Design and R&D for the DEMO Toroidal Field Coils based on Nb_3Sn React and Wind Method

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***Abstract*—In 2013, the Swiss Plasma Center (SPC) proposed a Toroidal Field (TF) layout for the DEMO-EUROfusion tokamak, based on a graded winding made of layers of Nb_3Sn (react&wind) and NbTi conductors. The R&D effort led in 2015 to a full size prototype conductor tested up to 82.4 kA at 12.35 T. The test continued in 2016 and new results are presented. In summer 2015 a new reference baseline was issued for the DEMO-EUROfusion tokamak, leading to an update of the TF requirements. The design update is presented in this paper, with the winding pack consisting of 12 single layers of Nb_3Sn with "invisible" (no protrusion) inter-layer joints. The high grade Nb_3Sn react&wind conductor operates at 63.3 kA, 12.23 T with T_{cs} > 6.5 K. A new prototype conductor is being manufactured. The main advantages of the graded approach, applied to both the superconductor and the stainless steel conduit, are a substantial space and cost saving compared to the wind&react approach with pancake winding.**

***Index Terms*— Conductor Design, DEMO, Forced Flow Conductors, React&Wind, Toroidal Field Coils.**

I. Introduction

The future, post-ITER European fusion tokamak DEMO is being developed by the EUROfusion Consortium [1]. The conceptual design of the magnet system [2] so far focused on the central solenoid and toroidal field (TF) magnet. The latter was proposed in four alternative designs – one based on HTS, and three employing the conventional LTS conductors [2]. The TF coil design proposed by the Swiss Plasma Center (SPC), described in this publication, is based on Nb_3Sn react&wind (RW) technology, and updates the previous SPC TF conductor design [3], [4], [5] proposed in 2014 and 2015. The new TF coil design is based on the PROCESS system code [6] and EUROfusion CAD model [7] defined in 2015.

There are two important differences of the SPC TF coil design compared to the ITER TF coil. First of all, the conductor is based on RW technology, which significantly reduces the thermal strain on Nb_3Sn strands at operating temperature, which in turn increases the critical current density of strands, leading to significant reduction of required amount of Nb_3Sn compared to the wind&react technology [8]. In addition, the jacketing becomes easier, as the welds of the conduit are not exposed to the heat treatment. The steel jacket can be made of two rolled/extruded half-profiles that are longitudinally welded together. Consequently, there is a big flexibility of the jacket shape, which can have variable thickness, e.g. different thickness in the radial and toroidal direction, as well as rectangular outer shape and oval inner shape, see section II. This allows optimizing the steel allocation according to mechanical loads in individual layers of the TF coil, and to avoid the radial plates used in ITER.

The second difference with respect to ITER TF coil is the conductor grading. Every coil layer contains just the right amount of superconductor, steel, copper and helium that is necessary to fulfill the criteria on temperature margin, maximum hot-spot temperature and to withstand the mechanical loads. The coil is well quench-protected in its full volume, as there are no regions of high temperature margin, in which the quench propagation (and consequently quench detection) might become problematic. The grading of the superconductor material reduces the direct material costs, the grading in steel leads to a very compact WP design, thus reduces the overall radial build of the WP, and consequently leads to the indirect cost reduction of the overall tokamak construction cost that are expected to be proportional to the third power of the tokamak radius.

These design choices lead to a winding pack (WP) design that minimizes the amount of used materials, of which especially Nb_3Sn is of the main interest, and the overall size of the WP. Consequently, the SPC TF coil design is the most economical design of all the four proposed [8].

II. DEMO TF Winding Pack and Conductor Design

A. Winding pack

The current DEMO design reference [6], [7] envisages the TF WP coil radial build of 500 mm, which turned out to be challengingly small, and has never been achieved in earlier DEMO TF WP designs. The reduced requirement on overall current per single TF coil, 14.3 MA [6], together with the choice of RW technology and the layer grading allowed us to meet this goal, as indicated in Fig. 1. However, a thorough mechanical evaluation confirming the mechanical stiffness of the proposed TF WP design still needs to be done.

