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B Stepanov et al.

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DEMO-EUROfusion Tokamak, Design of TF Coil Inter-layer Splice Joint

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Since the year 2013, the Swiss Plasma Center (SPC) has proposed a Toroidal Field (TF) layout for the DEMO-EUROfusion tokamak, based on a graded winding pack made of layers of Nb3Sn (react-and-wind) conductors. In summer 2015, a new reference baseline is issued for the DEMO- EUROfusion tokamak, leading to an update of the TF coil requirements, e.g. the operating current has been reduced from 80 kA to 63 kA. Consequently, the conductor layouts for every graded layer of the TF coil winding pack is re-designed in order to match the new requirements.

The each layer of TF coil winding pack has to be connected electrically in series to form the coil. The inter-layer Nb3Sn splice joint design which does not exceed the conductor dimensions is proposed in this paper for the updated 63 kA Nb3Sn TF conductor. This proposed joint design allows a continuous winding of TF coil winding pack from layer to layer, housing the joint at the zone of inter-layer transition. Ultimately, the all inter-layer joints should be arranged within the winding pack at the low-field and low mechanically stressed region of D-shaped TF coil.

Keywords: DEMO tokamak, TF coil, RW technology, layer winding, electrical joint, joint resistance.

1. Introduction

The electrical joint between the superconductors in the superconducting coil is one of the key technological components in the coil manufacturing. Obviously, the main key requirement for the joint is a low power generation. There is variety of the joint designs which depend very much on the conductor layout; the latest ones are successfully tested and well described in [1-6] for the large industrially manufactured superconducting coils.

In the latest 2016 design of Toroidal Field (TF) coil for the DEMO-EUROfusion Tokomak, the each TF Coil consists of 12 layers of wound with parametrically graded Nb_3Sn conductors [7]. The Manufacturing concept proposed by Swiss Plasma Center (SPC) is the "react-and-wind" (RW) concept, i.e. the TF coil is wound with the heat treated Nb_3Sn conductor.

The concept of electrical joint between the Nb_3Sn conductors of TF coil is developed and described in this paper for the high-field grade of conductor, Fig. 1. The joint is designed to be within the conductor dimensions and "invisible", i.e. placed under the TF coil ground insulation with helium cooling pipes protruding the coil.

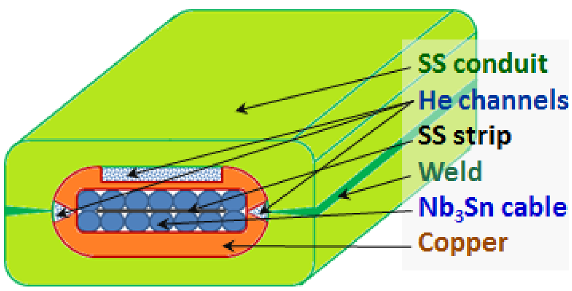

Fig. 1. DEMO-EUROfusion Tokamak, TF coil high-field conductor (1st layer).

2. Joint layout

The main reason to develop this joint is the layer winding of TF coil: the layer winding can be continuous. After completion of one layer winding, the conductor coming out from the pay-off spool can be joined to the wound layer. Then, the following layer can be wound above the previous one and so on, until the completion of coil winding. Certainly, only the soldering process is applicable for the joint of heat treated conductors.

The schematic view of proposed TF joint design is shown in Fig.2. The high-field Nb_3Sn cable is the flat calibrated twisted bilaminar cable (40.3x9.8 mm) with inserted at the middle stainless steel strip for reduction of AC loss. The cable last twist pitch (the twist pitch of all 14 sub-cables) is of 450 mm. The each laminar of cables is trimmed stepwise in order to be overlapped in length of 225 mm, 1/2 of cable twist pitch. The two copper profiles, identical to the conductor copper profiles (see Fig. 1) are applied above the joined cables. The trimmed cable ends are solder-filled; the inner surfaces of copper

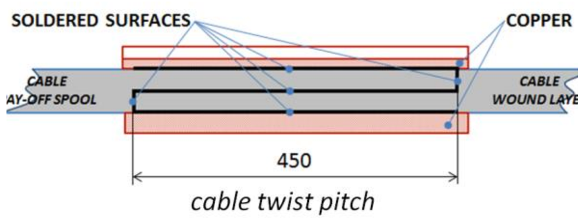

Fig. 2. Schematic view of TF inter-layer joint.

