 %) of their critical current, in spite of a significant overloading factor (> 2). Note that B_{ave} and B_{max} are the average and maximum fields in the cable cross section, respectively.

Table 1 : Most demanding strand operating conditions in PF6 coil (CEA DC model)

Time (s)	Turn	J_{max}/J_{ave}	J_{max}/J_c à B_{ave}	J_{max}/J_c à B_{max}
3700	inner	2.17	0.153	0.185
3700	outer	2.44	0.133	0.157
4100	inner	2.17	0.103	0.119
4100	outer	2.44	0.107	0.123

Due to the very low operating ratio (< 10 %) of transport current to critical current in the cable, no problems have to be envisaged, even with highly non-uniform current distribution among strands (overloading factor > 2).

Conclusion of this study

A conservative thermal-hydraulic analysis of the conductor of an ITER-FEAT PF Coil has been performed by combining highest field values and maximum heat loads values (real AC losses on the conductor and maximal thermal radiation and nuclear heating transmitted by conduction). The pressure rise (0.1 bar) and temperature rise observed during 5 pulses of plasma scenario are limited to acceptable values.

Exploring the situation for all the PF coils of ITER, the minimum ΔT margin (difference between current sharing temperature and operating temperature) was found in coils PF1 and PF6 (see figure 2). This margin is higher than 1.7 K. The ITER criteria of 1.5 K is then respected at any time and position in the PF coils. This subsequently validates the choice of NbTi for all PF Coils, thanks to their lower field.

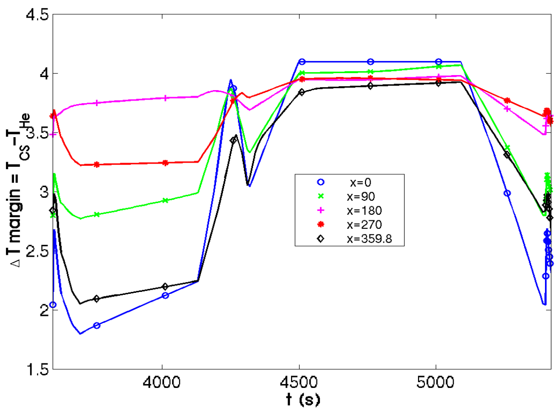


Figure 2 : Temperature margin in a PF6 regular pancake during the 3rd plasma scenario

The conductor design made by JCT is appropriate and the margins are respected. It is to be noted however that this situation is reached in spite of too optimistic data for NbTi.

On one hand the nominal operation characteristics in normal mode : B=6 T and T=5 K ([5] p.29 Table 6.2-3), on which the conductor design is based are never reached : the critical part is the inner turn of these coils where the field is maximum. The field there is never higher than 5.65T and the temperature never higher than 4.7 K.

On another hand within a simplified model the critical properties of NbTi taken into account by JCT are too optimistic ([5], p.27 Table 6.2-1) :

- Tc at 5 T equal to 7.17 K
- J_c non copper at 5 T, 4.2 K equal to 2900 A/mm^2

According to recent experimental results [2] instead :

- Tc at 5 T equal to 6.85 K
- J_c non copper at 5 T, 4.2 K equal to 2940 A/mm^2

This is more realistic and it can be seen that the temperature margin is reduced by 0.32 K, which is not negligible.

According to the study led within this contract, the two effects, the relaxation of the nominal operation parameters and the lower critical properties of NbTi compensate each another.

DESIGN AND ANALYSIS OF HELIUM INLETS FOR THE CENTRAL SOLENOID

Central Solenoid design

The Central Solenoid (CS) of ITER is composed of six independent stacked modules. Each module includes 42 pancakes and is designed to be manufactured in hexapancakes with helium inlets located at the innermost turns and helium outlets located at the outermost turns.

This configuration leads to three helium inlets by hexapancake and two helium outlets in addition to the two hexapancake joint terminations (figure 3). A total number of 126 helium inlets is thus needed for the whole Central Solenoid.

As the helium inlets are located at the innermost turns of the pancakes, they have to operate in the high field area, where the tensile stress in the conductor is maximum. The design of these helium inlets needs therefore to be optimised both on hydraulic and mechanical aspects. On one hand they have to provide efficient cooling of all subcables with minimum hydraulic resistance and on the other hand they have to provide limited overstressing in this highly stressed area.

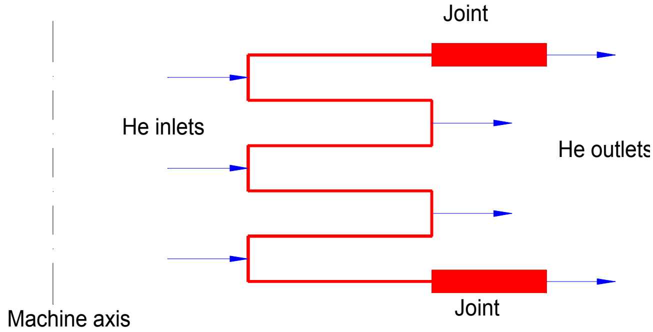
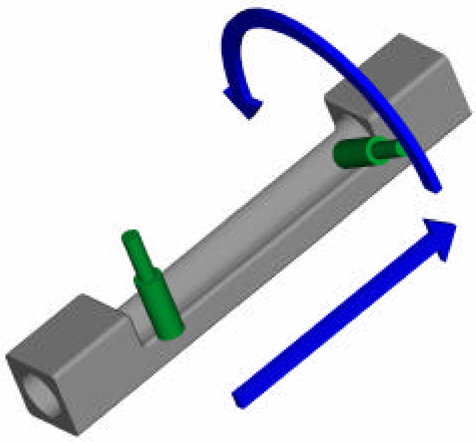


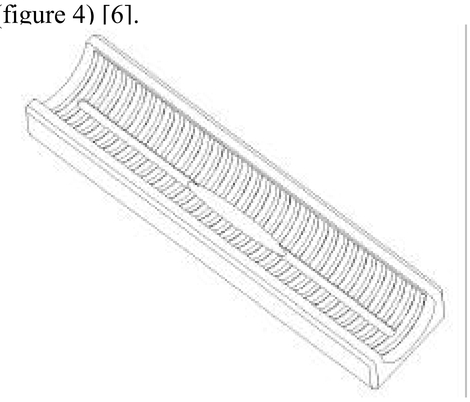
Figure 3 : CS hexapancake hydraulic scheme

Helium inlet design

The design proposed by CEA is a “window-type” helium inlet : a piece of jacket is removed locally and replaced by a premachined cover which is then welded to the conductor jacket (figure 4) [6].