Experience from the mechanical analysis of the previous design showed that the conductors need to be arranged into "columns" such that the conductor edges of neighboring layers are aligned, and the mechanical load in the radial direction is carried by the short conduit wall. The new WP layout consists of 12 layers × 19 turns (17 turns in the last layer), i.e. in total 226 turns, leading to the conductor operating current of

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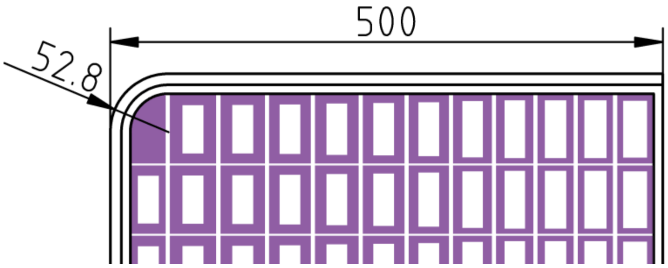

Fig. 1. Section of the TF winding pack proposed by SPC in 2016. The rectangles represent steel cable jacket (the inner corner rounding is not shown). The conductor turn near the WP rounded corner is replaced by steel spacer. The dimensions in the sketch are in mm. The overall WP size, including insertion gap, is 500 × 1243 mm.

63.3 kA. All 12 conductor grades are made of Nb_3Sn, unlike in [3] and [5], where six outer layers were made of NbTi. The old designs neglected the contributions of the magnetic field generated by CS and PF coils, which turned out to increase the peak magnetic field in the outermost layers by more than 1 T.

The winding is made by single layers in order to fully exploit the potential of the graded winding for superconductor and steel and to maintain realistic manufacturing lengths. The twelve layers are cooled in parallel, with cooling inlets and outlets located at the layer transitions. The length of 12 parallel hydraulic paths ranges from 805 m to 894 m. Both joints and cooling inlets/outlets are at the outboard region of the TF coil. The joints will be "invisible", i.e. they maintain the conductor size and do not protrude from the WP. The detailed joint design, inspired by the ITER CS joint, is reported in [9].

Some criteria common for all TF WP designs were agreed within the EUROfusion teams and summarized in [10]. The conductors are wrapped into 1 mm thick insulation. In addition, there are 2 mm thick insulation layers between individual conductor layers, and 8 mm thick ground insulation wrap around the WP. A 10 mm insertion gap between the WP

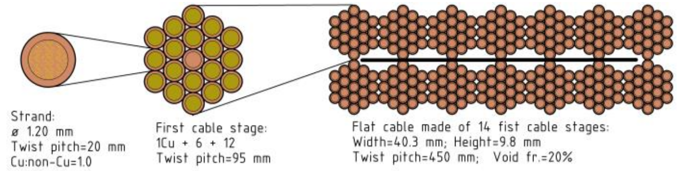

Fig. 2. Superconducting strand (left), first cable stage (middle) and flat cable (right) used in the SPC conductor of the first TF coil layer.

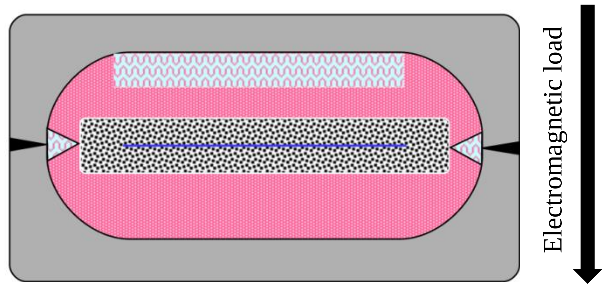

Fig. 3. Assembled conductor for the first TF coil layer. The superconducting cable located in the conductor center is surrounded by mixed matrix Cu/CuNi profile with two triangular and one rectangular cooling channels. The whole assembly is surrounded by a steel jacked, longitudinally welded near the triangular cooling channels (longitudinal welds are indicated by flat dark triangles).

and TF steel case is foreseen at three sides.

B. *Conductor design*

An important change with respect to previous years is the decrease of the voltage threshold for the quench detection from 0.5 V to 0.1 V, same as ITER. Also the delay time, i.e. the time needed for quench validation after reaching the 0.1 V threshold (0.1 s) and breakers opening (1.0 s) was reduced to the total value of 1.1 s from 2 s in 2015. The motivation behind these changes was not to "overdesign" the conductor by too conservative considerations (i.e. more stringent criteria than those already used in ITER). On the other hand, the quench initiation zone was reduced from 1 m to only 10 cm to