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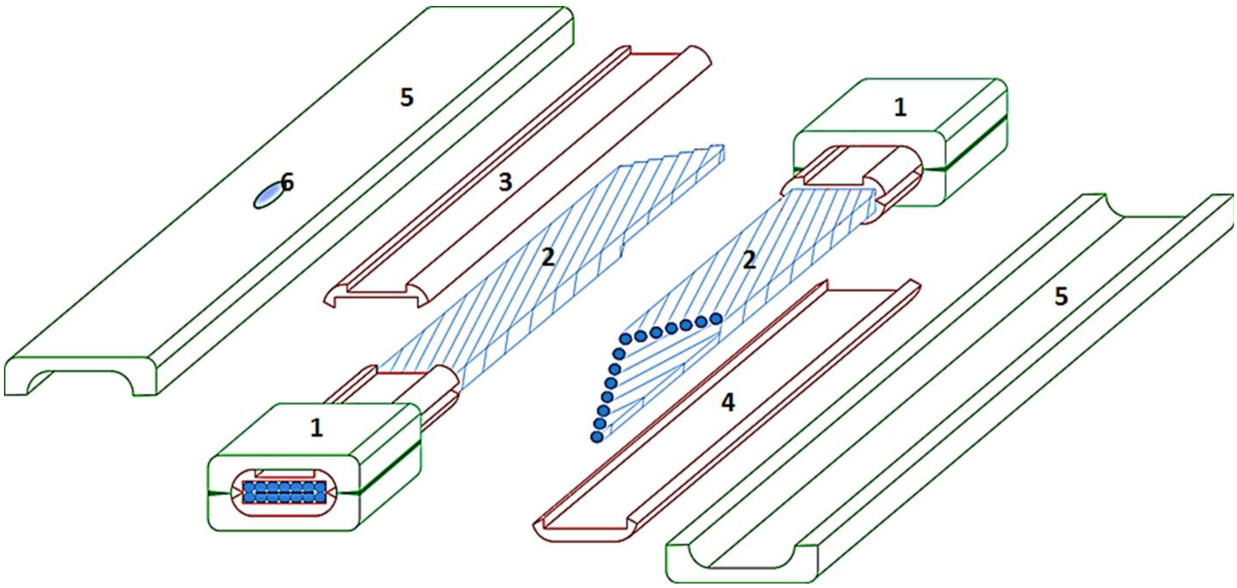

Fig. 3. DEMO-EUROfusion Tokamak, TF coil joint, simplified exploded view:

1. High-field Nb_3Sn conductor terminations to be joined
2. Prepared cable terminations to be electrically joined
3. Upper copper profile with cooling channel
4. Bottom copper profile
5. Halves of stainless steel conduit to be longitudinally welded together and butt welded to the conductor conduit
6. Hole for the helium inlet and outlet, leading to the cooling channel of the copper profile 3.

profiles are solder-coated in advance. The final soldering of the trimmed solder-filled cables and copper profiles is performed in one go with applied pressure.

Fig. 3, simplified exploded view, illustrates the joint design and its assembly. The ends of heat treated conductors at the wound layer and at the pay-off spool should be prepared for electrical joining:

1. Removal of the conductor jacket
2. Trimming of the upper and lower copper profiles above the cables
3. Preparation of the ends of free cables:
   - Cable trimming and Cr removal
   - Solder filling
4. Assembly of the trimmed solder-filled ends of cables and copper profiles in the technological jig.
5. Application of pressure
6. Heating of whole assembly
7. Removal of technological jig
8. Welding of two halves of stainless steel conduit

Assuming that the total soldered length is of 450 mm and the rest of trimmed conductor copper profiles are of 50 mm, the total length of the joint is 550 mm long.

In principal, when necessarily, an additional safety shell can be applied above the 550 mm long joint (about 1-2 mm thick and 650 mm long) and vacuum tight welded to the conductor conduits and cooling pipe. This shell must not carry a mechanical load.

The coolant inlet/outlet is performed through the hole in the applied conduit directly to the cooling channel of the joint and conductor itself. The design of the cooling inlet/outlet is out of scope of this paper due to the specific mechanical features during the coil operation. The presence of cooling inlet/outlet piping and need to pass the piping through the side walls of the coil case (90 degree bending of pipes is needed) leads to an increase of joint total radial build-up by 15-20 mm at least. The joint location is at layer-to-layer transition, and the space within the winding pack is well enough to fit the joint together with inlet/outlet cooling piping.

