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CEA studies and qualifications prior to the JT-60SA TF coils manufacture

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ABSTRACT

Following the first conceptual design activity in which the general design of the JT-60SA TF system was defined in agreement with all the participants in the project (CEA, ENEA, F4E), a second phase dealing with the detailed design was engaged by each of the voluntary contributors. For the French part which includes the procurement of 9 of the TF winding packs and their integration in the casing, an industrial contract was signed mid 2011 with Alstom (France). Several actions have been carried out to prepare the manufacturing phase.

To precisely define one of the main interfaces which is the temporary electrical connection of the coils to the current leads during cold test in the CEA facility as well as their final connection to the feeders at the Naka site, a design compatible with both requirements was developed by CEA, supported by the previous developments led on the joints and assembly techniques.

In addition to prepare the coils manufacture, hydraulic qualification was led on the first conductor qualification length to set the parameters which will be used by the coils manufacturer for conductor acceptance.

At last, mechanical characterizations of both the conductor and of the empty compacted jacket were performed in order to define as precisely as possible the elastic and plastic properties of these components. These are crucial properties used during the bending process which is one of the most important operations during the winding pack manufacture. These data will be very helpful for the winding machine parameters settings as well as for designing the local bending tooling needed to shape the conductors extremities at the connection area and at the double pancakes joggles.

1. Introduction

The mission of the JT-60SA project is to contribute to the early realization of fusion energy by addressing key physics issues for ITER and DEMO. The JT-60SA toroidal field coils (TF) magnet procurement is a part of the broader approach (BA) agreement. The design was optimized by collaboration between F4E and the voluntary contributors (VCs) in charge which are CEA for France and ENEA for Italy.

The TF magnet is composed of 18 TF coils which support the central solenoid (CS), and the equilibrium field (EF) coils, all superconducting, cooled by supercritical helium at 4.4 K and thermally protected in a cryostat. Each TF coil is constituted by a winding pack wound from a cable-in-conduit conductor (CICC) and embedded in a steel casing. The winding pack is constituted by a stack of 6 double pancakes, of 12 turns each, connected in series by inner joints of praying hand type located outside of the winding. The first and last double pancakes are connected to the feeders by dedicated terminals. Each of the six conductor unit length is cooled by 4.4 K forced helium flow, with an inlet at the middle point near the most loaded conductor and two outlets at the terminals or inner joints, and operates with a current of 25.7 kA under a magnetic field up to 5.7 T. Apart from the casing the coil structure includes intercoil supports and gravity supports.

On the basis of this agreed conceptual design supported by detailed analysis and experimental qualifications, further work was engaged by CEA to precise design solutions for the coil terminals support, insulation and electrical connexion as well as to characterize the hydraulic and mechanical behaviour of the first production conductors.

2. Coils connection design

2.1. Terminals support design

The coil terminals are of the twin box design [1] with electrical connection through a flat copper sole. They will have to be connected and disconnected easily to the cold test facility (CTF) busbars

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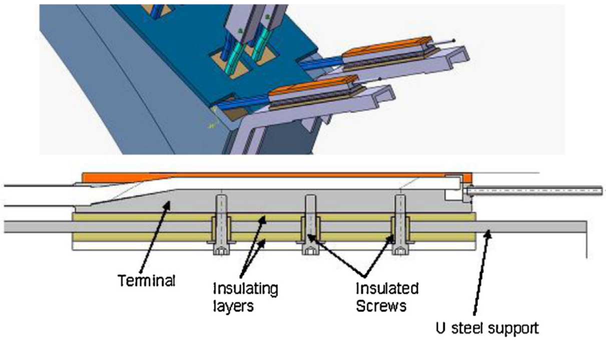

Fig. 1. Terminals support and insulation design proposal.

during cold testing at CEA Saclay and then will have to be definitively connected to the coils feeders at the Japan site. In addition to the connections requirements, the coil terminals must be ground insulated from the 1.4 kV requirement and supported against the electromagnetic loading due to coil operation.

A design was proposed by CEA to fulfil these requirements. Each support design relies on a stiff U shaped beam bolted on one side on to the coil casing with the coil terminal screwed against the straight part through insulating plates. Fig. 1 shows an overview of this design layout. Such support allows the straightening of the terminals which, due to the welding in the manufacture process, will be slightly deformed. Of course, a final machining of the terminal copper sole is required to recover suitable sole planarity and to correct any misalignment or positioning defect of the connection plane. The terminal straightening was qualified on a dedicated mock-up, and a consolidation of the proposed design is to be done by mechanical FEM analysis.