Jacket machining with a numerical milling machine



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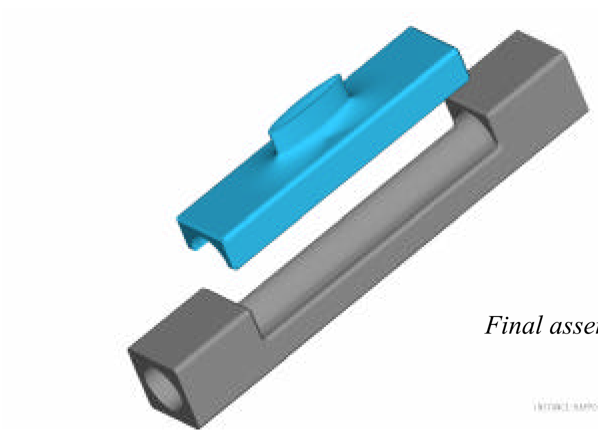

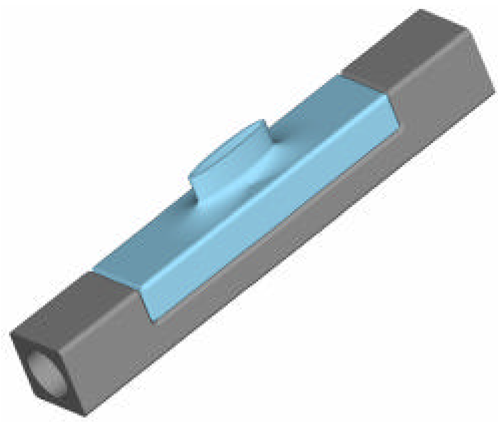

Final assembly

Figure 4 : Helium inlet manufacturing sequence

The machining of the CS jacket is performed during coil winding by insertion of a milling machine in the winding line.

The opening of the jacket is performed by machining a window on the lower, inner and upper faces of the inner turn.

The cable and subcable wrappings are locally removed to provide access for helium to subcables.

This avoids any modification of the contact between cable and jacket on the outer face of the turn, where the electromagnetic force acts, while allowing the six subcables to be wetted by helium on their outer perimeter.

Helium inlet mechanical analysis

A Finite Element model (figure 5) was built to optimise the mechanical design of the helium inlet by a parametric study.

The concentration factor could be limited to 1.14, which should be compatible with a fatigue life of 30 000 cycles and a safety factor of 2.

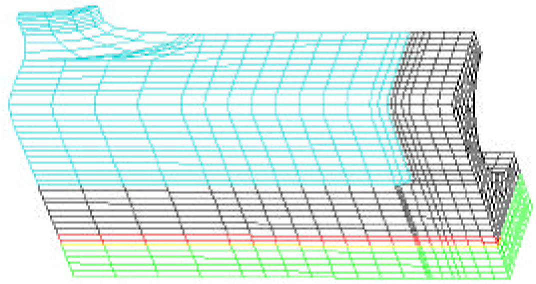

Figure 5 : Helium inlet finite element model

Helium inlet hydraulic behaviour

In order to investigate the hydraulic behaviour of the window-type helium inlet, it was decided to manufacture a prototype He inlet and to test it in the OTHELLO facility at CEA/Cadarache [7].

Due to unavailability of any CS conductor sample, a TFMC conductor sample was used to install the helium inlet prototype (figure 6).

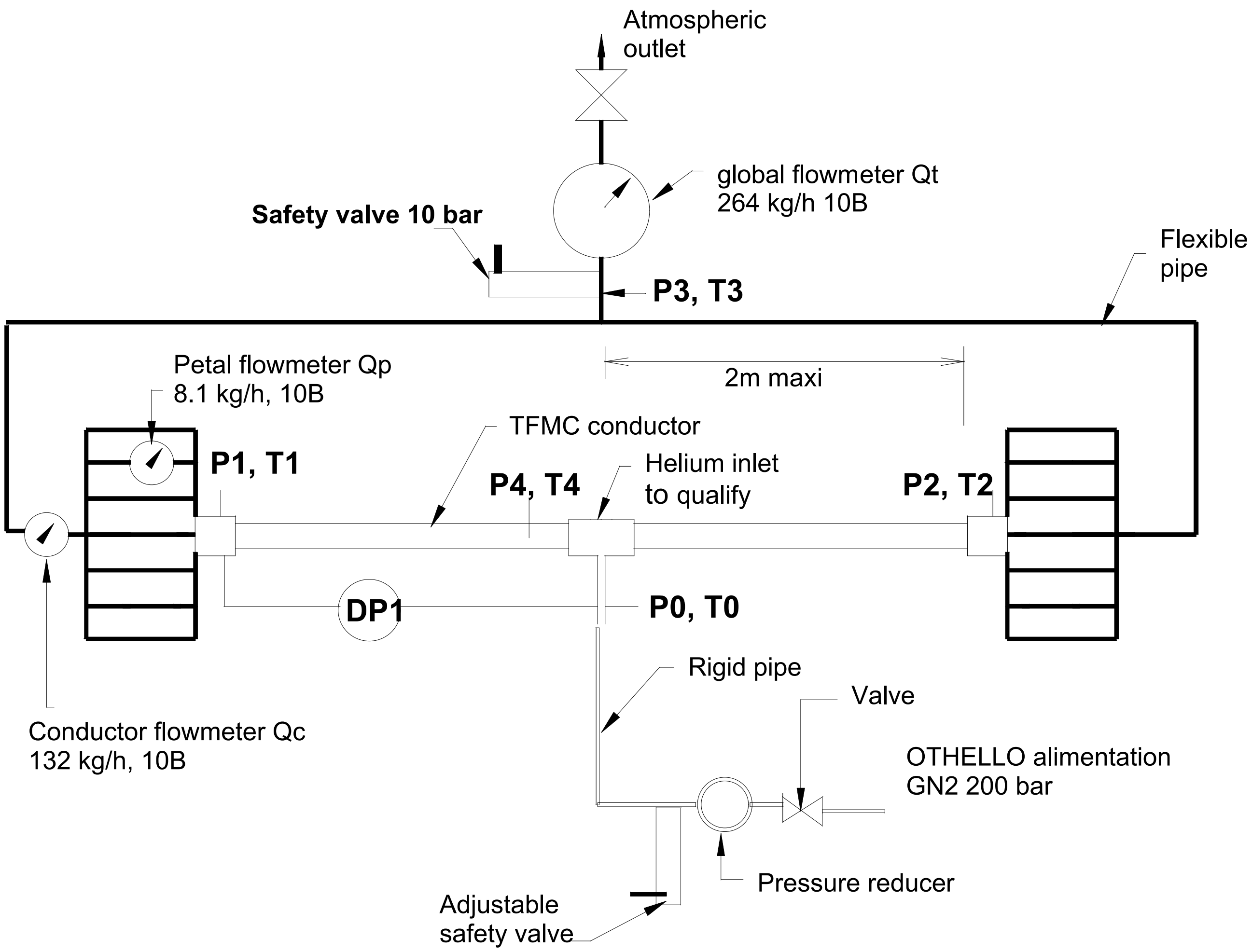

Figure 6 : Testing arrangement of an helium inlet prototype in the OTHELLO facility

An upgrade of the OTHELLO facility was required to allow measurement of the helium flow in each subcable and in the central channel of the conductor. A scheme of the installation is shown in figure 6. The assembly of the facility was carried out in Autumn 2001 to allow testing in early 2002.

