Large Superconducting Conductors and Joints for Fusion Magnets : from Conceptual Design to Test at Full Size Scale

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Abstract. A new kind of superconducting conductor, using the so-called cable-in-conduit concept, is emerging mainly involving fusion activity. It is to be noted that at present time no large Nb_3Sn magnet in the world is operating using this concept. The difficulty of this technology which has now been studied for 20 years, is that it has to integrate major progresses in multiple interconnected new fields such as : large number (1000) of superconducting strands, high current conductors (50 kA), forced flow cryogenics, Nb_3Sn technology, low loss conductors in pulsed operation, high current connections, high voltage insulation (10 kV), economical and industrial feasibility. CEA was very involved during these last 10 years in this development which took place in the frame of the NET and ITER technological programs. One major milestone was reached in 1998-1999 with the successful tests by our Association of three full size conductor and connection samples in the Sultan facility (Villigen, Switzerland).

1. Introduction

The large next step fusion machine projects like NET (Europe), then ITER (Europe, Japan, Russian Federation and USA), have strongly pushed for constant progress in superconducting magnets during these last ten years. This development work has involved not only laboratories but also industrial manufacturers over the world. The Euratom-CEA Association has strongly been participating in all of these activities.

2. Conductor for Next Fusion Machines

2.1 Evolution of the Conductor Concept

Since the original cable-in-conduit concept introduced by Hoenig in 1975 [1], substantial progress has been made in the conductor design to fit the specifications of large magnets for Fusion. The main purpose was to develop an adapted concept easy to transpose to industry. The cable is presented in Fig. 1. This so-called dual-channel cable-in-conduit is made of a bundle region with 6 twisted main subcables (petals) around a central hole. The circular outer shape of the cable offers decisive advantages with respect to the rectangular (or square) one as concern both the overall cable performance and the manufacture. This solution, with different grades depending on the magnet system (TF, CS or PF), has now been retained for all the magnets of the ITER project.

2.2 Cable Performance

The round shape offers basically the most symmetrical solution ; the cable is nearly fully transposed. In changing fields, this is the best situation for uniform current distribution and for minimising induced current loops. Due to the joints, current non uniformity is present even in DC condition, but it can be mitigated thanks to interstrand contact resistance. Local void fraction as low as 35 to 36 % has to be achieved to allow current redistribution. Again the

round shape allows to achieve uniformly this requirement, by an isotropic compaction during production with a minimum of deformation.
In fusion magnets due to changing fields, inconel wrappings are needed around the petals. Losses are then dominated by this last stage, with no effect of the cable shape (circular or rectangular), for any orientation of the field.
As concern the hydraulics, the size of the central hole can be adjusted such as to limit the pressure drop, according to the unit length and the needed mass flow rate. As a matter of fact, the heat removal capacity and the pumping cold work are linked to the pressure drop which must be kept at a low level. Low pressure drop systems offer in addition some flexibility in the project by playing with the mass flow rate in case of unexpected higher losses.

2.3 Conductor Manufacture

The circular cross section adopted at the beginning of the EDA phase confirmed its advantage during the industrial production of 6 km of conductor for the ITER model coils. This is true not only for the cable manufacture but also for the jacketing process.
With the symmetrical configuration, both operations are made with the minimum of deformation resulting in little strand damage. The whole unit length of the manufactured cable can be pulled easily due to the round shape, through a pre-assembled jacket. The jacket conduit can thus be fully inspected and leak tested before the insertion process, which is a key advantage for quality assurance.
A first demonstration of the validity of the concept was made in 1992 when 20 meters of a full size 40 kA conductor was ordered by CEA in the framework of a NET contract and manufactured at Dour Metal (Belgium). A full size sample was tested successfully at SULTAN (CRPP, Swiss), thus inaugurating a new step for this European test facility [2].

2.4 Design Criteria

The different components constituting the strands (non copper and copper contents in superconducting strands, extra copper strands) are chosen according to a set of design rules agreed among the whole fusion Community. These are the so-called hot spot, temperature margin, and Stekly criteria. These design criteria cannot be described in details here, but relevant information can be found in [3]. The characteristics of the TFMC conductor presented in Table I (see TFMC-FSJS) were chosen according to these design criteria.

3. Conceptual Design of the Joint

3.1 Evolution of the Joint Concept

The joints between superconducting cables are special components in which the nice structure of the regular cable (see Fig. 1) has to be partly destroyed or modified. The joints, which are located in lower magnetic field, must not be the weakest point of the coil.
Within the framework of the NET project, two tasks were launched at CEA/Cadarache for the study of electrical joints [4], the upgrading of a test facility for subsize samples [5], and the fabrication and the tests of subsize joints in laboratory [6]. When the ITER project started, from the experience gained during the first phase, an original design for the joints of the ITER coils was proposed by EU [7]. From the results of this extensive study, the EU joint design was definitively confirmed [8], [9].

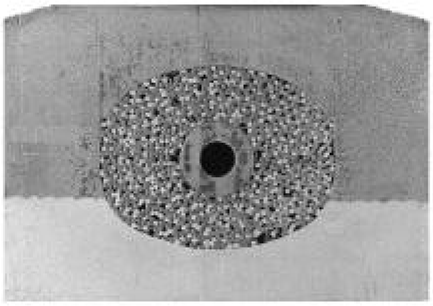

FIG. 1: Cross-section of SS-FSJS conductor.

FIG. 2: Cross-section of a TFMC joint box.

