

## Technology Transfer from Laboratory to Industry for Fabrication of Large Superconducting Coil Joints

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**Abstract:** The future magnetic thermonuclear fusion reactors will use superconducting magnets. The development during the last decade of the cable-in-conduit conductor (CICC) allows the transport of high current intensities. Nevertheless, the conductor units, which can be produced in industry with such conductors are not long enough to allow constitution of complete winding-pack out of one length. Therefore joints have to be implemented to connect electrically winding units with each other. These joints must fulfil electrical, mechanical, hydraulic and tightness requirements and their design must allow industrial feasibility. The twin-box concept, developed at CEA, was tested with 3 prototype joint samples, and applied to the joints of the ITER Toroidal Field Model Coil, manufactured in the European industry. The tests of this coil in 2001 showed successful operation of these joints, in particular low and reproducible resistances. The concept is now developed with niobium-titanium conductors for the ITER PF Coils and tested this year with a full size joint sample.

### 1. Introduction

The future magnetic thermonuclear fusion reactors will require the construction of large magnets for confinement of the plasma. The magnets should be able to produce reliably and routinely high magnetic fields during long pulses. Because of technological and economical reasons, these magnets should be built with superconducting materials, only able to carry a high electric current for long duration while needing low amount of energy to assure their cooling [1]. Machines for research activities on controlled fusion by magnetic confinement, already built as Tore Supra or LHD, under construction as W 7-X, or planned as ITER [2], relies thus already on the use of superconducting conductors.

The concept which emerged during the last decade to allow the transport of high intensities is the cable-in-conduit conductor (CICC) (Fig. 1) : a cable, made of a large number (in the range of thousand) of superconducting strands twisted together, is inserted inside a tight metallic jacket and cooled by internal circulation of supercritical helium to keep the conductor at cryogenic temperature (around 4.5 K) [3]. The metallic jacket provides mechanical stiffness as well as tightness. Nevertheless, the conductor units, which can be produced in industry, although their length can exceed one kilometre, are not long enough to allow constitution of complete winding-pack out of one length. It is therefore compulsory to constitute winding modules, for example double pancakes, to be connected with each other to constitute a complete winding-pack. A reliable joint technology to connect



Fig. 1 ITER TFMC conductor  
(40.7 mm  $\varnothing$ , 1080 strands)

these modules electrically and thermohydraulically is a major item in manufacturing of large superconducting magnets.

## 2. Joint specifications

The optimum location of joints in a coil is on the outer radius, so that they operate at lower magnetic field. The ITER Toroidal Field Model Coil (TFMC), manufactured with single pancakes, includes inner joints, operating at higher field, and outer joints, operating at low field. In the present ITER design [4], all joints are located at the outer radius, for the Toroidal Field (TF) coils as well as for the Central Solenoid (CS) coils and for the Poloidal Field (PF) coils. The joints are at the helium outlet of the conductor lengths so they do not impact on the conductor temperature. Nevertheless, several aspects have to be addressed when connecting two cable-in-conduit conductors :

- the lowest possible electrical resistance of the joint has to be achieved to minimize the required cooling power
- the joints are expected to stay stable during the coils operation including plasma disruption. As a first consequence, the mechanical cohesion of the superconducting cable has to be ensured to avoid any strand movement under electromagnetic loads, which would jeopardize the stability of the superconducting state. Second, the circulation of induced currents under the effect of magnetic field variation has to be limited, since it would cause local heating on one hand and increased transport current for some strands on the other hand, which could limit the current transport capacity. Third, uniform contact resistance at the level of the final substage of the cable must be achieved to provide an as homogeneous as possible current distribution between the strands
- the tightness of the joints is necessary to avoid any helium leak, which could lead to a degradation of the dielectrical insulation strength
- the manufacture of the joint has to be achievable in industry in a restricted volume.

## 3. The twin-box concept

The joints are usually divided into two families : the overlap joints and the butt joints. In the overlap joints, the two conductor lengths ends are put adjacent, so as to provide contact on their periphery, whereas in the butt joints the conductor end cross-sections are pressed against each other. The concept originally developed at CEA/Cadarache in the framework of NET tasks devoted to study electrical joints for cable-in-conduit conductors is an overlap joint [5]. This concept, named "twin-box", relies on the manufacture of a tight terminal at each end of a conductor unit. The jacket is removed from the conductor end and the cable inserted inside a terminal box (Fig. 2). Assembling to another conductor unit takes place by overlapping and pressing both terminations (Fig. 3).