DESIGN AND ANALYSIS OF PF COIL JOINTS

Conceptual design

The PF coils are designed with NbTi cable-in-conduit conductors wound in double pancakes, insulated with glass tapes impregnated with epoxy resin and are connected in series by joints located at the coil outer radius. As the conductor is wound "two-in-hand", each pancake contains one intermediate joint between the two conductors and two terminations to connect to adjacent pancakes.

These joints have to transfer high current (up to 45 kA) and to operate in the poloidal magnetic field which generate large varying forces.

The conceptual design of these joints, based on the overlap concept using the CEA "twin-box" design, is directly derived from the experience gained in the manufacture of the ITER Toroidal Field Model Coil (TFMC) and of the TFMC busbars and R&D on NbTi conductors.

The electrical and thermohydraulic analyses performed in 2000 showed that this concept is applicable to the ITER PF coils [1]. The mechanical design has to ensure that during operation the stresses and deformations in the joint area remain within acceptable limits.

The CEA proposal [8] is to make an overlap joint in shaking-hand configuration with an horizontal interface plane (figure 7). In order to limit mechanical stresses in the joint itself, it is chosen to bypass the joint by a mechanical link between the last turns of the adjacent pancakes to connect, which will carry the tensile load in the conductor coming from the hoop load (figure 8).

To prevent large overall deformations from arising under radial and vertical local forces on the joint area, an outer local support is installed and clamped to the coil itself.

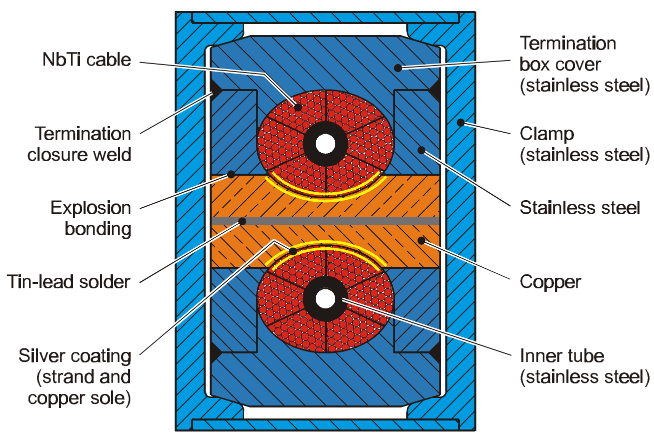

Figure 7 : Twin-box joint transversal cross-section

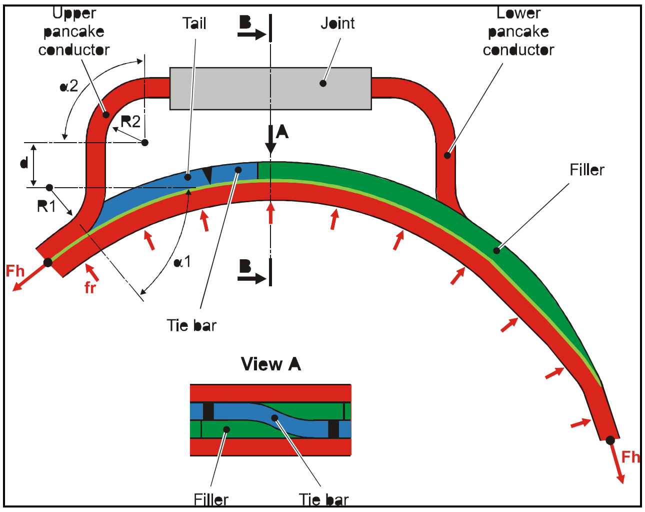

Figure 8 : PF joint support for hoop load

Mechanical Analysis

Several finite element mechanical models have been built to analyze the stresses and deformations in the joint area. The interaction of the vertical component of the induction with the current gives birth to a radial lineic force resulting in a hoop load on the coil inducing a tensile force on the conductors. In the joint area, it is necessary to verify that no debonding of the insulation occurs under shear stress where the conductor escapes from the winding-pack to the joint termination. The interaction of the horizontal component of the induction with the current produces a vertical lineic force resulting in a net vertical force, resisted by the PF coil supports fixed to the TF coils. The PF joints, located in between two adjacent supports, are thus submitted to local deformations arising under the bending and twisting moments due to the non-continuous support of the vertical force. Both in-plane and out-of-plane analyses have been performed to take into account these two interactions for each one of the PF coils. Their results show that, after optimisation of the out-of-plane support, the proposed joint area design allows limitation of shear stress in the underlying insulation below 20 MPa and of tensile stress applied to the electrical joint below 60 MPa. Local loads introduce high in-plane and out-of-plane bending stresses at the junction of the conductor to the coil and to the joint box, which brings locally the maximum combined stress up to 350 MPa, which should be compatible with operation for 30 000 cycles. The maximum stresses in the conductor jacket are summarized in table 2.

Table 2 : Maximum stresses on conductor jacket in joint area

Coil	Coil Tensile stress (MPa)	Joint Tensile force (kN)	In-plane bending stress (MPa)	Out-of-plane bending stress (MPa)
PF1	95	20	290	57
PF2	42	31	107	18
PF3	67	42	207	38
PF4	46	30	136	23
PF5	101	66	281	45
PF6	64	-21	288	63

CONCLUSION

The thermohydraulic analysis of the ITER PF conductor showed that the conductor design performed by the ITER JCT is appropriate and that the margins are kept during operation.

A design has been proposed for the helium inlets of the ITER CS and the mechanical analysis showed that it should allow operation for 30 000 cycles. A prototype has been manufactured and installed on a TFMC conductor to be hydraulically tested in the OTHELLO facility.

A mechanical design of the ITER PF coil joints has been proposed and the mechanical analysis showed that it should allow operation for 30 000 cycles.

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Task Title : DESIGN WORK ON MAGNET R&D

INTRODUCTION

This task, started in 1995, included design, participation to the follow-up of the manufacture of the ITER TF Model Coil (TFMC) and preparation of the tests of this coil.

The conceptual design of the TFMC was issued in 1995 [1] and the manufacture was carried out by the AGAN consortium (Ansaldo, Alstom, ACCEL, Babcock Noell Nuclear), selected after a call for tender, under a contract with EFDA [2].

The joints connecting the pancakes use the twin-box concept, developed by CEA [3],[4].

The coil was delivered in Karlsruhe on 11 January 2001, to be tested in single coil mode in the TOSKA facility at FZK in 2001.

2001 ACTIVITIES

INSTALLATION OF THE TF MODEL COIL IN THE TOSKA FACILITY

Once delivered in Karlsruhe (figure 1), the TFMC was inserted inside the Intercoil Structure (ICS), manufactured by AGAN and put in vertical position (figure 2).

The assembly was then inserted inside the TOSKA vessel (figure 3).

The electrical and hydraulical connections of the coil to the TOSKA facility was then carried out.

