A new Cabled Stabilizer for the Nb_3Sn React&Wind DEMO Conductor Prototype

Pierluigi Bruzzone, Kamil Sedlak, Boris Stepanov, Mithlesh Kumar, Vincenzo D'Auria

***Abstract*— A Nb_3Sn based, React&Wind flat cable, named RW2, was developed in the past three years at the Swiss Plasma Center in the scope of the EUROfusion conceptual studies for DEMO. The test results presented earlier proved an excellent DC performance, but large eddy currents loss in the segregated copper. Here we present the results of a prototype conductor assembled in late 2019 from an older section of RW2 cable and a novel stabilizer, made by two Rutherford cables of thick, high RRR copper wires extruded with a cladding of high resistivity CuNi alloy. The results of the test in SULTAN of the new prototype are discussed in terms of DC and AC loss performance. The AC loss is measured in both orientations, for sinusoidal and trapezoidal field pulses. The test is carried out at both 4.5 K and 20 K operating temperature, allowing separating the contribution of the eddy currents in the segregated copper from the other sources of ac loss, hysteresis and coupling loss. The goal of reducing the eddy currents to a level comparable to the coupling current loss is achieved with the cabled stabilizer, which is now retained as baseline for the React&Wind DEMO conductor.**

***Index Terms*—Nb_3Sn, React&Wind, Superconducting cable, Tokamak.**

I. Introduction

In the scope of the conceptual studies of the EUROfusion DEMO [1], the Swiss Plasma Center (SPC) of EPFL has developed since 2015 high current, high field Nb_3Sn conductors based on the React&Wind (RW) technology. The first RW prototype conductor for TF, named RW1, was developed and tested in 2015 [2-3] according to the DEMO baseline 2013, with B = 13.5 T and I = 82 kA. The stabilizer layout by a layer of high RRR Cr plated copper wires could not be perfectly applied and the poor mechanical support for the cable led to premature quench outside the high field region.

The main new features of the second prototype conductor RW2, designed according to the baseline 2015 (B = 12.23 T and I = 63.3 kA) are a smaller aspect ratio, no separated cooling channel and a solid Cu/CuNi mixed matrix stabilizer replacing the layer of copper wires in RW1 [4]. Eventually, in 2018 the sample with the mixed matrix stabilizer was assembled and tested. The main achievement was the full retention of the strand properties, with effective strain, ε_{eff} = -0.28%, identical to the predicted thermal strain, and no cyclic load degradation, thanks to the transverse pre-compression of the heat treated flat cable during the assembly of the conductor [5].

However, the AC loss was very high, due to the mixed matrix stabilizer, which failed to achieve the expected drastic reduction of the eddy currents loss [6]. The development and test of a new, low loss stabilizer was carried out at SPC in 2019 and is reported below. The main steps of the R&W development at SPC are gathered in Fig. 1, with cross sections of the RW1, RW2 with mixed matrix stabilizer and RW2 with the novel low loss cabled stabilizer.

P. Bruzzone, K. Sedlak, B. Stepanov, M. Kumar and V. D'Auria are with Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-5232 Villigen-PSI, Switzerland

II. Requirements and Manufacture of the Stabilizer

For an R&W conductor, where the Nb_3Sn superconductor must be kept close to the neutral bending axis in form of a flat cable, the copper cross section needed for quench protection, here named "stabilizer", is segregated from the superconducting cable and can be assembled with the flat cable after the heat treatment. In fact, in the former versions of RW2 the upper and lower stabilizers form a sandwich with the flat cable.

To allow the application of the transverse pre-compression at assembly, as assessed in [5], the stabilizer must be rigid, at least as rigid as the Nb_3Sn flat cable. A cooling channel as in the former version of RW2, see Fig. 1 middle, would not allow proper pre-compression. The cooling channel for pressure release must be moved next to the cable, as the perforated rectangular steel tube shown in Fig. 1 bottom.