The single box concept was given up to the benefit of the twin-box concept. While the former consisted in an electrical joint (between cables or assembled inside a single box welded to the conductor jackets, with mixing helium flows, the latter is based on the fabrication of twin terminals at both conductor ends, the joint being then realised thanks to the soldering of these terminals [7]. Such a design allows the cooling of the joint in series with the conductor, keeping the independence of the helium paths in the joint, as well as an easier dismantling of the joint. Each cable end (after some specific preparation) is compacted in a termination box machined in a bimetallic plate bonded by the explosive method (see Fig. 2). Thus handling of the brittle Nb_3Sn cable can be avoided after the heat treatment (needed to fabricate the superconductor), and helium leak tests can be performed before and after this heat treatment and therefore before the final coil assembly. In that way, one draws the full advantage of the twin-box concept [10].

In parallel to subsize sample tests, mechanical tests were performed by CEA to assess the properties of the bimetallic explosive bond either on steel-copper plate or on Incoloy-copper plate. These tests confirmed the capability of such plates in the joint application [10].

3.2 Transfer of Technology to Industry

All the subsize samples were fabricated in laboratory (CEA/Cadarache), while the full-scale joints were manufactured only in industry (AGAN/Ansaldo and AGAN/Alstom). The EU joint design was retained for the joints of the ITER Toroidal Field Model Coil [11], and within the framework of this project, three full-size joint samples were fabricated in industry and tested in the dedicated facility SULTAN.

Because of the more complex structure of a full-size cable compared to a subsize cable, the transfer of technology had to be carried out through complementary R&D performed in industry. This R&D also allowed to qualify the industrial fabrication process [10], as well as to train workers in industry in view of the TFMC joints fabrication.

Although all the three EU full-size samples look similar (two conductor legs connected by a joint) each sample has its own particular features as concern conductor or joint (see Table I). The SS-FSJS has a joint following the original CEA design which is relevant to the TFMC inner joints. The TFMC-FSJS exhibits a modification introduced by Alstom (copper pins + EB welding) to cope with the TFMC fabrication process (outer joint). The TF-FSJS uses Incoloy-copper joint boxes to allow helium tight welds with an Incoloy conductor. All conductors used the same internal tin Nb_3Sn strand, 0.81 mm in diameter, with 60% copper.

TAB. I: CHARACTERISTICS OF THE THREE TESTED EU SAMPLES

Conductor	**SS-FSJS**	**TFMC-FSJS**	**TF-FSJS**
Number of Nb_3Sn strands	1152	720	720
Number of pure copper strands	0	360	360
Cable twist pitch (mm)	440	440	440
Central spiral (mm)	10 x 12	10 x 12	10 x 12
Cable diameter (mm)	38.7	37.5	37.5
Jacket shape, outer size (mm)	square, 51	circular, 40.7	circular, 39.5
Jacket material	316LN	316LN	Incoloy 908
Joint	**SS-FSJS**	**TFMC-FSJS**	**TF-FSJS**
Joint box material	316LN-copper	316LN-copper	Incoloy-copper
Joint interface	tapered wedge	copper pins	no
Jointing technique	PbSn solder	EB weld	PbSn solder

4. Recent Experimental Results

4.1 Joint DC Resistance

The resistance of each joint exhibit a linear dependence as a function of applied magnetic field, characteristics are presented in Table II. The three EU samples show low joint resistances which means that this technology is ready for the TFMC. The CEA twin-box joint concept thus proved to be valid as well for stainless-steel as for incoloy jacketed conductors.

4.2 Current sharing and quench in joints

The three joints were able to operate at their theoretical current sharing temperature T_{cs} with only a slight increase of the joint resistance and without quench. Compared to the expected T_{cs}, the quench temperature was much higher (~ 1K) in the SS-FSJS, about 0.5 K higher in the TFMC-FSJS, and only about 0.1 K higher in the TF-FSJS.

4.3 Conductor Tests

Classically, the conductor results were compared to the expected critical currents (i.e. the sum of the strand critical currents). The assumption about the effect of the jacket on the strain of the Nb_3Sn filaments plays a major role in such comparisons. Unfortunately this strain, which cannot be measured separately, greatly influences the critical current density. The measured critical currents were higher than expected from strand properties in the SS-FSJS (assuming a strain of $\varepsilon = -0.65\%$), and reached hardly the expected values (with $\varepsilon = -0.60\%$) in the TFMC-

TAB. II: COMPARISON OF JOINT DC RESISTANCES

Sample	**Joint resistance @ 2 T (nΩ)**	**Joint resistance @ 7 T (nΩ)**
SS-FSJS	0.84	1.34
TFMC-FSJS	1.96	2.51
TF-FSJS	1.28	1.87

FSJS. In the TF-FSJS, the critical current was 20% higher than for the TFMC-FSJS, but reached only 75% of the expected values (with $\varepsilon = -0.25\%$).

5. Conclusions

With the successful tests of the three EU full-size conductor and joint samples, a major milestone was reached in 1998-1999. The results obtained for the conductor performances as well as for the joints met the ITER specifications. Six kilometres of such a conductor were produced during the fabrication of the ITER CS and TF model coils.
The recent success of the CS model coil tests at JAERI (Naka, Japan) has confirmed the good behaviour of this conductor. The TF model coil should be tested in 2001 (Karlsruhe, FRG).
It has therefore been demonstrated that this technology is ready and available for the construction of the future ITER coils

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