Figure 1 : TFMC delivered by AGAN at FZK (courtesy of FZK)

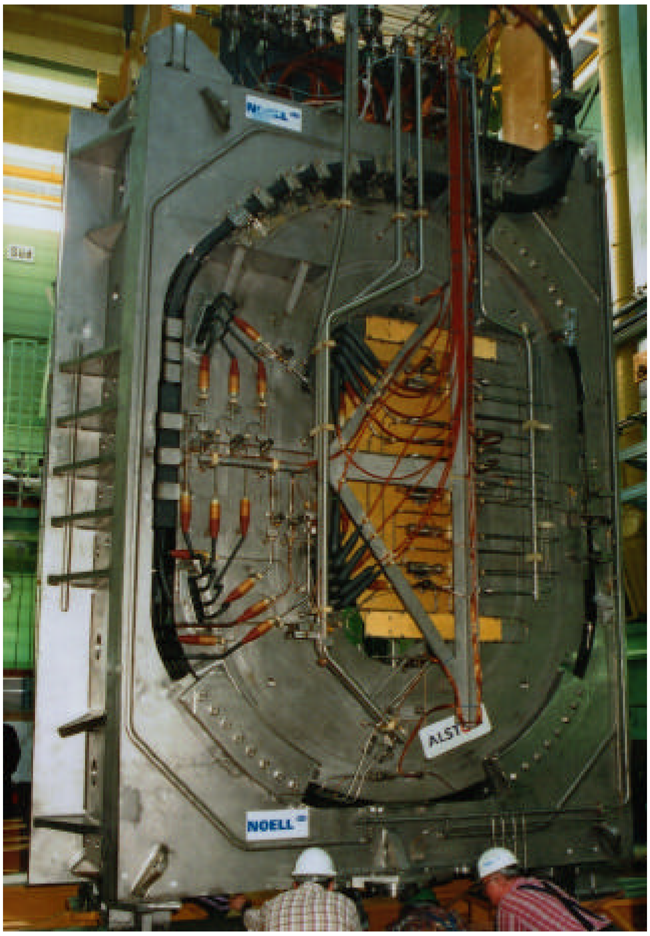

Figure 2 : TFMC inside ICS (courtesy of FZK)

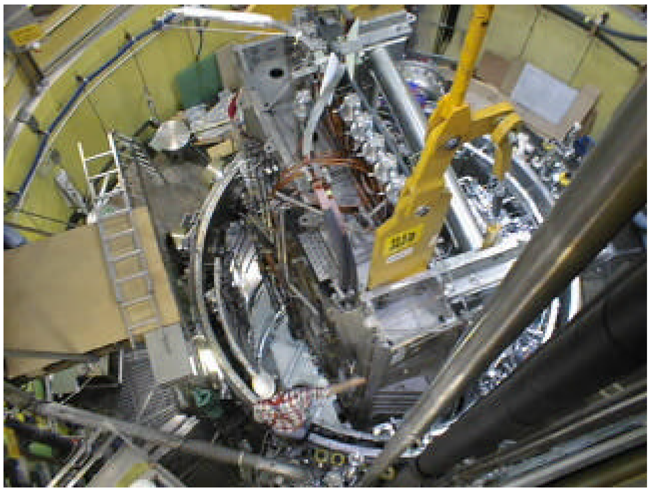

Figure 3 : TFMC and ICS lifted down inside the TOSKA vessel (courtesy of EFDA)

The busbars linked to the coil (BB1+ and BB1-) were connected to the busbars linked to the current leads (BB2+ and BB2-). A dismountable joint using a set of indium wires in the interface of the termination boxes was assembled and insulated by AGAN (figure 4). CEA followed up the R&D and assembly of these joints.

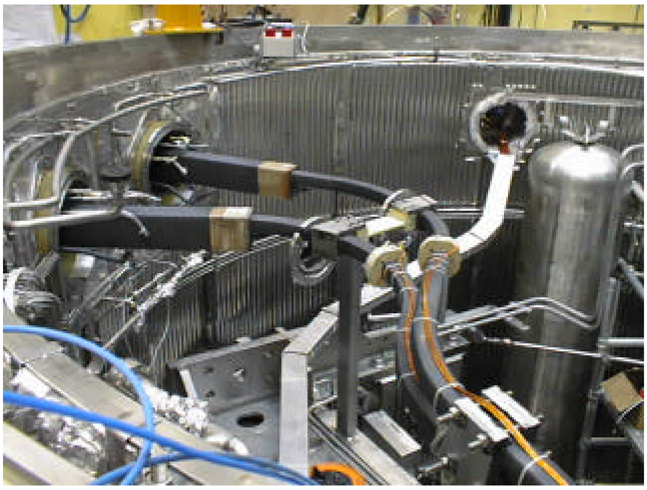

Figure 4 : Connection of busbars BB1 to busbars BB2 inside TOSKA vessel

A Hall probe system was designed, manufactured and installed by CEA on busbars BB1 to investigate the current distribution (figure 5).

Figure 5 : Hall probes installed on the BB1 busbars

After closure of the TOSKA vessel on 13 June 2001, tightness and electrical tests were performed at room temperature. An insulation defect was detected during the high voltage tests showing a breakdown at 1.2 kV in DC mode and strong dependence with the vacuum pressure inside the vessel.

As the voltage during safety discharge was not expected to exceed 536 V, it was decided to proceed with the cooldown of the TFMC/ICS assembly. Transition from normal to superconducting state was observed on 6 July 2001 (figure 6). The insulation defect was confirmed during the low temperature high voltage tests, leading to a breakdown voltage in DC mode at 5 kV. A small helium leak was detected, but at an acceptable level for test performance.