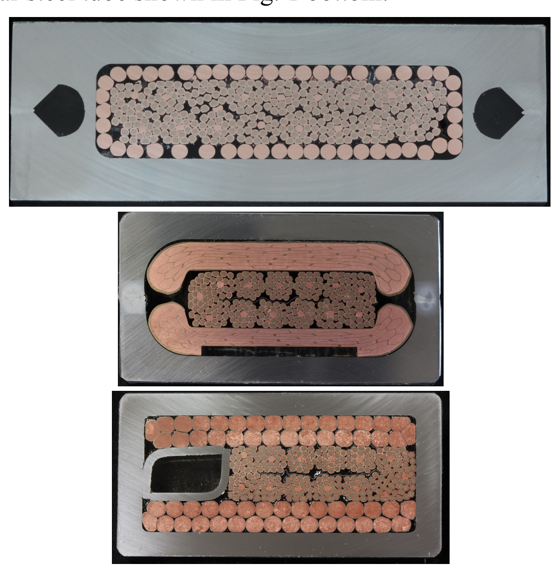

Fig. 1. Three milestones of the R&W prototype conductors at SPC. From top to bottom, RW1 (100x34 mm), RW2 (61.5x32.1 mm) with mixed matrix stabilizer and with cabled stabilizer.

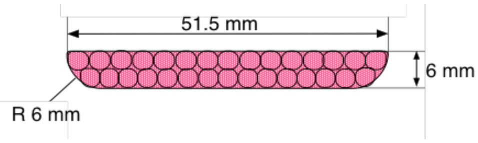

Fig. 2. Geometry of the Rutherford cable with rounded edges.

A solid copper block cannot be used as stabilizer because of the large eddy currents loss, which is proportional to the square of the width for field variations perpendicular to the broad side of the conductor. An example of solid copper stabilizer can be found in [3], where a copper profile replaced the layer of loose copper wires in the RW1 conductor.

On one hand, the quench protection requirement calls for a very low resistivity in longitudinal direction, $\rho_{\|}$. On the other hand, a large resistivity in transverse direction, $\rho_{\perp}$, is required to limit the eddy current loss. The mixed matrix stabilizer aimed at a ratio of resistivity $\rho_{\perp}/\rho_{\|} > 10$, but the real ratio was much lower, of the order of 3 [6].

The concept for a new stabilizer is a highly compacted flat cable (Rutherford cable) made of high RRR copper wires (RRR=420 measured) cladded by a thin sheath of Cu90Ni10, which builds a resistive barrier for eddy currents in transverse direction. Such barrier was not effective in the mixed matrix because the barriers were elongated due to the rolling process and because the metallic bonding between elements contributed to reduce the transverse resistance. In a Rutherford cable, there are only punctual pressure contacts between wires and the expected transverse resistance is over one order of magnitude larger than in the mixed matrix, although the cross section breakdown of Cu and CuNi is the same.

To prepare the mixed matrix stabilizer [5], a first extrusion was done with a high RRR copper billet in a can of CuNi. Then the extruded bars were re-stacked in a second billet for the mixed matrix. For the Rutherford cable, the CuNi clad copper wire was procured at WST, identical as the first stage of the mixed matrix. Two billets, each about 90 kg, were extruded and drawn down to 6 mm without intermediate annealing. The CuNi cross section was about 13% at the billet assembly and decreased during the extrusion/drawing process to about 10% of the overall cross section.

Two coiled lengths of wires were delivered to SPC in May 2019. One of the lengths was forwarded to Tratos (I) for further drawing and cabling. The layout of the Rutherford cable, with 30 wires ø = 3.35mm for a void fraction of ≈ 10% and a twist pitch of 500 mm, is shown in Fig. 2. The rounded edge R6, to fit the original jacket of RW2, could not be achieved because the wires were too hard after drawing to be suitably shaped by the rounded rolls. An intermediate vacuum annealing at 750 C is actually necessary before cabling. The sections of the Rutherford cable were delivered to SPC in September 2019 and annealed in the vacuum furnace before assembly into a RW2 conductor section named RW2rutstab.

III. Resistance Test and Analysis

The longitudinal resistance of the stabilizer is assessed by the RRR test of a single wire, extracted from the cable. The

TABLE I
SUMMARY OF RESISTANCE TESTS

	Longitudinal Orientation	Transverse Orientation
ρ @ 292 K	$1.66 \cdot 10^{-8}$ Ωm	$(1.13 \pm 0.65)\ 10^{-4}$ Ωm
ρ @ 4.2 K	$4.0 \cdot 10^{-11}$ Ωm	$(6.31 \pm 5.74)\ 10^{-4}$ Ωm
RRR	415 ± 11	<1