TABLE I
CONDUCTOR SPECIFICATIONS IN INDIVIDUAL LAYERS

Layer	Strand ø	Subcable layout	# SC strands per subcable	# Subcable	Total number of SC strands + Cu wires	SC (non-Cu) in the flat cable	Cu in the strands	Cu in the flat cable	Cu segragated	He in the bundle	He in cooling side channels (sum of two)	He in cooling upper channel	Inner corner rounding radius in the jacket	Steel Jacket	Conductor non-insul. size, width x heigh	Flat cable (SC only) width x height	Conduit toroidal thickness	Conduit radial thickness
	mm					mm2	mm2	mm2	mm2	mm2	mm2	mm2	mm	mm2	(mm x mm)	(mm x mm)	mm	mm
1	1.20	1Cu+(6+12) Sc	18	14	252 + 14	142.5	142.5	15.8	474.7	78.7	16.0	140.0	11.0	943	61.5 x 32.1	40.3 x 9.8	5.1	5
2	1.00	1Cu+(6+12) Sc	18	16	288 + 16	113.1	113.1	12.6	507.3	62.7	16.0	140.0	10.0	966	61.5 x 31.7	38.4 x 8.2	5.7	4.6
3	0.90	1Cu+(6+12) Sc	18	16	288 + 16	91.6	91.6	10.2	531.2	51.0	16.0	140.0	9.5	1036	61.5 x 32.3	34.6 x 7.4	6.4	4.6
4	0.90	1Cu+(6+12) Sc	18	14	252 + 14	80.2	80.2	8.9	543.9	44.8	16.0	120.0	9.5	1153	61.5 x 33.6	30.2 x 7.4	7.4	4.6
5	1.00	1Cu + 6Sc	6	29	174 + 29	68.3	68.3	22.8	541.9	42.3	16.0	115.0	9.5	1249	61.5 x 34.8	41.3 x 5.1	8	5.2
6	1.00	1Cu + 6Sc	6	25	150 + 25	58.9	58.9	19.6	554.5	36.6	16.0	95.0	9.5	1378	61.5 x 36.3	35.6 x 5.1	8.7	6.3
7	1.00	1Cu + 6Sc	6	21	126 + 21	49.5	49.5	16.5	567.0	30.8	16.0	85.0	9.5	1479	61.5 x 37.5	29.9 x 5.1	9.3	7
8	0.90	1Cu + 6Sc	6	23	138 + 23	43.9	43.9	14.6	574.5	27.4	16.0	70.0	9.5	1607	61.5 x 39.2	29.5 x 4.6	10.2	7.5
9	0.90	1Cu + 6Sc	6	22	132 + 22	42.0	42.0	14.0	577.0	26.3	16.0	60.0	9.5	1520	61.5 x 37.6	28.2 x 4.7	9.2	8.3
10	0.90	1Cu + 6Sc	6	21	126 + 21	40.1	40.1	13.4	579.6	25.1	16.0	50.0	9.5	1684	61.5 x 40.0	26.9 x 4.7	10.4	8.7
11	0.90	1Cu + 6Sc	6	20	120 + 20	38.2	38.2	12.7	582.1	24.0	16.0	40.0	9.5	1812	61.5 x 41.9	25.7 x 4.7	11.4	8.9
12	0.90	1Cu + 6Sc	6	19	114 + 19	36.3	36.3	12.1	584.7	22.8	16.0	40.0	9.5	1133	61.5 x 30.8	24.4 x 4.7	5.8	9.1

better match the real situation, where the actual initial normal zone can be very short. Such a quench is potentially the most dangerous one from the point of view of quench detection and consequently also for hot-spot temperature.

The choice of RW technology calls for a flat cable design, in which the strands are located as close as possible to the neutral bending axis [3]. This minimizes the bending strain during conductor manufacturing and coil winding on the heat-treated strands, whose excess could permanently degrade the conductor performance as it was the case e.g. in the conductor of T-15 tokamak [11]. The thermal strain assumed in the RW design was specified in [10] to be 0.35%, the value extracted from the 2015 test campaign of the first RW DEMO TF prototype [4].

The cable layout of the first conductor layer, in which the effective field reaches 12.23 T, is depicted in Fig. 2. Other layers are similar, some of them having just 7 strands in the first cable stage instead of 19, see Table I.

The conductor layout, see Fig. 3, is based on the earlier proposal [3] with two modifications. The first modification concerns the segregated copper, originally made by a layer of copper wires around the flat cable. The tests of the first conductor prototype (Fig. 4) revealed frequent voltage spikes in the DC measurements during current ramps, presumably due to strand movements over the gaps in the outer layer of the Cu wires [4]. In the new conductor design, the stabilizer is formed by a solid composite made of 95% Cu and 5% CuNi. The matrix with longitudinally-oriented high-RRR copper cells separated by thin CuNi barriers has very low resistance along the longitudinal conductor axis, but higher resistance in the transverse direction limiting the eddy current loss.