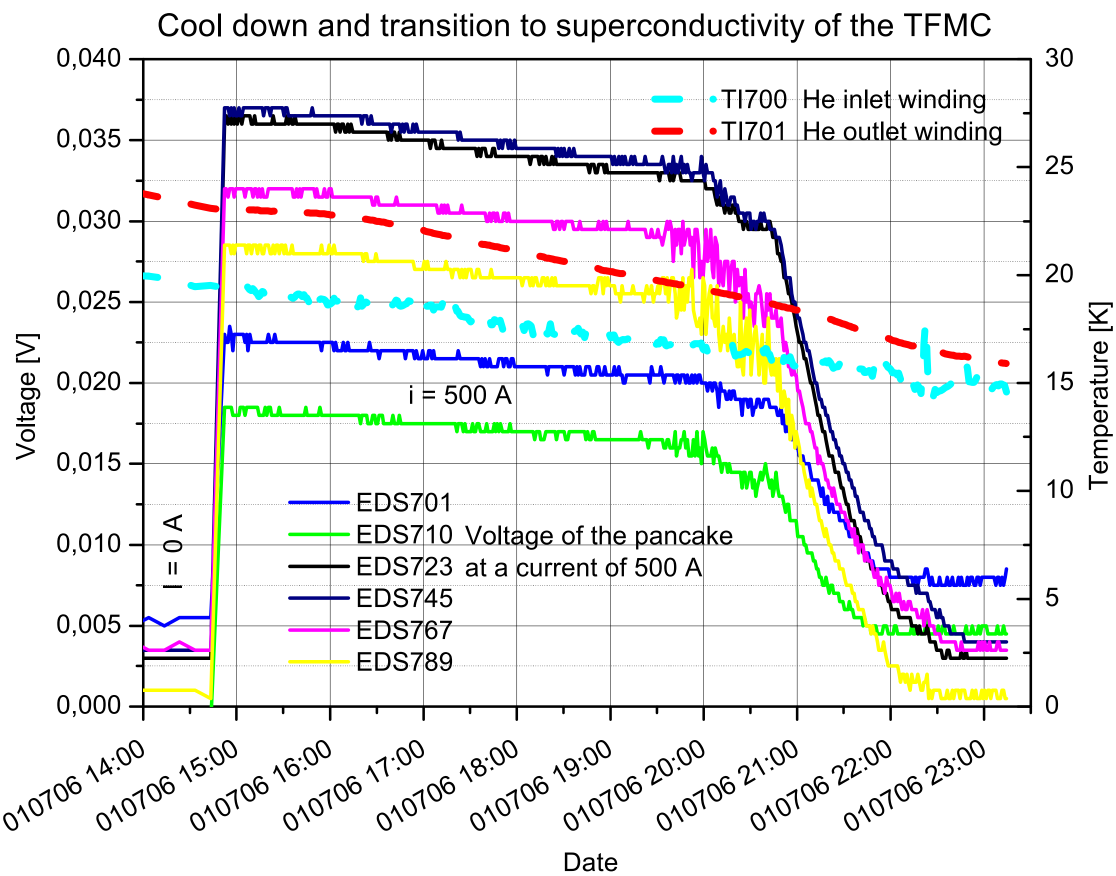

Figure 6 : Transition from normal to superconducting state of TFMC (courtesy of FZK)

TESTS OF THE TF MODEL COIL IN SINGLE COIL MODE

The TFMC tests in single coil mode were performed from July to October 2001.

Participation of CEA to these tests is reported in Task TW0-T400-1.

WARMING UP OF THE TFMC

After completion of the single coil tests, investigations were carried out by FZK to localise the insulation defect and the warming up to room temperature was started on 10 October 2001 and the vacuum vessel could be opened on 16 November 2001.

The investigations were continued at room temperature and led to the conclusion that defects were located at the crossing through the coil case of the helium piping and on the BB1 terminal insulation.

CONCLUSION

The assembly of the TFMC with ICS and the installation inside the TOSKA facility was completed at the beginning of June 2001.

CEA followed-up the busbar joints assembly, designed, manufactured and installed a Hall probe system on busbars BB1 to investigate the current distribution in the busbar conductor.

After cooldown, the single coil tests were performed from July to October 2001. Warming up occurred from October to November 2001.

Two insulation defects limiting the dielectric strength to 5 kV were localised by FZK.

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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:

- Characterization of NbTi strands in a range of temperature between 4K and 7K 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.

2001 ACTIVITIES

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

The critical current density of the two NbTi strands (Alstom with internal CuNi barrier and Europa Metalli with Ni coating) was measured under varying temperatures and magnetic field (relevant to the nominal ITER PF operation conditions).

The strands were inserted in the Variable Temperature Cryostat Facility (VTCF) developed and recently upgraded at CEA/Cadarache, and were tested at CNRS in the Grenoble High Magnetic Field Facility (GHMFL).

The results were relevant on two areas :

- For the determination of the better-adapted fitting factors in the “generalized Summer formula” related to the $J_C(B,T)$ in industrial NbTi strands. The results were globally in agreement with previous publications on the subject.

- For the determination of the more convenient strand for the PF Coil manufacturing. In that field, both strands meet the ITER PF specifications, but show a substantial room for improvement to be found optimized with respect to general working conditions in thermonuclear fusion. This can so lead to some industrial action.

MANUFACTURE OF TWO SAMPLES OF SUBSIZE CONNECTIONS AND CONDUCTORS RELEVANT TO PF OPERATION [2]

From the two selected strands: Alstom strand with CuNi barrier and Europa Metalli strand Ni coated, two 108 strands conductor lengths were cabled by Brugg Kabel AG (switzerland) and jacketed with a square 316 L jacket by Europa Metalli (Italy) under ENEA monitoring. The conductor twist pitches as well as the void fraction were as expected.

From these two conductor lengths, two subsize joint samples were manufactured in the CEA laboratory. The joint was designed using the so called twin box concept which was previously used by CEA for the Nb_3Sn joint samples. A specific adaptation to the NbTi conductor where there is no reaction heat treatment, was developed, specially to define the best surface preparation for the contact between the strands and the copper sole. The lowest contact resistance was found with a silver coating of the strand as well as of the copper sole.

After a preparation in this way of the conductors added with a mechanical nickel removal in the particular case of the Europa Metalli conductor, the two subsize joints were compacted up to a void fraction of about 28 %. The joint assembly was performed by 60/40 tin/lead soldering before the final clamping and the piping. The samples were then instrumented with inlet and outlet temperature sensors, Hall probes, voltage taps and magnetization pickup coils on the joint as well as on the conductor. A specific device with 4 Hall probes was placed on one conductor length near the joint to measure the current distribution inside the conductor.

The first sample, called PF1-SSJS, using the Alstom strand was installed in the JOSEFA test facility for testing. The second sample, PF2-SSJS, using the Europa Metalli strand will be tested within the year 2002.

A subsize joint sample near its JOSEFA support
The JOSEFA cryostat at the rear

The upgraded JOSEFA sliding sample cryostat
with the magnet at the bottom

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

The upgrading of the facility was installed by the end of 1999. The tests of the first subsize NbTi joint sample was started during the year at various temperature under magnetic field up to 3.5 T and with a transport current through the samples up to 10 kA. The new command control system of the facility was operational although some parameters of the temperature regulation have to be improved. The first tests were performed in the joint position (upper position). The lower position for conductor test will be used during the year 2002.

MANUFACTURE OF THE PF FULL SIZE JOINT SAMPLE [3]

The CEA proposal for the conception of the first NbTi full size joint sample was to use the so called twin box concept successfully developed for Nb_3Sn joint samples.

A conceptual design of the PF-FSJS was developed by CEA, taking into account the experience gained during the manufacture of the three Nb_3Sn full size joint samples performed in the previous tasks, and using the developments on the contact between NbTi strands and copper sole led in this task. This conceptual design served as the basis for the technical specifications of the call for tender issued by ENEA.The manufacture of the sample by industry and the tests in the SULTAN test facility are planned in the year 2002.

CONCLUSION

During the year 2001, two industrial NbTi stands were characterised (critical current density) for varying magnetic fields and temperatures. Two 108 strands NbTi conductors were manufactured by industry using the two previously selected strands. Two subsize joint samples were assembled from these conductors and instrumented for conductor as well as for joint characterization. The upgraded test facility JOSEFA was operational and the tests of the first joint sample were started.

A design of the first PF Full Size Joint Sample was proposed and a call for tender was launched in industry.

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TW0-T400/01

Task Title : CSMC AND TFMC INSTALLATION AND TEST

INTRODUCTION

The first phase of tests of the TF Model Coil (TFMC) of ITER took place at the Forschungszentrum Karlsruhe (Germany) from 16 July to 8 August and from 10 September to 28 September 2001.

In this phase the TFMC was tested as a single coil.