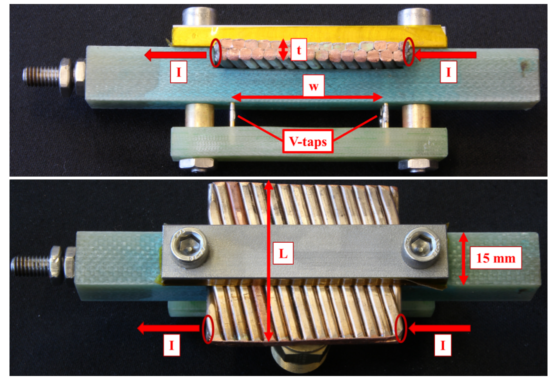

Fig. 3. Sample holder for transverse resistance of the stabilizer.

results are gathered in Table I. Both RRR and resistivity are meant for the overall composite consisting of pure copper core and CuNi cladding.

The transverse resistance of the stabilizer is measured on five 45 mm long sections of cable, see Fig. 3. On such a short length, the cable tends to fall apart, as the contacts between copper wires are not bonded. A small G10 clamp is used to keep the cable together. Once in the clamp, the cable is cut by electron erosion for L = 45 mm. The voltage taps are spring-loaded pins spaced by 45 mm. Each sample is tested twice at 4.2 K and at 292 K, with one intermediate warm-up. The frictional nature of the contacts between wires does not allow a correct assessment of RRR (which is by definition a metal property). The transverse "resistivity", $\rho_{\perp}$, is defined here as

$$\rho_{\perp} = R\frac{t \cdot L}{w},$$

where t is the thickness of the cable, 6 mm, and w is the distance between voltage taps, 45 mm, along the width of the cable. The 10 values of $\rho_{\perp}$ obtained for the five samples at room temperature have a broad range, see Table I, with four orders of magnitude higher than copper. RRR is lower than 1 in each sample. Such a result would be unphysical if the sample was a unique block of material, but it consists of unbounded strands,

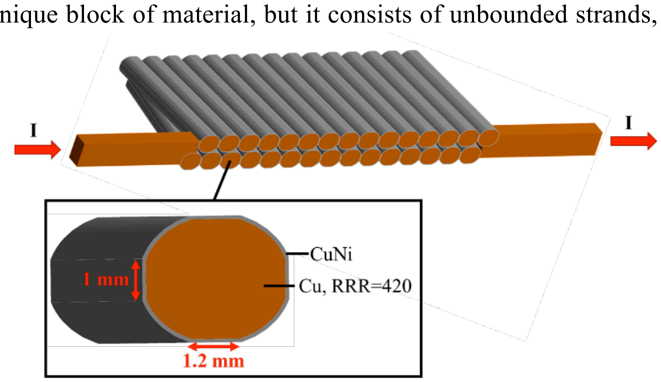

Fig. 4. Electrical DC model of the section of the Rutherford stabilizer.

Fig. 5. Assembly phases of the RW2rutstab conductor.

whose contacts change with thermal expansion/contraction.

With all caveats about reproducibility of the resistance results, the ratio between transverse and longitudinal resistivity for the Rutherford cable stabilizer at low temperature is $\rho_{\perp} / \rho_{\parallel} > 1.4 \cdot 10^{6}$.

The mechanical constraints set on the stabilizer by the steel jacket and Nb_3Sn cable are different from the ones set by the G10 clamp. The incertitude of the real $\rho_{\perp}$ motivated the development of a computational model with the goal of estimating the most conservative $\rho_{\perp} / \rho_{\parallel}$ for this stabilizer design. The computational model (Fig. 4) tries to reproduce the 45 mm long stabilizer section, whose RRR was experimentally measured. Each strand has the same geometry, set such that the cross-section (51.7 x 6 mm^2 and 10% void fraction) and the materials volume of Cu and CuNi are respected. Perfect contact among strands is assumed. Current is injected as in the RRR measurement. With such conservative assumptions, it is obtained that $\rho_{\perp} / \rho_{\parallel}$=600 at low temperature. With such a very high ratio, the only AC loss expected in the conductor is the eddy currents loss within the individual copper wires.

IV. The RW2rutstab Sample

The Nb_3Sn flat cable for the RW2rutstab conductor was recycled from a section of RW2brass, assembled and tested in 2016 [5]. The cable terminations were unsoldered and the steel jacket was longitudinally cut and removed.

The jacket sections for RW2rutstab are machined to the same outer size as RW2. The inner corners have R2 instead of R6 because of the above-mentioned issue with the cabling of the stabilizer.