The second modification concerns the helium side cooling channels. The mechanical analysis [12] revealed mechanical drawbacks of circular channels positioned in the steel conduit originally proposed in [3], due to the large aspect ratio. In the new design, the triangular side cooling channels serve mainly to allow full penetration of the longitudinal weld and its quality control, while the rectangular cooling channel on top of the conductor guarantees the sufficient helium flow through the conductor. The two stabilizer profiles (upper and lower) encase the flat cable without any welding or soldering. The helium exchange between all helium volumes is allowed, and the pressure in the bundle and in all three cooling channels tends to equalize both during normal operation and in case of quench.

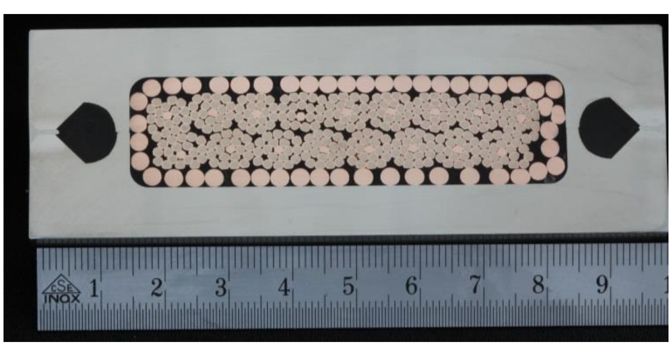

Fig. 4. The first RW DEMO TF conductor prototype designed for operating current of 82.4 kA and magnetic field of 13.24 T.

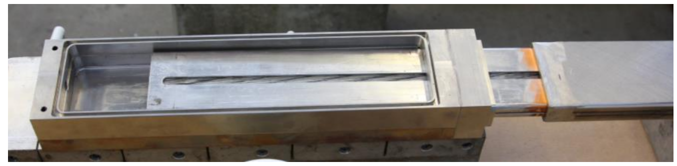

Fig. 5. The cable, in which the outer layer of Cu wires is replaced by two copper U-profiles, is being slid into the termination box.

The conductors are designed for the nuclear heat load defined in 2015 [14]. The required temperature margin is set to 1.5 K [10], and accommodates the nuclear heat load, the ohmic heating at the inlet joint (1 nΩ) and Joule-Thomson heating due to the pressure drop along the conductor. The inlet and outlet pressure are 6 and 5 bar, respectively. The detail conductor specification for all layers is summarized in Table I.

III. Test of the 82.4 kA Conductor Prototype

A 82.4 kA prototype conductor was manufactured in 2014 according to the 2012 reference and tested in 2015 [4]. The performance measured during the first test campaign was not as high as expected. Resistive sections in the conductor region near the bottom joint and upper terminations, voltage spikes during current ramp-up, and sudden quenches in the low field sample region at currents above 82 kA all compromised the DC performance at high current. The reason for the underperformance is believed to be a poor current transfer at the terminations and an inadequate lateral support of the flat cable due to the imperfect alignment of the outer layer of copper wires – see the voids between the wires in Fig. 4.

A few attempts were done to improve the performance. Already in 2015 all four termination boxes were opened and resoldered, which led to the improvement of T_{cs} [4]. Another improvement was tried in 2016, when the outer layer of cooper-wires was replaced by two solid copper U-section profiles, obtained by folding a 2 mm thick copper sheet, and surrounded by a thicker (3.9 mm wall) steel jacket.

The Cu profile sections extending into the termination were pre-tinned and had slots/holes to allow the penetration of the solder. After longitudinal welding of the jacket U-profiles, the cable ends were heated to smooth the solder residual on the flat cable. Then the termination boxes, i.e. copper/steel brazed assembly, were slid over both conductor ends, welded to the jacket, soldered to the cable and eventually sealed by the welded lid. A slot in the profile on the side opposite to the contact surface provides a channel for the helium. A phase of the termination assembly is shown in Fig. 5.

The re-test of the improved sample started in EDIPO in May 2016. After two days of testing, EDIPO failed, and the test campaign continued in SULTAN at slightly lower field. All termination resistances substantially decreased, however the resistance between the bottom joint and the high field region remained non-zero (0.29 nΩ and 0.13 nΩ in the right and left section, respectively). The former current limitation around 80 kA in high field disappeared. The current could be raised up to 100 kA in field without quenching.

The DC performance evolution during gradual sample improvement at 70 kA and 12.35 T background field is summarized in Fig. 6. The final improvement compared to the best result of 2015 is in the range of 0.5 K for both conductor sections (Fig. 7). The left conductor section performs slightly better than the right one. The results suggest that the conductor underperformance has been mitigated, but some likely irreversible degradation occurred, at least in the right section.

