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Development of the ITER PF Coils

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***Abstract*—The ITER Poloidal Field (PF) magnet system consists of six coils. Niobium-Titanium (NbTi) is used as superconducting material and cable-in-conduit conductor(CICC) type are used as a conductor. All coils are fabricated by stacking 6 to 9 double-pancakes wound by two-in-hand winding scheme. The six PF coils (PF1 to PF6) are attached to the Toroidal Field (TF) coil cases through flexible plates or sliding supports to allow small radial and vertical displacements. The outer diameters of the coils vary between 8 m and 24 m. Since the PF coil system provides magnetic field for plasma shaping and position control together with the Central Solenoid (CS) coil, it needs to operate in fast pulse mode, leading to induced voltages of up to 14 kV on the coil terminals during operation.**

PF coils will be procured by the European and Russian domestic agencies under separate procurement arrangements (PA). Manufacturing design, equipment installation including design and commissioning, and component qualification are the required first steps before entering series production.

This paper presents the updated design for manufacturing of components such as tail, joint, clamp and protection cover. Their fabrication and assembly methods are also described. The paper concludes with a summary states report on component qualification program.

***Index Terms*—Fusion, ITER, PF coil, superconductor.**

I. Introduction

The ITER Poloidal Field (PF) magnet system consists of six PF coils procured by the European and Russian domestic agencies under separate procurement arrangements (PA). The two PAs between IO (ITER Organization) and each domestic agency have been signed and beginning in 2011 these PAs enter the manufacturing phase. All coils use Niobium-Titanium (NbTi) superconducting conductor. The PF coil provides the position equilibrium of plasma current (i.e. the fields to confine the plasma pressure) and the plasma vertical stability.

All coils are built by stacking 6 to 9 double-pancake (DP) windings wound with NbTi superconducting cable-in-conduit conductors (CICC) by two-in-hand winding scheme. The outer diameters of the coils vary between 8 and 24 m. To allow radial displacements, the six PF coils (PF1 to PF6) are attached to the Toroidal Field (TF) coil cases through flexible plates or sliding supports [1]. All PF coils are designed to allow a DP to be bypassed with a superconducting jumper bus in the event of failure to avoid major disassembly of the tokamak in order to extract a PF coil and repair a failed DP. The loss of Ampere-turns in the repaired coil is recovered by increasing the operating current [2]. In 2008, the PF coils design and PF conductor layouts were changed to give a greater operational window for low-internal inductance plasmas during burn, to extend the operating window for plasmas with currents above 15 MA, and to improve the plasma vertical stability control [3]. Several coil components were also updated after the final design review held in early 2009.

In this paper, the design parameters and the design are described. Then each updated sub-components such as tail, joint, terminal and support and protection cover are described together with their fabrication and assembly methods. The assessments of several components are also described. Finally the paper concludes with a summary of the component qualification program.

II. Main Parameters and Tolerances

The main parameters such as current, peak field and operating temperature for each PF coil are given in Table I. Since the PF coil system provides magnetic fields for plasma shaping and position control with the Central Solenoid (CS) coil, it needs to be pulsed with fast variations of the coil current, leading to induced voltages of up to 14 kV on the coil terminals during operation [2]. The maximum current allowed in any PF coil is between 48 and 55 kA. The coils are built to allow a DP to be bypassed in the event of failure (e.g., an electrical short). The drop in mega ampere turn (MAT) for PF1 $\sim$ 6 is recovered by increasing the operating current and/or decreasing coil operation temperature by 0.3–0.4 K. The bypass operation is achieved by: i) open circuiting the failed pancake by opening the inter-pancake joint, ii) connecting via a jumper the DPs intra pancake terminals. One of the ITER design requirements is that the coils should be able to withstand the operating voltage between the terminals. Consequently, the design of the insulation, coil terminal regions, joints and helium inlets has to take this high voltage into account with sufficient margin, since a failure would mean a major interruption of the Tokamak operation [2].