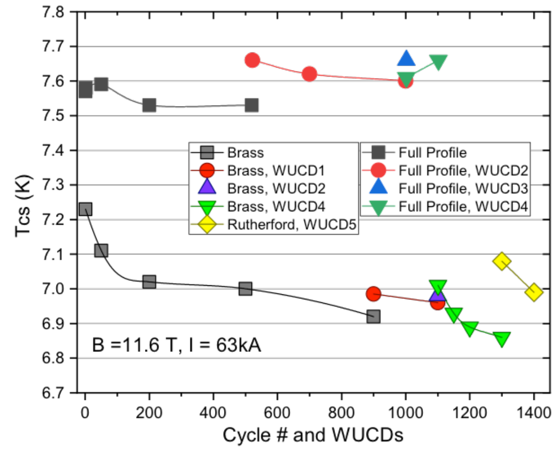

Fig. 6. Evolution of T_{cs} along electromagnetic and thermal cycles.

The cooling channel was prepared by bending at 90° two stainless strip, 2mm thick, and spot welding at the corners. Few holes were drilled for better exchange of coolant. The experience showed that 1 mm thickness would be sufficient. For real long length manufacture, a round perforated pipe, wall thickness 1 mm, could be fit in the assembly. By applying transverse pressure, the round pipe would deform to cancel the assembly gaps and block the cable along the broad side.

A preliminary assembly of the stabilizer into the jacket was carried out to assess the matching tolerance, Fig. 5 top. The cooling channel also fits between the cable and the jacket with zero tolerance, Fig. 5 middle. The two jacket halves are pressed together for longitudinal welding. The RW2rutstab conductor is assembled into a SULTAN sample together with the RW2fullMM (full profile of mixed matrix), whose results were reported in [5]. The instrumentation is identical to the one applied in the earlier RW2 samples [5-6].

V. DC Measurements

The reference DC test is the current sharing temperature, T_{cs}, at 63 kA operating current and 11.6 T (background and self field). The T_{cs} test was carried out immediately after cool-

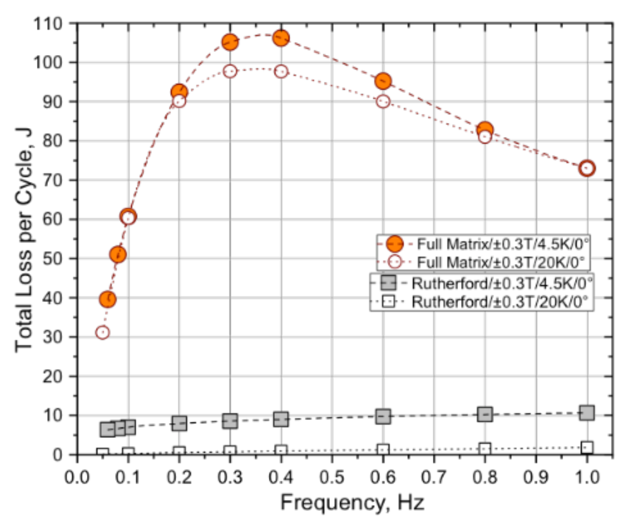

Fig. 7. AC loss results for AC field orientation perpendicular to the broad side of the cable at 4.5 K and 20 K, for both RW2fullMM and RW2rutstab.

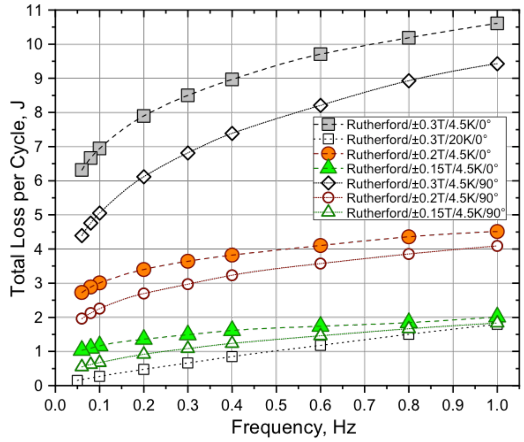

Fig. 8. AC loss results for orientation parallel to the broad side of the cable.

down and after 100 load cycles. The results are summarized in Fig. 6. The cable section now assembled into RW2rutstab was earlier tested as RW2brass. The assembly of RW2brass was done without pre-compression: the performance started at ≈ 7.25 K and was degraded with electromagnetic and thermal (WUCD = warm-up/cool-down) cycles down to ≈ 6.85 K. The cable extracted from RW2brass and assembled with pre-compression into RW2rutstab has now a slightly better performance (yellow diamond in Fig. 6), suggesting that a fraction of the degradation in RW2brass was reversible. The performance of the other conductor, with full profile mixed matrix, remains stable as in the earlier test campaign, between 7.6 K and 7.7 K, confirming the effectiveness of the pre-compression at assembly [5].

