New results and remaining issues in superconducting magnets for ITER and associated R&D in Europe

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Abstract. The magnetic system of ITER is very challenging. Both the CS (Central Solenoid) coils and the TF (Toroidal Field) coils in ITER will use Nb_3Sn as superconducting material, very sensitive to applied strain and actually having a limited production. However 517 t will be required for ITER. PF and CC coils will use NbTi strands, but no conductors, carrying 45 kA and operating in pulse mode in a tokamak, have ever been produced.
For Nb_3Sn conductors, the tests of two model coils, the Central Solenoid Model Coil (CSMC) and the Toroidal Field Model Coil (TFMC) showed a reduced operating margin, compared to what was expected from strand measurements. This induced in 2003 a revision of the design of these conductors and a complementary R&D programme to qualify the modified design. Nevertheless, the first results show that more effort is still needed. For NbTi conductors for PF coils an important milestone will be the upcoming tests of a an ~ 50 m long PF conductor, wound in a single layer solenoid and inserted in the CSMC bore.
Although manufacturing techniques for TF and CS coils have been qualified by the construction of the model coils, nevertheless, several points require further development, like the metallic screen inside the insulation of the PF conductor, aiming at control of the dielectric quality of the insulation through the life of the machine, or the insulation system of the TF coils, for which it is necessary to demonstrate the feasibility of using radiation-resistant resins, such as cyanate-ester based systems.
Contrary to the model coils, the CS, TF coils and PF coils will be wound into multiple pancakes, which implies the insertion of helium inlets at the innermost turn and a specific development, including as well mechanical qualification as hydraulic qualification. Dedicated developments are also carried out to demonstrate the manufacturing feasibility as well of the radial plates into which the TF conductor will be wound as of the pre-compression rings of the TF magnet and to qualify the PF tail design.

1. Introduction

The magnetic system of ITER will use superconductors as well for the Central Solenoid (CS) as for the Toroidal Field (TF) coils or for the Poloidal Field (PF) coils or the Correction Coils (CC). Although several fusion devices using superconducting magnets are now in operation, the large size and the high magnetic field of ITER make the construction of these magnets a challenge. Whereas the experience in superconducting fusion machines is mainly provided by the use of NbTi as superconducting material, both the CS coils and the TF coils in ITER will use Nb_3Sn as superconducting material. This choice resulted from the selection of 13 T as design point for the maximum induction in these magnets. Contrary to NbTi for which a large market exists for MRI magnets, the Nb_3Sn yearly production is still limited to few tens of tons, which makes the production of the 517 t required for ITER a novel goal for the strand manufacturers. Another difficulty comes from the particular sensitivity of Nb_3Sn to applied strain. As far as PF and CC coils are concerned, the maximum magnetic induction does not exceed 6 T which allows the use of NbTi strands, although no conductors, carrying 45 kA and operating in pulse mode in a tokamak, have ever been produced.

Conductor issues are considered first, addressing Nb_3Sn and NbTi conductors, then coil issues. For each item, are presented the associated R&D and the already available results.

2. Conductor development

For Nb_3Sn conductors, a major R&D programme was carried out from 1992 to 2002 in the framework of the EDA phase of the project [1]. The main milestones of this programme were the manufacture and tests of two model coils, the Central Solenoid Model Coil (CSMC) and the Toroidal Field Model Coil (TFMC). The tests of these coils in 2000-2002 were a major step in the qualification of the conductor and coil design [2],[3]. We will focus first on the outcome of these tests and the following additional R&D programme which they induced and then on the ongoing NbTi conductors development.