One of the most critical items in the manufacturing procedure is the tolerances. Tight tolerance control is required throughout the manufacturing to ensure that subcomponents interface correctly (typical examples are the conductor winding into the molding jig for VPI (Vacuum Pressure Impregnation) of DP, the stacking of the DPs to form the winding pack, and the fitting of the winding pack into the coil). The manufacturing scheme has therefore been defined with an allocation of overall tolerances

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TABLE I
PF COIL PARAMETERS

Coil	PF1	PF2~5	PF6
Maximum current (kA)	48	55(52 for PF 5)	48(52 for sub-cooling)
Bath temperature (K)	4.2	4.2	4.2(3.8 for sub-cooling)
Peak magnetic field (T)	6.4	4.8(5.7 for PF5)	6.4(6.8 for sub-cooling)
Maximum operating terminal voltage (including fast discharge, kV)	10	14	10
Turn-to-turn (radial) maximum operating voltage (kV)	0.63	1.17	0.56
Maximum terminal voltage(kV) in faulted operation	28	28	28
Maximum test DC Voltage (kV) Ground to Terminal	29	29	29

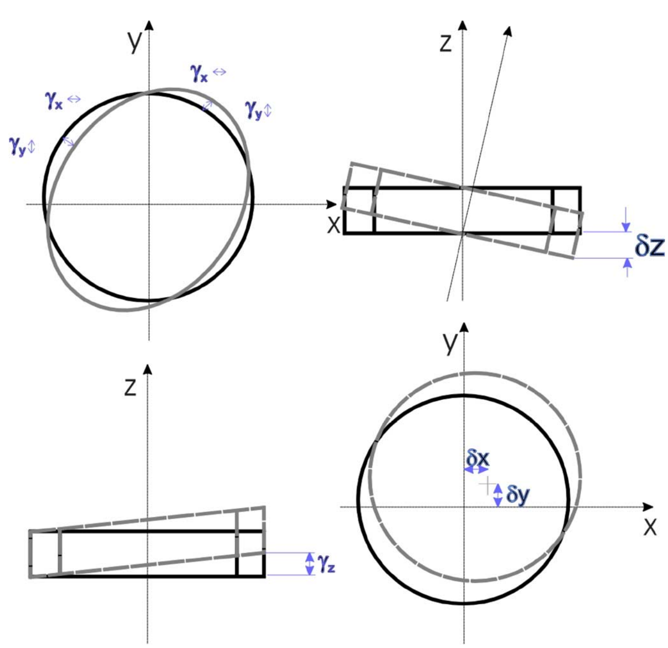

Fig. 1. Assembly errors (left) and manufacturing errors (right) for the PF Coils.

in the coil current centerline position at the different manufacturing stages, and the possibility to allow reductions in position errors during the winding—DP stacking. Assembly errors and manufacturing errors for the PF coils are defined in Fig. 1. The target acceptable tolerances for the PF coil winding pack are defined in Table II These are the target tolerances deemed necessary to achieve the required accuracy in plasma control. However the final acceptable tolerances will be determined by mutual agreement among the IO, DA (Domestic Agency) and the selected supplier following a trade-off study between plasma control requirements, industrial capabilities and cost.

TABLE II
TARGET TOLERANCES FOR THE PF COIL

Coil	PF1	PF2~5	PF6
γx (mm)	± 3	± 3	± 4
γy (mm)	± 3	± 3	± 4
γz (mm)	± 3	± 3	± 3
δx (mm)	± 2	± 2	± 2
δy (mm)	± 2	± 2	± 2
δz (mm)	± 1	± 1	± 1

III. UPDATED COMPONENT DESIGN

A. Joint

There are four types of electrical connection for the PF conductors: i) joint between the two conductors within a DP, called a pancake joint (PJ), ii) joint between two double pancakes (DP joint), iii) joint of the terminals, and iv) joint to the jumper in the case of bypassing a faulted DP. In PF coil, the required joint total resistance at the temperature range of 4.5–5 K, operating current of 55 kA and external field of 2 T is $< 2\ \mathrm{n}\Omega$. As shown in Fig. 2, a twin-box type lap joint was chosen for all joints in the PF coils [4]. It is selected as PF joint for its proven performance and ease of connection/disconnection. In this concept, the conductor cable end is pressed into a bi-metallic box machined from an explosively bonded (or equivalent) stainless steel/copper plate to form a termination. The box is welded to the jacket of conductor on one end with a stainless steel pipe for liquid helium cooling exiting on the other end. The copper soles of the two terminations are soldered together and form the electrical connection. The joints are subject to radial force inwards and axial force towards to coil mid plane. A supporting plate located on the outer surface of the coil is mechanically held with fiber glass tape wrapping around the ground insulated winding pack before the vacuum pressurized impregnation (VPI). The radial load on the joint is supported by an insulated radial spacer mounted on the supporting plate. The axial load in the joint is supported by two washer plates installed on the top and bottom of the insulated joint. The washer plate is an angle plate with the vertical flange wedged between the radial spacer and the supporting plate, which prevents the horizontal flange from rotation.

B. Tail

The tensile hoop stress to be transferred to the winding pack in the PF conductor is on the order of 200 MPa. The main function of the tail is to transfer the tensile or compression force from the end of the outermost conductor to the adjacent turns by shear force through an appropriate thickness of insulation.