CEA participated actively to this phase and delegated 4 persons to attend the tests. In particular, J.L Duchateau as the Deputy Testing group Leader for these tests spent 4 weeks at FZK. CEA contributed to the analysis of the electromagnetic, thermohydraulic and mechanical properties of the coil.

During this experiment the TFMC current was progressively and successfully increased up to its nominal current of 80 kA.

After the tests, in November, the 15 th Test and Analysis Meeting was held at Cadarache. During this meeting, the main conclusions of these tests were presented.

CEA was mainly involved in the measurement of the joint resistances, in the measurement of the cold losses developed in the radial plates during transients and in the estimation of the critical performances of the conductor.

2001 ACTIVITIES

MEASUREMENT OF COLD LOSSES IN THE RADIAL PLATES

The presence of the radial plates TFMC (figure 1) in which the conductors are inserted is a very representative and very specific component of the ITER TF coils.

These plates play a leading part in ITER to sustain the very important centring force in the magnetic system due to the magnetic load.

Due to these plates the insulation system is also very specific and was tested in the TFMC. In addition, in transients, cold losses are generated in the plates and transferred through the insulation to the helium channels.

A model for these cold losses was developed at CEA/Cadarache [1] and calorimetrically measured in experiments such as safety discharges and trapezoidal cycles of currents at different ramp rates.

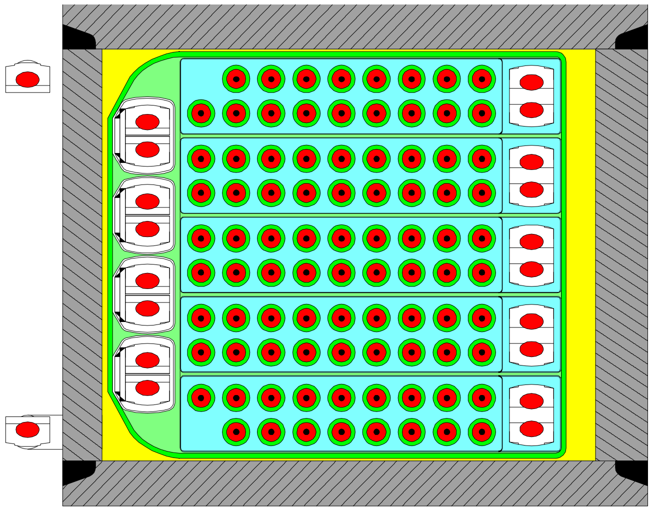

Figure1 : Cross-section of the TFMC with plates and conductors

It was found that the model was quite adequate to predict the behaviour as it can be shown for instance in figure 2 as concern the trapezoidal runs.

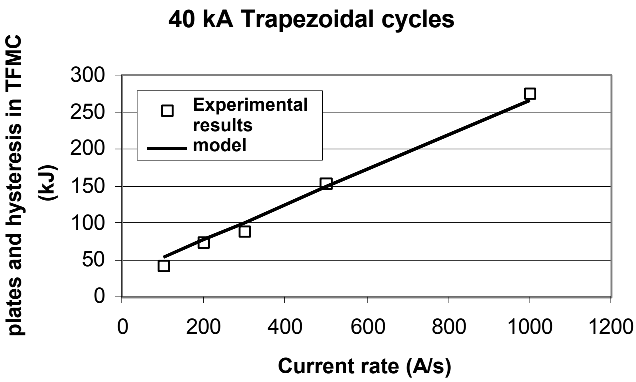

Figure 2 : TFMC Plates and hysteresis losses : comparison of prediction and measurements

Due to the voltage ripple of the power supply voltage at 600 Hz, it turned out that a sinusoidal wave was permanently induced in the radial plates producing a constant heat load.

This heat load, which was not expected, was about 2.5 W per plate and practically independent on the power supply current.

MEASUREMENT OF THE JOINT RESISTANCES

The TFMC experiment was a first opportunity to test an important number of joints of the type developed by CEA, the so called « twin box » joint.

15 joints were present in the TFMC :

- 5 inner joints at high field, connecting the two pancakes of the same module,
- 4 outer joints at low field, connecting adjacent modules,
- 2 mix joints Nb_3Sn-NbTi connecting the NbTi busbars to the coil terminals,
- 2 NbTi-NbTi joints connecting the two parts of the busbars,
- 2 NbTi-Nb_3Sn joints connecting the busbars to the current leads.

The joint resistances were estimated by direct electric voltage measurements across the inner joints and by calorimetric measurements on the 10 parallel hydraulic circuits of the coil.

The results are presented in figure 3.

The resistances are quite low and in agreement with the first results observed in the 2 prototypes tested at the Sultan Test facility (TFMC-FSJS and SS-FSJS) [2], [3].

As all these joints have been fabricated in industry (Alstom and Ansaldo), this good result demonstrated a successful transfer of technology from laboratory to industry.

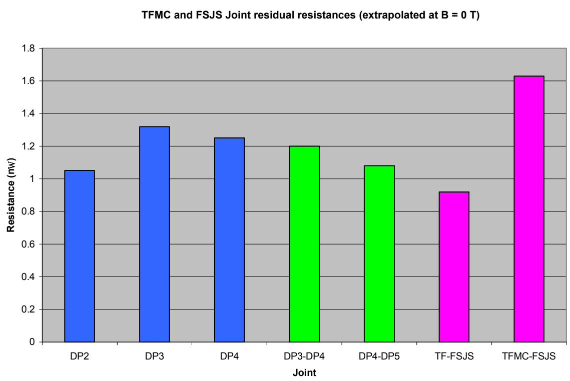

Figure 3 : TFMC resistances at 0 T compared to TFMC-FSJS and SS-FSJS samples resistances

ESTIMATION OF THE CRITICAL PERFORMANCES OF THE CONDUCTOR

In such a coil, cooled by forced flow helium, it is possible to explore the critical properties and the margins of the conductors by increasing very slowly the temperature of the helium injected in a given pancake at a given current and current density J in the conductor.

This was done for the DP1.2 pancake of the TFMC. In theses conditions it is possible to reach the current sharing temperature Tcs of the conductor which can be defined as : Jconductor=Jc(Tcs,B).

This operation has been done at three current values : 80 kA, 69 kA and 56.6 kA.

For these current it is possible to compare the expected current sharing temperature and the observed experimental current sharing temperatures.

The expected Tcs can be estimated from the measurement of the strand at variable temperature and from the insurance quality process during the fabrication of the cable.

The observed Tcs is delicate to calculate as the only measured temperature is located at the helium inlet of the pancake, the current sharing point being situated at about 1 m from the inlet at the high field point of the pancake.

The result is presented in figure 4. It can be seen that the conductor reach the expectations.

However from strand properties to conductor behaviour, it is now admitted by the Magnet Community that some degradation occurs, the origin of which is not yet understood. This degradation is expressed through a lower value of the "n" value and a decrease of the current sharing temperature from strand to conductor if referred to the same electrical field.