2.1 Sensitivity of Nb_3Sn to strain

The sensitivity of Nb_3Sn to strain appears clearly when plotting the variation of the critical current density J_c in the non-copper area of strands versus the applied longitudinal strain [4]. To avoid inducing strain during manufacture, a heat treatment at 650°C is introduced in the manufacturing process of the coils using such strands, so as to produce Nb_3Sn inside strands only after cabling, jacketing and winding the conductor. In this way, the resulting applied strain to the superconducting material is limited. The effective strain ε_{eff} is then the sum of two components : $\varepsilon_{eff} = \varepsilon_{th} + \varepsilon_{op}$, ε_{th} standing for the strain induced by the differential thermal contraction from 650°C to 4 K and ε_{op} for the strain induced by the electromagnetic forces during operation. In order to limit ε_{th}, the use of low thermal contraction coefficient materials matching that of Nb_3Sn, as Incoloy 908 or titanium was planned for the conductor jacket.

2.2 Conductor design

A key criterion to design conductors is the temperature margin $\Delta T_{cs} = T_{cs} - T_{op}$, where T_{cs} stands for the current sharing temperature (conventionally defined at an average electric field in the conductor of 10 μV/m) and T_{op} for the operating temperature. The temperature margin is a simple mean to evaluate the ability of the conductor to continue to run current while being submitted to temperature increase due to perturbations. These perturbations can be estimated by using models taking into account on one hand the planned operation scenarios and on the other hand the thermohydraulic behaviour of the conductor. Nevertheless, accurate prediction of the exact behaviour of the conductor for all kinds of possible events becomes very difficult and requires performing codes, validated on a large database. In order to account for uncertainties (engineering margin), when the R&D programme was launched in 1992, a temperature margin of 2 K for an operating temperature of 5 K was thus used for the design of the ITER Nb_3Sn conductors. The assumption for ε_{th} was respectively of -0.35% when using a thick Incoloy 908 jacket, -0.25% when using a thin titanium jacket and –0.68% when using a thin stainless steel jacket.

2.3 Results of the model coils

The model coil programme included first the manufacture of the CSMC and TFMC, aiming at the qualification of the manufacturing techniques of the CS and TF coils and second the manufacture of Inserts coils, to be tested in the inner bore of the CSMC. The aim of these Inserts was to qualify the design of the conductors on significant lengths in testing them with full instrumentation in relevant current, magnetic field and temperature conditions. The CS Insert (CSI) was tested in 2000, the TF Insert (TFI) in 2001 and the TFMC in 2001-2002.
Although as well the CSI as the TFI achieved operation at relevant currents in 13 T magnetic field, in both cases the measured temperature margin was much lower than expected. In addition, a reduction of this temperature margin was observed when cycling the CS Insert with current [5]. It was shown a linear decrease of T_{cs} when increasing the electromagnetic load, as also observed in the TFMC [6]. To account for this unforeseen effect, an additional term ε_{extra} was added in the evaluation of the effective strain : $\varepsilon_{eff} = \varepsilon_{th} + \varepsilon_{op} + \varepsilon_{extra}$ with : $\varepsilon_{extra} = -\gamma\, I\times B_{ave}$ where I is the current and B_{ave} is the average magnetic field in the conductor cross section. Table I gives a summary of the achieved performances in the model coils and inserts.

TABLE I : TEMPERATURE MARGIN IN ITER MODEL COILS

Coil	CSI	TFI	TFMC
Jacket material	Incoloy 908	Titanium	316LN stainless steel
Expected ΔT_{cs}	2 K	2 K	2 K
ΔT_{cs} before cycling	1 K	0.5 K	1 K
ΔT_{cs} after cycling	0.7 K	0.43 K	1 K
ΔT_{cs} reduction	- 1.3 K	- 1.57 K	- 1 K

2.4 Nb_3Sn conductor design revision and additional R&D

Following the results of the model coils and inserts tests, a new design of the ITER Nb_3Sn conductors was issued in 2003 [6], assuming on one hand the use of newly developed "advanced" strands having a higher current carrying capability and of stainless steel as jacket material and on the other hand a temperature margin of 0.7 K instead of 2 K. Owing to the analyses of the model coil test results, the assumed effective strain was revised at -0.74% for the CS coil and -0.77% for the TF coil and the magnetic field used for the calculation of Jc was the average field in the conductor cross-section B_{eff} (11.2 T for TF coil) instead of the maximum field B_{max} (11.8 T for TF coil). *FIG. 1* summarizes the guidelines of this design.

