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B Stepanov et al.

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TF Coil Inter-Layer Joint for EUROfusion DEMO Tokamak

Boris Stepanov, Pierluigi Bruzzone, Vincenzo D'Auria

EPFL-SPC, Fusion Technology, Switzerland

The Swiss Plasma Center (SPC) has developed a Toroidal Field (TF) layout for the EUROfusion DEMO tokamak, based on a reference baseline of 2015. Each TF coil winding pack consists of 12 single layers wound with Nb_3Sn graded conductors, connected in series by the inter-layer joints. The react-and-wind (R&W) manufacturing technique is foreseen for TF coil winding. Hence, the inter-layer joints are prepared with heat treated ends of each coil layer. The development of inter-layer joint is being continued at SPC in 2018 in frame of R&D program for TF coil of EUROfusion DEMO tokamak.

The high-grade Nb_3Sn conductor, operating at 63 kA and 12.4 T (T_{cs} >6.5 K) has been tested at SPC, and afterwards this conductor is going to be used for the preparation of TF coil inter-layer joint and for the following test in the SULTAN test facility. The trials of manufacture of inter-layer joint were performed at SPC. The copper dummy conductor has been used for the different methods of copper cladding of the conductor surface and for the different methods of joining of two copper-cladded conductors.

The inter-layer joint will be prepared as an overlap-type joint in the sample for test in the SULTAN test facility. The two ends of conductor will be copper-cladded by a plasma-spraying or other method and will be joined together by a diffusion bonding at applied pressure and temperature.

Keywords: DEMO tokamak, TF coil, RW technology, layer winding, inter-layer joint

1. Introduction

The work on design of the toroidal field (TF) coil for EUROfusin DEMO tokamak had begun at Swiss Plasma Center (SPC) in 2016, basing on the new reference baseline of year 2015. Each TF Coil consists of 12 layers of wound with parametrically graded Nb_3Sn conductors [1]. The design of joint must fulfill the react-and-wind (RW) technological process of TF coil manufacture, i.e. the two conductor ends for joining are heat treated in the each coil layer. The high-grade conductor, operating at 63 kA and 12.4 T, has been manufactured by ENEA at TRATOS (Italy) and is available at SPC, Fig.1.

The splice inter-layer joint [2] has been developed in 2016. This developed splice joint provides the electrical connection between the sub-cables of conductor, the cross-sectional dimension of joint is the same as for the conductor. The trials of joint preparation with use of dummy conductor showed that the helical trimming of sub-cables at heat treated conductor is extremely difficult without overbending and damage of sub-cables. Also, the realization of splice joint for the conductors coming from the different coil layers and having the different geometry and number of sub-cables is questionable.

The work on design of inter-layer joint was continued in 2017. The bridge-type of joint has been developed and has been tested in the SULTAN test facility [3]. The resistance of joint was about 13.5 nΩ at operating 60 kA current and 8 T field. Later on, after 100 electromechanical cycle loads, the resistance has increased up to 16 nΩ at 20 kA current and 8 T field. The opening of joint and visual inspection of all joining surfaces has not highlighted any damage in the joint.

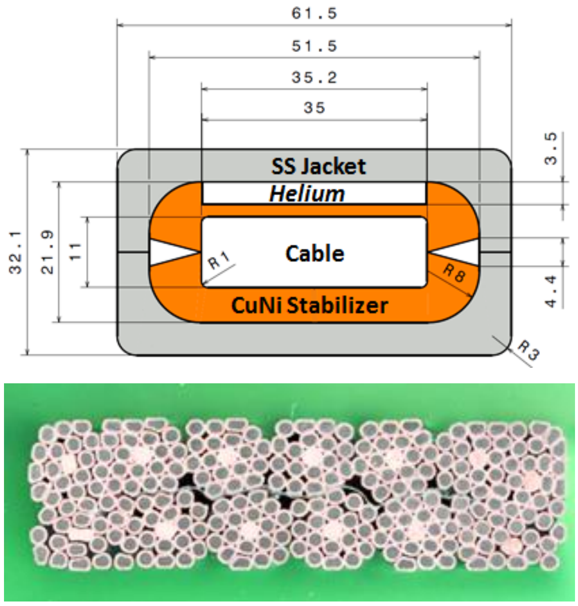

Fig. 1. Layout of high-grade 63 kA, 12.4 T conductor (top) and its cable (bottom).