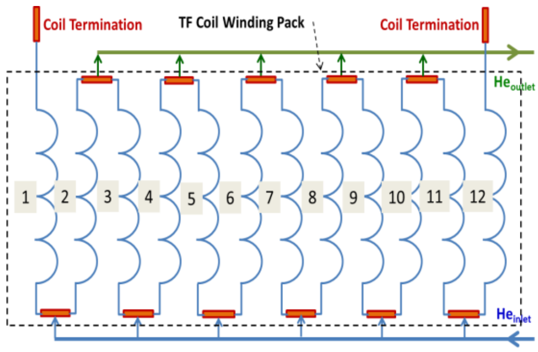

Fig. 4. TF coil, circuit of cooling for layers of winding and for inter-layer joints.

The hydraulic scheme of cooling circuit is shown in Fig. 4. The TF coil winding pack includes 11 inter-layer joints in total. The coil terminations must be dismountable and have to be design further.

3. Location of joints and required space

The joints are located at the side surfaces (beginning and ending of the each layer winding) of TF coil, in the small displacement area [8], Fig. 5. The cooling pipes are coming out from the coil case at the side walls of the

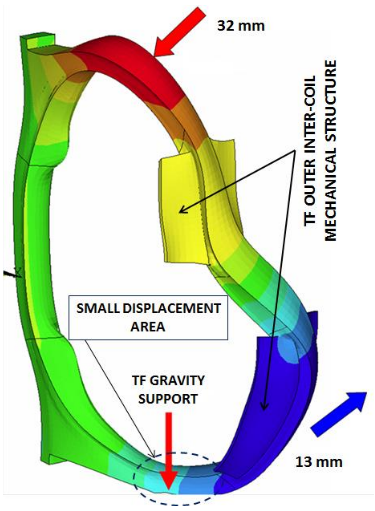

Fig. 5. TF displacement map under out-of-plane loading.

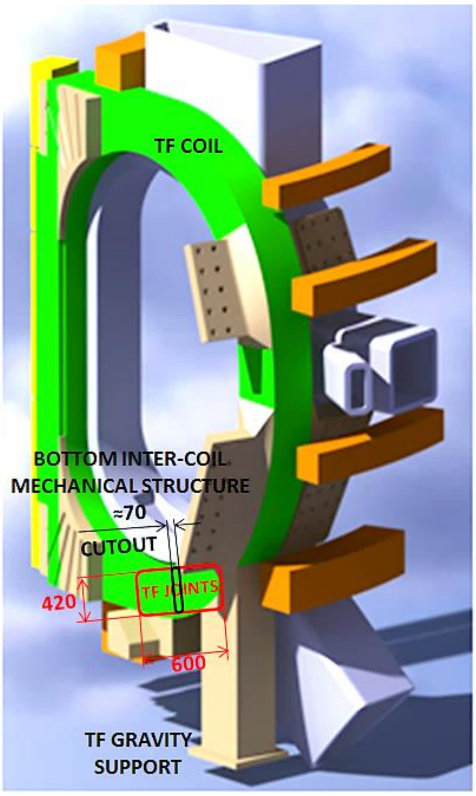

Fig. 6. Location of TF inter-layer joints, required space to allocate the arrangement of joints and cutout in the TF coil case for coming out cooling pipes and coil terminations.

coil case, through the cutouts. This area is between the TF coil gravity support and the bottom inter-coil mechanical structure.

Since the layer winding is continuous, and the inter-layer joints are within the winding pack dimensions, the joints with length of 550 mm can be aligned radially in one row during the winding process. The each joint is located between the wound layers, at the layer-to-layer transition. Thus, taking into account the 12 coil layers, the total area required for the joints is ≈600 mm long and ≈420 mm wide, Fig. 6. The required cutouts in the side walls of TF coil case can be narrow (≈70 mm) to pass the coming out cooling pipes and coil terminals, but anyway ≈420 mm long. The mechanically weakened side wall of the coil case can be strengthened by adding the structural material around the contour of cutouts.

4. Joint resistance

The current re-distribution between the strand-bundle of the cable and copper shoe plays a significant role in the overall joint resistance, up to 50% of the overall resistance [9]. In this, described above, joint the current distribution is implemented mainly between the sub-cable strands; the copper profiles play a role of accessory elements for current distribution of the outer non-contacting each other strands.