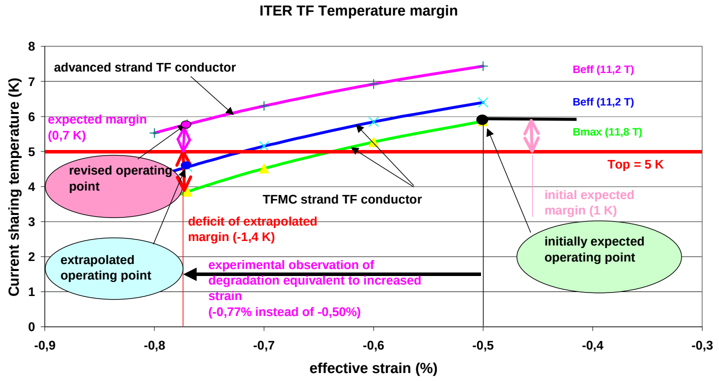

FIG. 1 ITER TF conductor temperature margin

A worldwide additional R&D programme was then launched in the ITER Participant Teams (PTs) to qualify this new conductor design. In Europe, 2 full-size conductor samples, named TFAS1 and TFAS2, built according to the TFMC conductor design but using “advanced” strands have been tested in 2006 in the SULTAN facility in Villigen (Switzerland) and the results of these tests have been recently presented [7]. Unfortunately, the achieved performances of these conductors are far below expectations: they all exhibit a low current sharing temperature, which is further reduced when applying current cycling [8]. After 1100 cycles, the Tcs range is [4.8 K – 5.2 K] whereas the target was 5.7 K. Although these conductors are not relevant to the TF conductor design since they were built according to the TFMC conductor design, it seems that their behaviour is linked to the increased sensitivity of the “advanced” strands to bending under transverse load. In the next months, in the framework of the R&D programme defined in 2003, 4 relevant TF conductor samples are planned to be delivered by Europe, Russia, Korea and Japan to be tested in the SULTAN test facility. The results of these tests will be a first step toward the final qualification of the new TF conductor design. If the tests of these upcoming samples were to confirm the behaviour of the TFAS1 and TFAS2 samples, it is clear that a new revision of the conductor design would be necessary. In that case, improvement of conductor performances could come first from the use of strands having higher mechanical resistance under bending and second from the use of cables providing better support for the strands. Another source of improvement could be the reduction of the force per unit strand length, which could result from a lower current in each strand and correlatively an increase of the number of superconducting strands in the cable.

2.5 NbTi conductors

The development of NbTi conductors for the ITER PF coils has been undertaken in Europe in 1999. In a similar way to that followed for the Nb_3Sn conductors, the development includes tests of full-size conductor samples in SULTAN and tests of an Insert coil in the CSMC. Two full-size conductor samples were manufactured and tested in SULTAN : the PF-FSJS, using strands produced by two European manufacturers and the PFCI-FSJS, using strands produced by a Russian manufacturer. The tests of the PF-FSJS, performed in 2002 [9], and that of the PFCI-FSJS, performed in 2004 [10], showed that the 3 conductors were achieving a current capacity of 45 kA at 6 T but failed to meet the temperature margin assumed in the ITER design, as shown in Table II. In addition, these conductors showed a surprising tendency for premature “sudden” quench at relatively low currents – an issue likely related to the non-uniformity of temperature, field and current on the conductor cross section. The next step of the programme are now the tests of the PF Insert (PFI) in the CSMC, which should occur in 2007 [12]. The manufacture of this coil in European industry (*FIG. 2*) which started in 2003, using a 50 m length of the same conductor as that used in the PFCI-FSJS, is about completion [13] and the tests in 2007 might lead to a NbTi conductor design revision.