The work in a direction of overlap joint design was conducted at SPC in 2018. This work has been mainly devoted for the methods of joining of copper-cladded and non-cladded ends of cable and for the methods of copper deposition at the ends of cable.

2. Location of joints at TF coil, required space and joint dimensions

author's email: boris.stepanov@psi.ch

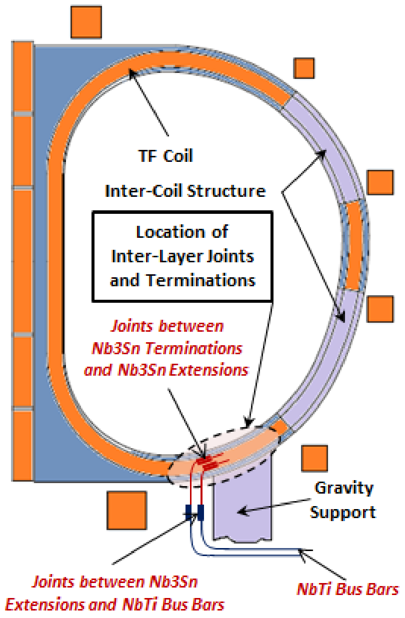

Fig. 2. Location of TF coil inter-layer joint and terminations at side surface of coil.

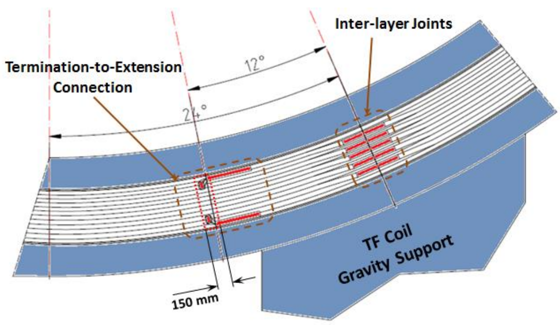

Fig. 3. Toroidal and radial location of TF coil inter-layer joint and terminations at side surface, the side wall of TF coil casing is not shown.

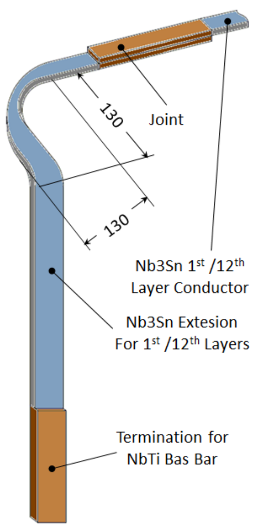

Fig. 4. Intermediate bent, twisted and then heat treated Nb_3Sn extension between Nb_3Sn TF coil termination and NbTi bus bar.

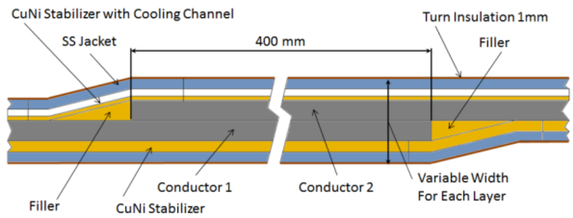

Fig. 5. Layout of inter-layer joint. The joint thickness varies at each inter-layer joint in accordance with the dimension of graded conductors; the joined length of conductors is always 400 mm.

TABLE I
THICKNESS OF CONDUCTORS IN LAYERS AND OF THEIR JOINTS

Extension and Layer #	Conductor Thickness with Turn Insulation mm	Joint Thickness with Turn Insulation mm
High-Grade Extesion	34.1	
		43.9
#1	34.1	
		42.3
#2	33.7	
		41.1
#3	34.3	
		41.7
#4	35.6	
		40.7
#5	36.8	
		41.9
#6	38.3	
		43.4
#7	39.5	
		44.1
#8	41.2	
		45.9
#9	39.6	
		44.3
#10	42	
		46.7
#11	43.9	
		48.6
#12	32.8	
		37.5
Low-grade Extension	32.8	

The joints are located at the side surface of coil (between the beginning and ending of the each layer winding) of TF coil, in the small displacement area [4], in vicinity of TF coil gravity support. The TF coil terminations with their connections to bus bar are allocated at the same place and are shifted toroidally in respect to inter-layer joints for better access during their preparation (Fig. 2 and Fig 3). The intermediate bent and twisted Nb_3Sn conductor section (extension), heat treated afterwards, connects the coil termination and the bus bar, Fig. 4.