It requires the achievement of a tight mechanical link between the conductor jacket and the termination box and a low electrical resistance between the two boxes. This is realized by the use of a composite box machined out of a bimetallic plate, manufactured by explosion bonding and prebent at one end in order to allow welding of the conductor jacket to the box after cable insertion. The low electrical resistance is provided by the direct contact of the cable strands pressed to the copper sole of the box and by soldering of adjacent copper faces of the two boxes. The low electrical conductivity of the stainless steel part of the box prevents from the

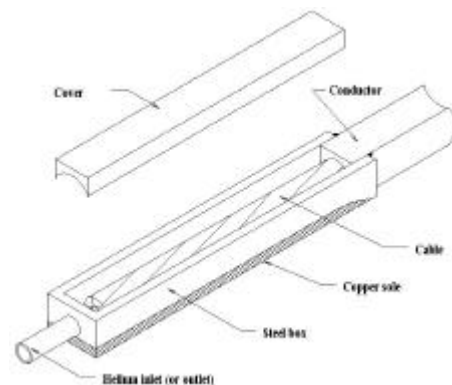


Fig. 2 : Terminal box

circulation of eddy currents and reduces the AC losses under varying field. The homogeneity of current distribution in the conductor is reached by extending the contact area between cable and copper over the whole length of one twist pitch of the final cabling stage, allowing thus each subcable to come into contact with the copper sole. This concept was first applied to subsize conductors joints tested in the JOSEFA facility at CEA/Cadarache [6].

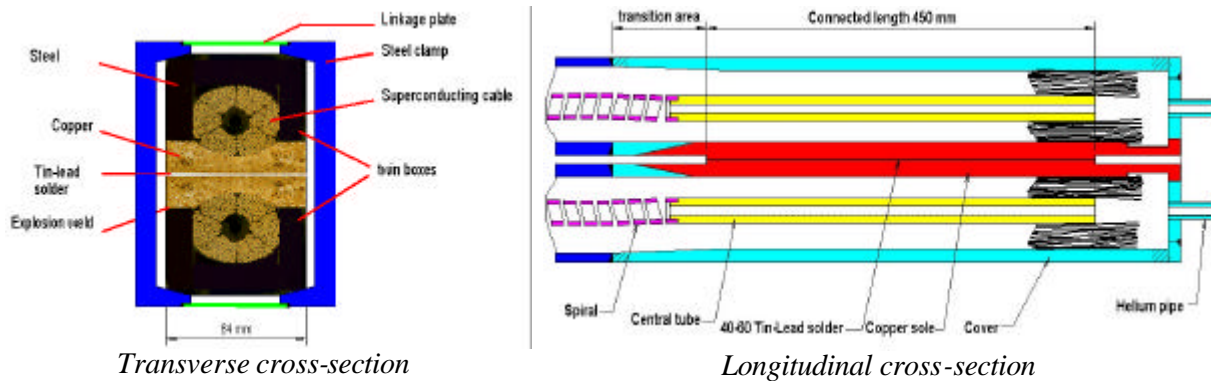


Fig. 3 : The twin-box joint

#### 4 Application to full-size Nb<sub>3</sub>Sn conductors

A design was then proposed for full-size niobium-tin conductors and qualified by the industrial manufacture of 3 prototype joint samples, which were extensively tested in the SULTAN facility at CRPP [7]. These prototypes using conductors with a thick square stainless steel jacket, a thin circular stainless steel jacket and a thin Incoloy 908 jacket,

showed that resistances below 2.5 mΩ under 8 T could be achieved [8]. Successful results obtained with these prototypes allowed the manufacture according to this technique of all the joints of the ITER Toroidal Field Model Coil [9]. This coil using a Nb<sub>3</sub>Sn CICC includes 5 inner joints and 4 outer joints, all located inside the coil case (Fig. 4) and operating under field up to 6.7 T, when the coil is energized at 80 kA. In addition 6 joints using the same concept are implemented in the busbars connecting the coil to the current leads and operate at field up to 2 T for 80 kA [10]. In a first phase, this coil was tested alone in the TOSKA facility at FZK in 2001 and it will be tested with the LCT coil in a second phase in 2002. The results of the first phase tests showed that all joints achieved very low and reproducible resistances (Fig. 5) [11]. In addition, a set of Hall probes installed on the busbars showed that the current distribution among subcables was quite homogeneous [12]. The maximum deviation from nominal average current in each subcable is found to be less than 10%, which is a very good result.