TABLE II : TEMPERATURE MARGIN IN ITER PF CONDUCTORS

Coil	PF-FSJS/Alstom	PF-FSJS/EM	PFCI-FSJS/Bochvar
Jacket material	316LN stainless steel	316LN stainless steel	316LN stainless steel
Expected ΔT_{cs}	1.5 K	1.5 K	1.5 K
ΔT_{cs} before cycling	1.4 K	1.25 K	1.1 K
ΔT_{cs} after cycling	1.4 K	1.25 K	1.1 K
ΔT_{cs} reduction	-0.1 K	-0.25 K	-0.4 K

FIG. 2 ITER PF Insert during manufacture

An additional development addresses the qualification of high copper content NbTi strands, expected to be used for the low field PF conductors (PF2 to PF5).

3. Coil development

In the framework of the EDA phase, manufacturing techniques for TF and CS coils have been qualified by the construction of the model coils. Nevertheless, several points require further development. We will address here the metallic screen inside the insulation of the PF conductors, the development of a new resin for the TF coils, the development of helium inlets for TF and CS coils, the study of manufacturing techniques for radial plates for the TF coils, the development of pre-compression rings and of PF tails.

3.1 Metallic screen inside PF conductor insulation

This first item can be classified as a conceptual design issue : to control the dielectric quality of the insulation through the life of the machine, it is planned to install a metallic screen inside the insulation of the PF conductor. Two aspects have thus to be considered: the efficiency of this screen, which requires analysis, and its manufacturing feasibility.

As far as the manufacturing feasibility is concerned, trials performed in industry showed that the use of a continuous stainless steel ribbon wrapped inside the insulation was not suitable and the use of a stainless steel cloth was recommended.

3.2 Radiation-resistant resin for the TF coils

The TFMC used a classical multilayer glass-polyimide composite, impregnated by DGEBA epoxy resin. This system could be used for the ITER TF coils, but mechanical tests on small samples have shown that, although good mechanical properties are maintained after low fluence neutron irradiation, the performance degrades significantly when reaching the ITER design fluence of fast neutrons (10^{22} m^{-2}, E>0.1 MeV). This was an incentive for investigating possible alternative solutions, using radiation resistant resins, which could be applied for ITER and future fusion freactors (*FIG. 3*). A specific development is being carried out in Europe, including the manufacture of a reduced size mock-up to demonstrate the feasibility of using new resins, such as cyanate ester based systems, in the TF coils.

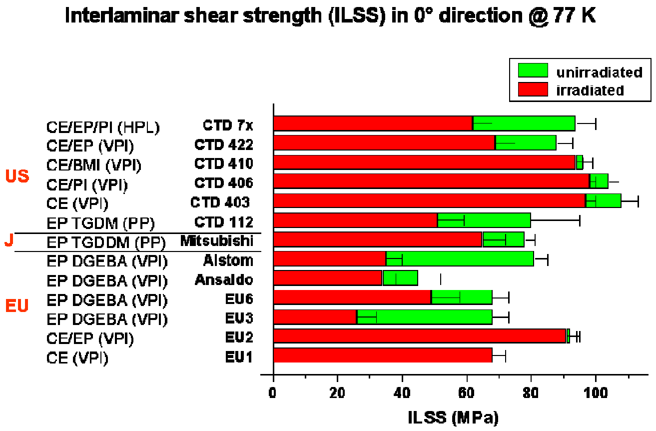

FIG. 3 : Mechanical performance of resins

As demonstrated by the tests done at ATI [14], cyanate ester/epoxy resin blends, also with different ratios, seem to be very interesting because of their good mechanical properties after irradiation. Nevertheless, the formulation initially proposed by Hunstman (PY 306 : 60 ppw; AroCy 10-L : 40 ppw; Mn-acetyl-acetonate in nonyl-phenole : 1.5 ppw) shows characteristics (short pot life, curing temperature 177-180°C, toxicity of the catalyst), which are not directly applicable to the vacuum impregnation process of the ITER TF coils on an industrial scale. Indeed, the resin has to fulfil the following requirements:
- due to the large dimensions of the coils to be impregnated, a pot life of at least 24 hours is required at the impregnation temperature (between 40°C and 70°C). The viscosity is initially lower than 100 mPa.s and should not exceed 200 mPa.s at the end of the pot life time. The pot life and also the exothermic reactivity have to be adjusted by choosing the right quantity of catalyst.
- the safety aspect is important: it could be very difficult, even impossible, to use in an industrial environment a catalyst classified as slightly carcinogenic.
- due to the constitutive elements of the coil, the curing temperature cannot exceed 150 °C.
- the system has to support several curing cycles to promote better polymerisation.