The dashed lines in Fig. 6 give the theoretical performance assessment at ε = -0.28% and ε = -0.35%. The scaling law parameters used in the assessment are not the same as in [4]. The parameters used in Fig. 6 are taken from the final report [15], which presents the most recent set of scaling law parameters for the 1.5 mm Nb_3Sn WST strands used in the sample prototype.

All the DC results collected in EDIPO and SULTAN in 2016 are gathered together in Fig. 7. The I_c data are systematically better than the T_{cs} data. Despite the impressive performance improvement after sample re-assembly, some doubt is left whether the present performance is really the ultimate one.

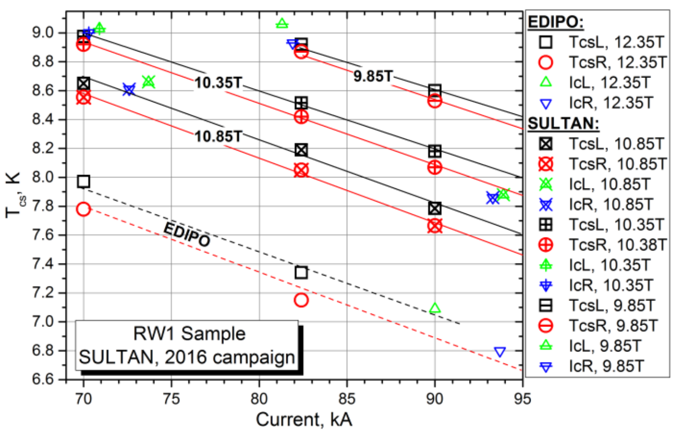

Fig. 6. Summary of the DC tests in SULTAN and EDIPO in 2016.

IV. Next Conductor Prototype

The updated layout of SPC TF WP presented in section II is the basis for the second prototype conductor, which will be manufactured in late 2016. Due to the reduced operating current (from 82.4 kA to 63.3 kA), reduced magnetic field (from 13.24 T to 12.23 T), and modified conduit layout, the non-insulated size of the present highest grade conductor is 61.5 mm x 32.1 mm, with aspect ratio AR < 2 compared to AR > 3 in the former prototype. It can fit into the SULTAN/EDIPO test well without any compromise on the jacket.

Short lengths of WST strands, ø = 1.20 mm, Cu:nonCu = 1, were tested at SPC in May 2016. After heat treatment, the preliminary results of I_c suggest up to 10% better performance compared to the WST strands procured in 2014 for the first prototype. For this reason, the new prototype of the high grade TF conductor will be build out of 13 instead of 14 subcables envisaged in Table I.

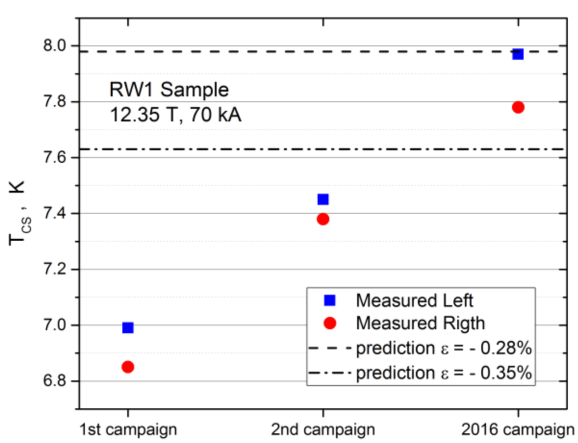

Fig. 7. Comparison of the T_{cs} performance of 2015 and 2016.

V. Conclusion

The 2016 DEMO TF coil design proposed by SPC meets the stringent space allocation specified in the 2015 DEMO reference. The choice of RW technology together with layer grading leads to a cost effective and space saving WP design.

The conductor prototype build in 2014 revealed some weaknesses of the earlier design, e.g. the outer layer of copper wires, and confirmed feasibility of some technological choices, e.g. jacketing done on the heat-treated cable. After several improvements of the prototype sample, the DC performance corresponds to the prediction based on the single strand measurements scaled by the usual (ITER-like) scaling law with applied strain $\varepsilon_{th} = \sim -0.30\%$, which is close to the value expected for the RW technology ($\varepsilon_{th} = 0.28\%$ in [4]). The thermal strain assumed in the 2016 design is 0.35% [10], providing us with some additional design margin.

The manufacture of a new high grade prototype conductor has already started with a more ambitious layout.

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