The conductor tail consists of a pre-shaped and insulated hollow square jacket welded to the start of the outward radial joggle near the joint or termination. The tail is electrically insulated from the surrounding conductors as the peak turn-to-turn voltage can be as high as 1.75 kV in PF2 coil. Bonding of the

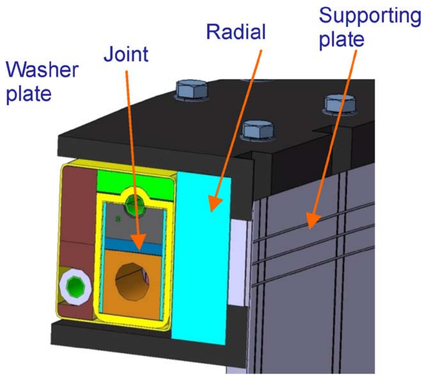

Fig. 2. Updated PF joint design.

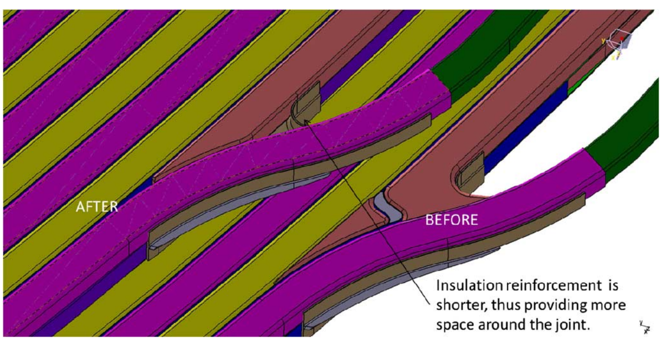

Fig. 3. Updated design before and after removing the tail in joint region.

tail to the neighboring turn is accomplished during VPI of the DP [4].

However its manufacturing is complex (welds, high voltage insulation of protruding components, limited accessibility, tolerances) requiring specific insulating filler around the tail. Due to the specific design of the PF coil joint and joint supports, the mechanical function of the tail is already ensured by the joint itself. As the joint boxes are welded together and to the conductors, the joint mechanically closes the turn (Fig. 3). In the case of the pancake joint and the double pancake joint, as the vertical and radial forces are reacted by the joint support to the coil, it is confirmed that the deformation of the conductor where the conductor exits the coil is the same as for a 'normal' turn and therefore there is no change in the stresses in the insulation.

C. Minor Design Improvement (Clamp and Protection Cover)

The main functions of supports including clamps are: i) to hold PF coils in position on TF coil structure, ii) to accommodate radial and vertical displacement of the PF coils with respect to the TF coils and iii) to accommodate the operational TF coil out of plane deformations. There was however the possibility of slip between clamp and coil since there was no stopper to prevent slip. The clamping of the PF supports relied only on coil/clamp friction. Recent analysis shows that the coils could be moved with respect to its supports clamps during extreme conditions in certain scenario. In the current design, if there is a force (movement), the clamping relies only on the friction between the two components and the coil could be moved. So, to block any potential movements, small bumpers are added on the WP protection plates (Fig. 4).

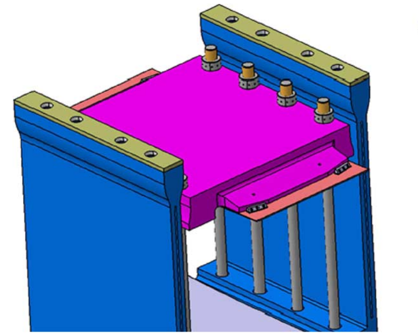

Fig. 4. Small bumpers on the WP protection plate.

The winding body with ground insulation, high potential cooling pipes from all joints and terminations of the coil are covered by a thin metallic grounded protection cover between (but not underneath) the coil mounting clamps. This is made of segments of 304L steel and is welded in place. Nine segments are required for PF6 and eighteen for PF3. Gaps are used to break electrical continuity in the toroidal direction, with each gap adjacent to a PF coil support.

It is necessary that the front protection cover needs to be removable for possible repair operations. Since the access on these three coils is limited, splitting the front cover into three sections reduces the weight of each piece to be lifted (from the current 130 kg weight, to one third for each section). To ease any maintenance operation, the front protection cover for PF3, PF4 and PF5 is split into 3 (smaller) sections. The other three coils are easily accessible with lifting tools and an entire cover can be removed.