The inter-layer joints are located at magnetic field varying from 8T (inner D-shaped profile) to 6 T (outer D-shaped profile). The estimation of joint resistance (high-field conductor at 8 T field, 450 mm length) is performed assuming the use of PbSn solder for the joint ($\rho = 5.4\cdot10^{-9}$ Ω·m, 0.2 mm average thickness) and re-use of copper profiles trimmed of conductor (RRR = 400, 4.5 mm average thickness). Thus, the estimated resistance of this high-field (8 T) joint is of ≈0.2 nΩ, the current re-distribution between the strands and copper is neglected in the estimation. The joint resistance for the rest layers can be approximately scaled-down (the conductors are smaller with decreasing of field, and the magnetoresistance of copper changes marginally from 8 to 6 T field) proportionally to the average copper perimeter, the joint length is the same for the all coil layers.

The power generated by the joints with 63 kA operating current varies from 1 W (first layer) to 0.75 W (twelfth layer); the total generated by the inter-layer joints power is of ≈10 W (11 joints in total).

The new reference 2015 baseline issued for the DEMO-EUROfusion tokamak restricts the resistance of each joint by 1 nΩ, i.e. the generated by the each joint power must not exceed 4 W at 63 kA operating current.

It should be noted, that the resistance of joints for ITER samples prepared at SPC lies statistically in the narrow range of 0.4-0.5 nΩ.

5. AC losses

The eddy current losses in the copper parts are the largest source of AC losses in any joint, containing the copper parts, in applied transversal AC field. The eddy current losses in parallel AC field are not significant in the copper profiles of joint.

The two copper profiles have either big contact electrical resistance or even a gap at V-shaped cooling channels (see Fig. 1 and Fig. 3). The further redaction of eddy current losses in AC transversal field can be achieved segmenting the copper profile in longitudinal direction with inserted resistive barriers of CuNi, which can be obtained by co-extrusion or brazing [10], i.e. the

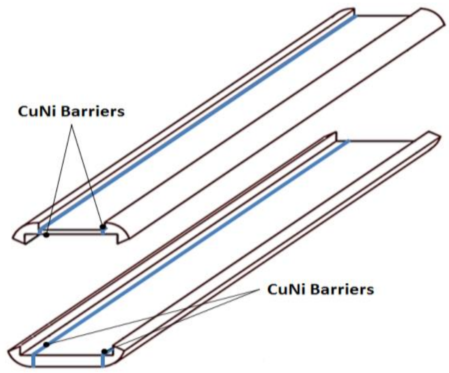

Fig. 7. CuNi barriers for reduction of addy current losses in the copper profiles.

special, devoted to the joint copper profiles should be fabricated, Fig. 7.

6. Future plans

There is intention to prepare and to test the sample at SPC in 2017 with such kind of joint made of high-field conductors in the SULTAN test facility [11], where the field is available up to 11 T, and the conductor current is limited by 100 kA.

The high-field conductor will be manufactured with "advanced", i.e. with enhanced current density strands, 1.2 mm diameter (WST, China), which will lead to a reduction of sub-cable number from 14, which is in present conductor, to 13. Respectively, the overall conductor dimensions will be reduced, and the sample can be fit inside the test well of SULTAN test facility. As a return conductor, the one conductor of the conductor sample will be used after entire test of high-field conductor.

During the joint manufacture for the SULTAN sample, the technological nuances will be developed, such as: trimming procedure of the cable without damage of the heat treated conductor outside the joint region, technological jigs for the joint assembly and soldering, welding of applied joint conduit, etc.

7. Conclusion

The proposed inter-layer splice joint has an attractive layout for electrical connection between the TF coil layers for a flat cable of DEMO-EUROfusion tokamak. This joint is characterized by easy, with industrial approach, assembly. The preparation of each inter-layer joint can be performed along the winding process at comfortable free and open space where the technological equipment can installed.

The all inter-layer joints are concluded inside the TF coil winding pack, they are inaccessible for repair. So, the inter-layer joints must be as much reliable as possible for repeatability of low resistance and for integrity of vacuum tightness during the coil operation.

The all 11 inter-layer joints do not require a big space. The cut outs in the TF coil case are needed only to lead out the cooling pipes and the coil terminations. These cutouts are narrow enough, and the TF coil case does not become dramatically weak in mechanical performance.

The assessed ohmic power generation in this joint is much smaller than the specified one in the project. The contribution of addy current losses can be reduced by longitudinal sectioning of the copper profiles.

Acknowledgments

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