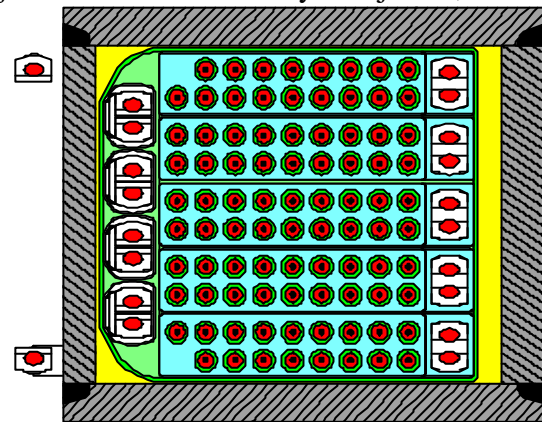


Fig. 4 : ITER TFMC equatorial cross-section (outer leg)

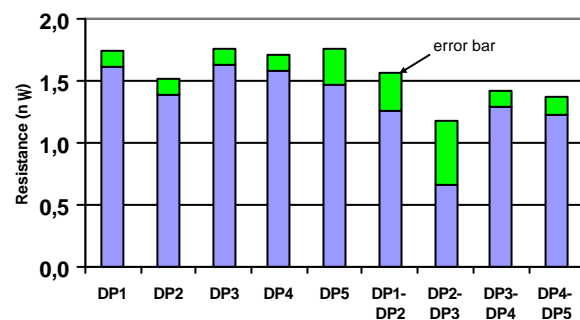


Fig. 5 : ITER TFMC joint resistance at 80 kA

## 5 Application to full-size NbTi conductors

A first step in the application of the twin-box joint concept to NbTi conductors, was the manufacture of the busbar joints of the ITER TFMC, which operate at high current (80 kA) and low field (2.5 T in the second phase of tests) and use niobium titanium strands with an internal copper-nickel barrier. The manufacturing sequence was directly derived from that used for the first niobium-tin prototype joint, using a square stainless steel jacket, and further applied to the TFMC joints. The main difference came from the absence of heat treatment for the niobium-titanium conductor, which allowed to investigate several possibilities to improve the contact between cable and copper sole inside the terminal box. The solution retained for these busbar terminals was to perform an indium coating of the copper sole so as to increase the contact area and to perform a silver coating of the cable strands facing the copper sole. The measurement performed during the TFMC tests showed that the busbar joint resistance was in the range of  $1 \text{ n}\Omega$  at 80 kA. In addition, as mentioned in section 3, the current distribution appeared to be very homogeneous.

Meanwhile, in the framework of an EFDA task, a programme was initiated at CEA and ENEA to develop NbTi CICC for the ITER PF coils. A design study, carried out at CEA, had shown that it should be possible to use twin-box joints for these coils too [13]. In a similar way as that followed for the development of niobium-tin joints, the first step was the manufacture and test in the JOSEFA facility of subsize joint samples using subsize conductors made with the candidate niobium-titanium strands for the PF coils [14]. The chosen manufacturing technique took into account the experience gained with the manufacture of the TFMC busbar joints and resulted from some additional R&D. For these samples, one using a strand with internal copper-nickel barrier, the other a nickel coated strand, both the copper sole and the cable were silver coated before insertion of the cable inside the box. The test results showed that resistance in the range of  $1.5 \text{ n}\Omega$  should be achievable for full-size joints. A prototype full-size joint was then manufactured in industry, according to the procedure developed for the subsize joints [15]. As for the niobium-tin prototype joints, the transfer of technology was ensured by continuous attendance of the laboratory representatives to the manufacturing sequence in the manufacturer's premises in particular during the termination manufacture and joint assembly. The tests of this prototype sample are presently being carried out at the SULTAN facility and the first preliminary results show that at low field a joint resistance of  $1.25 \text{ n}\Omega$  at 40 kA has been achieved. Specific joint tests are scheduled under magnetic fields up to 5 T. The next step of the development programme will be the manufacture in European industry of a PF Conductor Insert coil, which should include such a twin-box joint, to be tested in relevant varying current and magnetic field in the ITER Central Solenoid Model Coil (CSMC) at the JAERI facility in Naka [16].

## 6 Conclusion

An overlap joint design, relying on the twin-box concept, has been developed at CEA with subsize samples to connect niobium-tin cable-in-conduit conductors. This technology has been then transferred to industry to manufacture prototype full-size samples and then applied to the manufacture of the joints of the ITER TFMC. The test results of this model coil demonstrated the good behaviour of these joints for the low resistance achieved as well as for the homogeneous current distribution provided, which makes this technology available for the ITER TF coils. The industrial production was reproducible and has delivered resistance values within acceptable tolerances. A similar development has been carried out with niobium-titanium conductors for PF coils and should be finally qualified by the manufacture in

industry of a PF Insert coil to be tested in the ITER CSMC. In both cases, developments carried out at subscale level in laboratory were successfully transferred to industry by deep involvement of laboratory representatives in the manufacturing process.

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