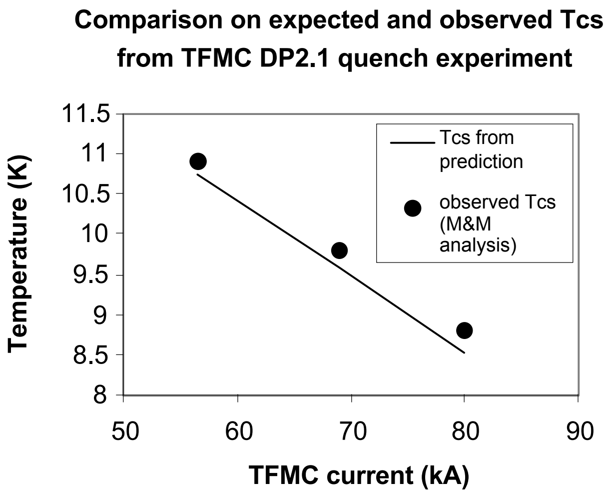

Figure 4 : Comparison of observed and expected Tcs in the TFMC

CONCLUSION

The successful test of the ITER TFMC in the first phase demonstrated the reliability of the design options for the ITER TF coils. A second phase of the tests is in preparation for 2002. During this second phase, the TFMC will be tested together with the LCT coil, which will allow to simulate the operation of a coil in the TF magnet. In particular, the quench behaviour will be studied at higher field and the coil will experience both in-plane and out-of-plane mechanical loading. The data acquisition system of the facility will be improved in view of these tests.

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TW1-TMC-CODES

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Task Title : DESIGN AND INTERPRETATION CODES

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INTRODUCTION

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A significant design parameter of the cooling systems of the ITER superconducting magnets is the "recooling time" Tr.

This recooling time is the time necessary for the conductor to recover the initial temperature after a temperature increase due to heat power induced by AC losses in the coils.

The conductors used in ITER as well for the Toroidal Field (TF) magnet as for the Central Solenoid (CS) magnet or the Poloidal Field (PF) magnet are all of the circular cable with central channel CICC type (Cable-In- Conduit-Conductor).

They are cooled by two supercritical helium flows in parallel:

- a flow in an annular channel containing the cable, with a relatively low flow velocity (0.1 m/s),

- a flow in a central channel with a higher flow velocity (1 m/s).

One conductor length L is approximately 1000 m.

The "recooling time " Tr depends primarily on two parameters:

- the heat transfer coefficient Hac between the two channels in parallels,

- the fluid velocity in each channel.

If the value of heat transfer coefficient Hac is very small, each channel is adiabatically insulated and the recooling time Tr can be calculated by considering the flow velocity Ua in the annular channel (Tr = L/Ua).

On contrary, if the value of the heat transfer coefficient Hac is large, which corresponds to an ideal case, the recooling time Tr in the CICC is identical to a flow in a conductor having only one channel with an equivalent velocity V given by the ratio between the total mass flow rate and the sum of the helium cross sections of each channel [1]. The recooling time Tr is then equal to L/V.

The objective of the Task CODES is twofold :

- to investigate the influence of the geometry of the central spiral limiting the central channel on the hydraulic resistance of the ITER conductors,

- to determine the heat transfer coefficient between both channels of the ITER conductors.

2001 ACTIVITIES

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MEASUREMENT OF THE HYDRAULIC RESISTANCE OF THE CENTRAL CHANNEL

The hydraulic resistance measurement of the central channel of the ITER model coil conductors had been performed at CEA/Cadarache in the OTHELLO facility [1]. The facility will be used again in 2002 to perform measurement of mass-flow and pressure drop on spiral samples. Several spiral samples will be procured with different diameters, twist pitch, gap and profiles in order to allow parametric study of the hydraulic resistance.

MEASUREMENT OF THE HEAT TRANSFER COEFFICIENT Hac

Method to determine Hac

Following a jump of temperature at the inlet of the conductor, the evolution of the temperature at the exit of the conductor depends on the heat transfer coefficient Hac and the flow velocity in each channel. The temperature at the end of the annular channel remains at constant temperature until the hot fluid flowing at a high velocity Uc in the central channel reaches the end of the conductor, i.e. at the moment L/Uc (result of heat transfer between these two channels). As the hot fluid in the annular channel flows at a low velocity Ua, the value of the recoolig time, at the exit of the conductor, lies between these two extreme values: L/Uc and L/Ua.

A numerical and analytical model [1] was developed to predict the evolution of the temperature of a CICC following a jump of temperature at the entry or a jump of thermal power along the conductor. This model uses the heat transfer coefficient Hac between the two channels in parallel as a variable parameter. By comparing the evolution of temperature at the exit of the conductor obtained in experiments with that obtained by the model we can thus determine a correlation giving the heat transfer coefficient according to the adimensional parameters of the flow (Reynolds number and Prandtl number).

Design of a facility

Conductor sample

The tests will be performed with the conductor (figure 1) used for the manufacture of the ITER Toroidal Field Model Coil (TFMC). A 10m long conductor sample is available at CEA/Cadarache.

The principal characteristics of the conductor are indicated in table 1.

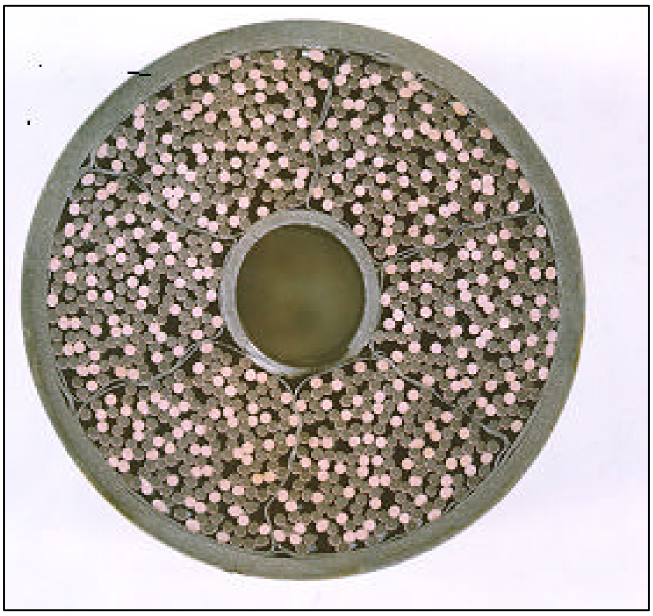

Figure 1 : TFMC conductor cross-section

Table 1 : Geometry of the TFMC conductor

CONDUCTOR	Annular area	Central area
External diameter = 40.5 mm	Helium cross section = 344.4 mm²	Helium cross section = 76.8 mm²
Cross section = 1097.2 mm²	Wetter perimeter = 3.051 m	Wetter perimeter = 31 mm

Design of the test loop

A test loop, (figure 2), has been designed to operate with pressurized water (2 bar at the aspiration of the pump) and at a maximum temperature of 100 °C. It will include a pump with a maximum mass flow rate of 10 m^3/h and with a total head of 400 m (40 bar), a heater of 30 kW to increase the temperature of the loop up to 100 °C, an heat exchanger of 100 kW to reduce the temperature of the loop to the initial temperature and a pressuriser for on the one hand absorbing dilations during the heating and on the other hand to maintain the loop under a pressure of 2 bar. It will be instrumented with a flowmeter, a transmitter of differential pressure and temperature sensors. The velocity in the networks will not have to exceed 2 m/s for a mass flow rate of 10 m^3/h, which dimensions the diameter of conduits (DN 50).