2.2. Coils connection

The connection proposed at CTF use indium wires squeezed by the way of an external insulated clamping system which surrounds the terminal and support. A specific manufacture process using thin carbon coating of the contact surfaces was developed through mockups and has shown efficient connection as well as easy dismantling after cold test [1].

For the final connection, two solutions are proposed. A first one is a classical soft soldered connection secured by the welded clamps of the twin box design. A corresponding assembly procedure in real situation was defined on a dedicated mockup. Fig. 2 illustrates these different designs which have both shown DC resistance lower than 2 nΩ [1]. Nevertheless, the nearly vertical terminations position associated with low accessibility in the tokamak hall indicate the soldered solution as a delicate operation. The CTF solution using indium wires with clamped system could be a backup. To address the problem of the lifetime of this connection on which degradation due to indium creeping can be suspected, a cryogenic test on relevant mockup is planned by CEA before the end of 2012.

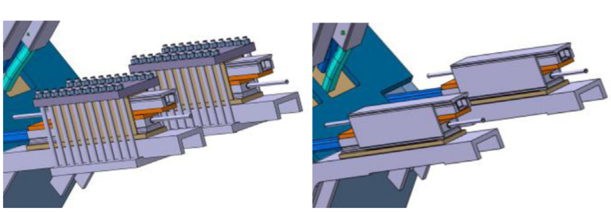

Fig. 2. Temporary CTF (left) and definitive (right) connection designs.

Table 1
Conductors data.

	TFCR	TFQL-1
Strand o.d.	0.81 mm	0.81 mm
Nb. str.	486	486
Cable v_f	0.34	0.317
A_w	127.3 mm^2	125.53 mm^2
D_h	0.456 mm	0.45494 mm

3. Conductors characterization

3.1. Hydraulic

The hydraulic characterization of the conductor is a key input for the cryoplant specification which is one of the French procurement in the BA agreement. In addition, the conductor hydraulic acceptance by the coils manufacturer is to be properly defined as it will give a reference for further hydraulic checks of the double pancakes flow distribution at final coil acceptance.

A first hydraulic check was performed on the TF qualification length (TFQL-1) produced to tune all parameters of the conductor manufacture process. Except a reduced length of 80 m, this unit length was delivered to CEA as a single spool with empty pipes at both extremities as foreseen for the real 240 m unit lengths. In addition to classical pressure at pipe ends and flow rate measurements, pressure taps were implemented on the conductor part at 0.2 m from the cable ends to check their influence. The tests were performed using GN2 at room temperature, increasing the inlet pressure by steps up to 2 MPa with atmospheric outlet.

A first analysis shows no pressure drop at inlet between the empty pipe and the pressure tap on conductor regular section, and a maximum value of about 0.04 MPa due to highest gas speed at the outlet. Regarding an overall pressure drop of 2 MPa, this local perturbation will not significantly impact the result of the acceptance test at coil manufacturer site.

The friction factor and Reynolds number were calculated using classical hydraulic formulae (1) and (2) and compared to the TFCR conductor [2,3] using characteristics given in Table 1. The only difference between production and reference conductors is the addition of a cable wrapping for manufacture purpose which results in a decrease of the helium area and then of the average void fraction.

$$f = \frac{2\rho\Delta P}{Q_m^2} \times \frac{D_h A_w^2}{l} \quad (1)$$

$$R_e = \frac{Q_m}{\mu}\frac{d_h}{A_w} \quad (2)$$

Despite a low R_e value due to conductor length and limited pressure drop, an increase of the friction factor compared to TFCR was detected. To confirm such trend, additional measurements on a short length of the TFQL-1 conductor extracted from the middle of the spool and on following production samples were led. These samples were checked in dedicated CEA OTHELLO facility operating with pressurized GN2 with some cross check on HECOL using water as shown in Table 2.

Assuming production conductors data identical, the friction factor and R_e were calculated as shown in Fig. 3. The results between

Table 2
Tested conductor samples.

Sample	Length	Test conditions
TFQL-1C	0.785 m	GN_2
JTF-S00	1.83 m	GN_2
JTF01-SHT	1.285 m	$GN_2 + H_2O$
JTF02-SHT	1.286 m	$GN_2 + H_2O$