IV. Assessment of Updated Components

The PF coils are designed to be able to withstand the loads during their lifetime operation which occur at the 15 MA ITER baseline scenarios. It is also confirmed that the coil can operate with 17 MA plasmas for a restricted number of pulses. The loads and mechanical behavior of the PF coils have been analyzed with 3D Finite Element models. An analysis was performed on the mechanical behavior of the PF5 joint and the stress/strain distribution in the joint area (including supports) due to assembly/fabrication and during operation (that is, during cool down from room temperature to 4 K and after energizing the coils). The analysis results show the design criteria are met, but the current joint design needs to be further checked and optimized to increase the safety margin and to improve joint manufacturing.

To optimize the joint design with the aim to reduce the AC losses, joint resistance and current non-uniformity between the superconducting strands, a coupled electromagnetic and thermo hydraulic model has been developed. The inputs for the model are the joint electrical properties (including interstrand contact resistance distribution, strand to copper sole resistances, self- and mutual inductances) and the magnetic field and the transport current variation in time governed by the ITER plasma reference scenario. The preliminary results confirm that the current design of the PF joints is satisfactory.

To assess the removing of the tail, an analysis on the tail in the PF joint region (except terminal joint) was carried out. The goal of the analysis was to check if the tail is really necessary for the functioning of the joint. The PF 5 joint was selected for analysis as it could be affected by the highest operational loads (Lorentz forces) among PF joints.

The absence of the tail has no impact on the results during cool down and operation. The loads are mainly sustained by the support. The analysis shows the same level of stress in the joint, conductor and insulation with or without the tail.

But regarding the terminal joint, the analysis result shows that the terminal tail is still required to react the hoop load of the terminal conductor on the outside of the winding pack.

The total number of pancake joints and double pancake joints is 176. Removing the 176 joint tails will lead to a substantial cost reduction (in terms of material, tooling, manufacturing time, weld inspection), accelerate schedule and reduce risks. The qualification phase of the tail is still required since there are tails left at the terminals.

V. Qualification of Components

For further risk reduction, each critical component will be qualified through tests scheduled during procurement arrangement execution. The qualification will cover not only the fabrication procedure, but also the components themselves. Regarding helium inlet, full size samples with the helium inlet shall be manufactured under the same conditions as planned for the real inlets in order to qualify the manufacturing process. The weld test such as leak test and full penetration test will be performed. The fatigue test will be performed at 77 K and the conductor jacket shall withstand a cyclic longitudinal strain at 77 K. The leak test will be carried out after fatigue test.

Regarding the PF joint, prior to the full size short sample fabrication, it is required to assemble at least one joint (two terminations and a complete joint box) from the short dummy joint with copper cable conductor to establish the detailed fabrication procedure.

After that a full size joint sample will be built to verify that the manufacturing process is able to fabricate the joint while meeting performance specifications. The electrical properties such as joint total resistance (in the temperature range of 4.5–5 K) and AC Losses will be measured.

The insulation is to be qualified electrically and mechanically. Tests are to be performed both in small samples of insulation layer, and on a stack of 3×3 insulated conductor sections (e.g., empty jackets). Important outcomes of the test are: insulation performance under high voltage test, insulation performance and adhesion after thermal and mechanical cycling, and bond strength between impregnated insulation and steel jacket.

The tail qualification in terminal region will be performed to qualify the manufacturing process of a bonded tail and to verify the mechanical and electrical performance of a bonded tail. The tests such as welding test, fatigue tensile test at 77 K and interturn insulation test and winding pack to ground insulation test will be carried out.

After each component qualification, the double pancake fabrication using dummy conductor will qualify critical fabrication processes of the full DP: winding process, transitions forming, insulation application, inlets installation, joint terminations preparation, installation of the spacers to maintain tight tolerances, assembly of the internal joints and VPI process.

After completion of all double pancake tests, the dummy double pancake shall be cut into 9 roughly equal sectors (the cut plane shall contain the axis of symmetry). Each cross section shall be inspected for voids and their average size and one of the pieces shall be cut further for visual inspection of the turn insulation. The 8 pieces cut from the dummy double are used to simulate the stacking of the winding pack, the ground plane insulation. Then they are impregnated to qualify the VPI process of the full PF Coil. The 8 pieces are stacked following the same procedure than for the stacking of real double pancakes, i.e. insulation shims and bonding layers are inserted to fulfill the impregnation and coil dimensions.

VI. Conclusion

The main requirements and the updated design of ITER PF coil system have been described along with their fabrication and assembly methods. The results of the analyses show that the modified design satisfies ITER design criteria.

For further risk reduction, each critical component will be qualified through tests to be performed during procurement arrangement execution.

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