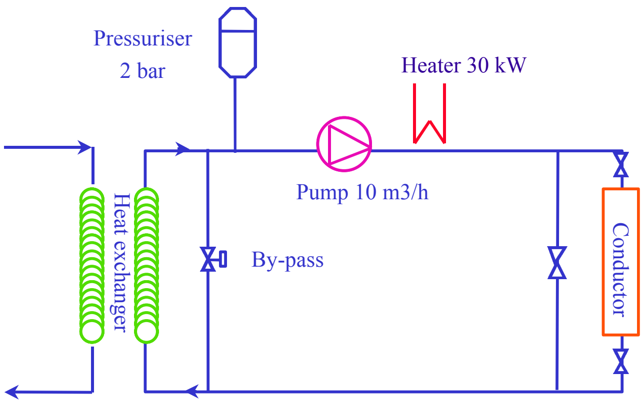

Figure 2 : Pressurized water test loop

Evaluation of the heat transfer coefficient Hac

By using the dimensional analysis and the principle of similarity of the flows (Reynolds analogy), one can derive the real case (supercritical helium) from the results obtained with pressurized water at 100°C.

For the three types of conductor used for the PF, CS and TF ITER coils, are indicated, in the table 2, the maximum value of the Reynolds number of the flow in the central channel and in the annular channel of the conductor.

Table 2 : The maximum Reynolds numbers in each ITER conductor

Conductor	PF	CS	TF
Reynolds number (central channel)	Rec max ~ 1.7 10^5	~ 1.5 10^5	~ 7. 10^4
Reynolds number (annular channel)	~ 2200	Rea max ~ 3000	~ 2500

For tests with a pressurized water loop at 100 °C, it is thus necessary to choose flows in a Reynolds number range including the maximum values indicated in table 2 to obtain the similarity of the flows.

Evolution of the temperature at the conductor exit

For a total mass flow rate of 0.25 kg/s and an initial temperature of 100°C, we determined, by using the numerical model, the evolution of the temperature at the exit of the conductor following a step of 10°C of the inlet temperature.

Figure 3 presents the evolution of the temperature at the exit of the conductor for various values of the heat transfer coefficient Hac.

For a temperature variation of 10°C, a precision on the temperature measurement of 0.1°C allows to evaluate the heat transfer coefficient with a precision of ± 25 W/m².°C.

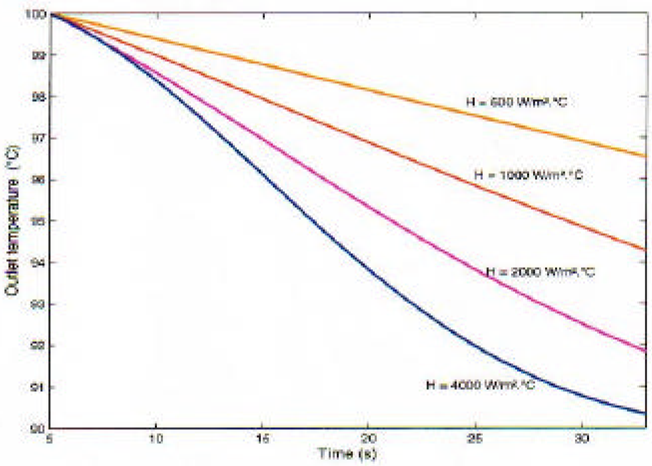

Figure 3 : Evolution of the temperature at the exit of the conductor for various values of the heat transfer coefficient Hac

CONCLUSIONS

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The OTHELLO facility will be used to measure the hydraulic resistance of several central spirals. A pressurized water loop, operated at 2 bar and 100°C was designed in order to carry out tests allowing to evaluate the heat transfer coefficient between the fluid of the annular channel and the fluid of the central channel of a dual channel CICC.

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[2] Internal note CEA/DSM/DRFC P/EM/93.18 "Supercritical helium cooling of a cable-in-conduit conductor with an inner tube", A. Martinez and B. Turck.

TASK LEADER

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TW1-TMC-SCABLE

Task Title : CABLE AND CONDUCTOR CHARACTERIZATION

INTRODUCTION

In the framework of R&D for the design and manufacturing of the coils of the ITER magnetic system, CEA is in charge of the electromagnetic characterization of several strands chosen to be included in specific Insert Coils to be tested in the Central Solenoid Model Coil (CSMC) at Naka (Japan) : the main ones are the Poloidal Field Coil Insert (PFCI) and the Toroidal Field Coil Insert (TFCI).

The strand are made of NbTi (PFCI) and Nb_3Sn (TFCI) and have been manufactured by VNIIKP (Russia).

Concerning the Nb_3Sn strands, the heat treatment will be done at CEA/Cadarache in a dedicated oven.

The aim of the experimental program is to define the properties of the strands and subcables :

- Critical current density measurements of the strands at various magnetic fields and temperatures.

  This will be achieved in the CEA Variable Temperature Cryostat Facility (see Figure1) in collaboration with the Grenoble High Magnetic Field Laboratory (CNRS, Grenoble). This was already performed for other ITER strands [1].

- AC losses measurements of 36-strands subsize cables. This is to be held in the JOint Subsize Experimental Facility (JOSEFA) at CEA/Cadarache, at various temperatures.

These characterizations will constitute a basic reference for modeling and understanding of the Model Coils behaviour and for a better control on the meeting of the industrial ITER requirements.

2001 ACTIVITIES

Due to administrative difficulties, the strands shipping from Russia has been delayed to the beginning of the year 2002.

The test campaign is then previewed to be held in the middle of the year 2002.

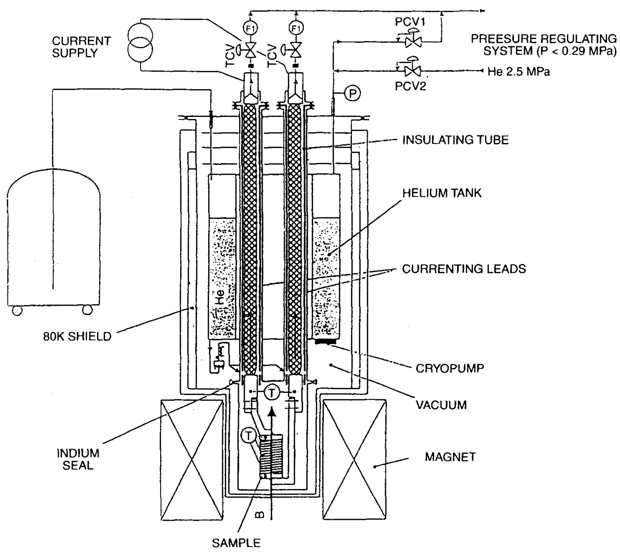

Figure 1 : Variable Temperature Cryostat scheme

CONCLUSION

A test programme of actual strands used in Insert Coils for ITER is established and facilities available to carry out this programme. Delay in the strand delivery postponed the tests to 2002

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