The layout of joint is shown in Fig. 5. This particular presented joint consists of two identical high-grade conductors, which is appropriate for the termination-to-extension connection and is supposed to be used for the sample preparation and test at SPC. The joint thickness is variable and depends on joined graded conductors, i.e. depends on cable space and on thickness of jacket. The graded conductor thickness and the thickness of their inter-layer joints are gathered in Table I. The thickness of conductors and joints includes the turn insulation of 1 mm thickness.

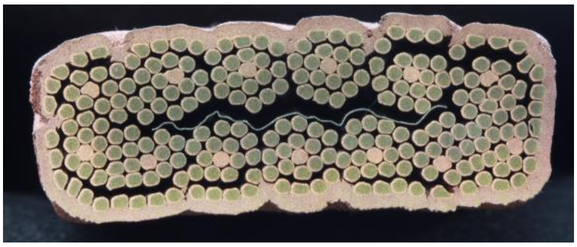

Fig. 6. DEMO TF coil dummy conductor with copper deposited by arc-spray method.

Fig. 7. Clamping fixture made of stainless steel plates, bolts and disc springs

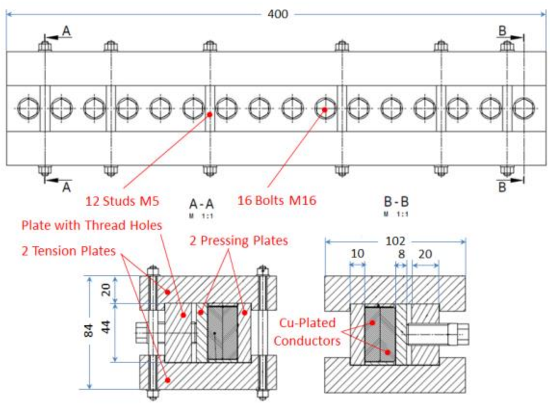

Fig. 8. Bonding fixture for bonding procedure of two TF copper-plated conductors at 650°C temperature and 30 MPa pressure.

The thickness of joints assumes the bare cables, i.e. the copper cladding thickness is not taken into account. The thickness of joints with copper-cladded conductor ends can be 2-3 mm thicker.

The one side of TF coil contains the five joints and two terminations; the other side of coil contains only six joints. The gap between the joints varies within 30-40 mm. This space is enough for allocation of insulated cooling piping ∅12 mm, which can be passed away through the coil case together with the terminations of coil in the cutout of 150 mm width (see Fig. 3).

3. Performed R&D for development of joint

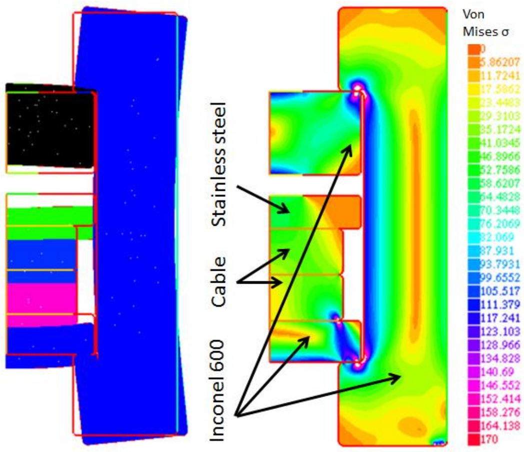

Fig. 9. Result of thermomechanical analysis of bonding fixture at 650°C temperature and 30 MPa pressure: deformation (left) and mechanical stress in MPa (right).

The most promising approach for inter-layer joint could be the diffusion bonding or soldering, the stainless steel strip is left for both methods.

The further R&D work at SPC is in the direction of developing an overlap diffusion bonded joint. With respect to an overlap soldered joint with solder between the two cables, an overlap diffusion bonded joint is more attractive because it is potentially more shear resistant, avoids the use of fluxing agents, has lower strand adjacent resistance (diffusion bonding can occur also between strands of the same cable). However, preliminarily to the inter-layer joint assembly, a cable surface treatment is necessary for increasing the contact surface between the two cables. The treatment consists in filling the cable surface void fraction with copper thermal spray and subsequently machining it for flattening it.