Since 2005, Huntsman has been working to adjust the resin formulation to the coil requirements. According to their latest results,
- a suitable viscosity profile can be obtained with pure cyanate ester and with the “reference” resin formulation (60 % epoxy + 40 % cyanate ester) the pot life is reaching 22 hours.
- for this purpose, the catalyst system has been changed, by using another solvent. The catalyst is no more classified as potentially carcinogenic.

Two issues need to be addressed:
- the polymerisation cycle still needs to be optimised to achieve good mechanical properties while keeping the curing temperature around 150°C .
- large scale application and safety studies still need to be performed.

3.3 Helium inlets

Contrary to the CSMC, wound in layers, the CS coils will be wound into multiple pancakes. In a similar way, the TF coils will be wound in double pancakes, whereas the TFMC used single pancakes connected by inner joints. This design implies the insertion of helium inlets at the innermost turn in the highest field area. A dedicated development has been carried out in Europe, including on one hand mechanical qualification to withstand the large hoop load and on the other hand hydraulic qualification to ensure that helium flow is evenly distributed inside the cable so as to provide efficient cooling of the most critical area from the electrical point of view. Two specific designs have been developed : one for the TF He inlet and one for the CS He inlet. In both cases, hydraulic qualification was met through tests of dedicated full-size mock-ups [15]. However, the mechanical qualification of the TF He inlet is not yet complete, since the tests of the relevant mock-up at 4 K led to a premature failure at 476 117 cycles instead of the required 600 000 cycles [16]. On the other hand, mechanical qualification of the CS He inlet is still to be performed, when relevant CS conductor jacket material becomes available.

3.4 Radial plates

A specific feature of the TF coils is the use of stainless steel radial plates, inside which the conductor lengths are embedded. The manufacture of full-size radial plates matching the tight tolerances is far from being straightforward, since these plates cannot be produced from a single forged piece, as done for the TFMC. A manufacturing feasibility study has thus been undertaken [17]. As best solution the premachining of three large segments with grooves was identified which gives the advantage of having an inner leg forged in one piece to withstand the high stresses and saves fabrication time in parallel.

3.5 Precompression rings

As far as structures are concerned, one of the items to manufacture are the precompression rings, which will ensure convenient operation of the TF magnet from the mechanical point of view. The high loads to resist in these two rings, located at top and bottom of the TF coils, require development of a high resistance composite built with filamentary glass-fibers using a roving technique. Prototypes are to be built in a development programme underway.

3.6 PF Tail

Key structural elements of the PF coils are the PF Tails, which allows transfer of the hoop force from the outermost turns toward the adjacent ones by shear inside the insulation. A prototype mock-up has been manufactured to demonstrate feasibility and effectiveness of the PF tail design [18] and fatigue tests at 77 K are planned in a near future.

4. Conclusions

The development of conductors for the ITER coils is still underway and important milestones are scheduled for early 2007. Nevertheless, preliminary tests performed as well on Nb_3Sn conductors as on NbTi conductors show that success is far from being granted. In a similar way, as far as coil components are concerned, radiation-resistant resin development for the TF coils is not straightforward and mechanical qualification of helium inlets and PF tails is not yet completed.

However, manufacture of large radial plates seem feasible and encouraging results are available for the manufacture of the pre-compression rings.

A huge effort is nevertheless now necessary to move toward optimisation of industrial processes to ensure success of the manufacture of the ITER coils. As far as the conductors are concerned, the strain issue in Nb_3Sn strands should be tackled by improving the mechanical support of the strands and by considering the use of “robust” Nb_3Sn strands. An increase of the temperature margin should also be included in the design.

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