As a first trial, the arc-spray method of copper deposition on TF conductor was performed but failed, Fig. 6. The delamination and distortion of conductor have happened during the deposition of copper. This is undesirable for the real conductor, the distortion and delamination can be a reason for damage of heat treated superconductor. Further investigation is going on to understand the reasons of the distortion and further copper spray trials are planned.

4. Preparation work for diffusion bonding of inter-layer joint

The best results of diffusion bonding can be achieved at 650 °C temperature and at applied pressure of 30 MPa [5]. In order to reach the 30 MPa pressure at 650 °C, the clamping fixture for diffusion bonding of two copper-cladded TF conductors was designed and fabricated at SPC. This feature was designed in such a way, that the applied pressure distribution at the joint is uniform; and the uniform bonding promotes an uniform current distribution.

Previous experiences with a clamping fixture made of stainless steel plates and bolts (Fig. 7) convinced us to change completely the fixture layout and materials. Indeed, such a fixture requires thick pressing plates because the load is concentrated mostly at the cable edges, but the load has to be smoothed along the cable surface. The required high pressure at 650°C leads to an overpressure applied at room temperature. In order to come up to required pressure at 650°C, such a fixture force us to use the cumbersome disc springs due to the different thermal expansion between cable and fixture.

In the adopted fixture (Fig. 8), instead, the load is applied in the center and its layout and materials are meant to exploit the different components thermal expansion to gain pressure in the joint region when going from room temperature to 650 °C. The choice of the materials and materials thicknesses was also such, that the pressure at room temperature is not null, or 30 MPa at 650 °C would be exceeded involving possible cable damage or fixture plastic deformation. Therefore, all the parts of bonding fixture, excluding the pressing plate under the bolts, are fabricated of Inconel 600. The pressing plate under the bolts is stainless steel.

First, the conductors are pre-compressed to 23.5 MPa at room temperature by means of 16 bolts M16, and uniform spread of pressure is provided by the pressing plate under the bolts. Due to a different thermal expansion of fixture parts and cables the pressure at 650°C temperature reaches the required 30 MPa. The result of thermomechanical analysis of bonding fixture at condition of bonding is shown in Fig. 9. The maximal, above 170 MPa stress is concentrated at the inner corners of C-shaped tension plate.

5. Conclusion

The overlap joint for DEMO TF coil inter-layer joints has been proposed by SPC for the further development. The geometry of such a kind of joint is determined and location of joints at TF coil is identified. The inter-layer joints are fabricated during the coil winding; the free space around the joints is available for portable equipment of diffusion bonding.

The intermediate bent and twisted section of conductor is needed for the terminal-to-bus bar connection. The terminations of coil should be shifted toroidally to provide a good access for connection of intermediate conductors to the coil terminals.

The bonding at high temperature and applied pressure is proposed and is being in progress. The ends of conductors are copper-cladded by means plasma or arc-spray method. The fixture for bonding process is developed and fabricated at SPC. This bonding fixture will be used for manufacturing of inter-layer joint at SPC and for preparation of sample for further test in the SULTAN test facility.

Acknowledgments

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References

[1] K. Sedlak, P. Bruzzone, X. Sarasola and B. Stepanov, “Design and R&D for the Toroidal Field Coils of DEMO by React and Wind Method”, *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 4800105, ACS 2016, Denver, Colorado.

[2] B. Stepanov and P. Bruzzone, “New Design of Inter-Layer Splice Joint for the TF Coils of the DEMO- EUROfusion Tokamak”, *Fusion Engineering and Design*, vol. 124, pp. 49-53, SOFT 2016, Prague, Czech Republic.

[3] B. Stepanov, P. Bruzone and K. Sedlak, “Inter-layer Joint for the TF Coils of DEMO – Design and Test Results, *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, 4201104, Amsterdam, the Netherlands.

[4] V. Corato, et al., “Progress in the design of the superconducting magnets for the EU DEMO”, *Fusion Engineering and Design*, in press.

[5] K. Kizu et al., “Development of Central Solenoid for JT-60SA”, *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, 2013.