VI. AC Loss Results

The AC loss runs include sinusoidal and trapezoidal sweep, at 4.5 K and 20 K operating temperature and pulsed field orientation perpendicular (0°) and parallel (90º) to the broad face of the flat cable. Fig. 7 reports the sinusoidal AC loss for 0° orientation at 4.5 K and 20 K, for both RW2fullMM and RW2rutstab. The open symbols, i.e. the results at 20 K, represent the eddy current loss. For RW2fullMM, the eddy currents loss makes over 90% of the overall loss. For RW2rutstab the eddy currents loss is a small fraction, ≈10%, of the overall loss. The coupling currents loss is substantially the difference of full minus open symbols and it is the same, as expected, for RW2fullMM and RW2rutstab. For a straight comparison of the eddy currents loss, the cabled stabilizer has < 1% of the loss of the full mixed matrix. In fact, the eddy currents are limited to the single copper wire and can be neglected for practical purposes.

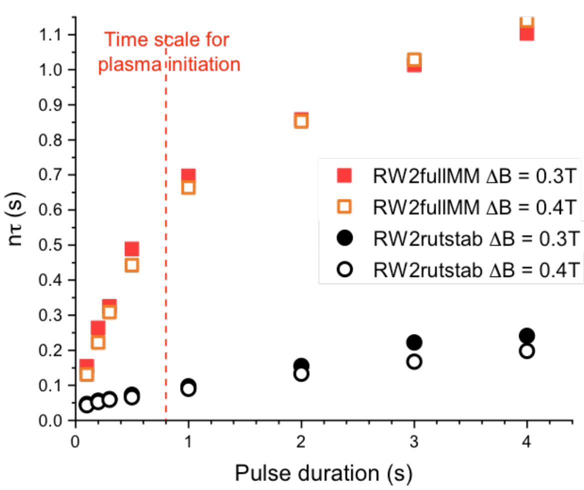

Fig. 9. Coupling loss time constant, nτ, from trapezoidal field loss in perpendicular orientation, see [7] for procedure.

The loss of RW2rutstab at 90° orientation is reported in Fig. 8. A straight comparison of 0° to 90° (square gray vs. open diamond), shows that the loss at 90° is only ≈20% lower than 0°, with a similar behavior vs. frequency. The similarity can be justified with the effective role of the stainless steel strip in the median plane of the flat cable, i.e. the loss of the flat cable is dominated by the loss of the first cable stage.

From the AC loss in trapezoidal pulse, the coupling time constant, nτ, can be evaluated at the CS plasma initiation, which lasts 0.8 s in DEMO see [7]. The plot in Fig. 9 suggests that for RW2rutstab nτ is below 100ms.

VII. Conclusion

The R&D for a high current React&Wind Nb_3Sn fusion conductor is completed with the last prototype, RW2rutstab. Two major results have been achieved:

1. Retain the strand performance at the level of the thermal strain (ε_{eff}=ε_{th}=-0.28%) by the application of a transverse load during conductor assembly.

2. Optimize the layout of the segregated copper for protection (stabilizer) for a reliable mechanical support during conductor assembly and for a negligibly low contribution to the overall AC loss. The cabled stabilizer by CuNi clad copper wires fulfils the two objectives at very reasonable cost. The cabled stabilizer is over 50% cheaper than the mixed matrix and can be manufactured in km lengths without joints, opposite to the mixed matrix, which requires a joint every 50 m.

A baseline is now established for Nb_3Sn, R&W conductors for DEMO, applicable to both TF and CS magnets for a broad range of operating current.

The main technology demonstration step toward the industrial manufacture of long length conductor is the synchronous longitudinal laser welding of the jacket over 1 km length. Such demonstration, including QA procedures, is planned in 2022.

Acknowledgment

The authors thank Paul Scherrer Institute PSI for its technical support, and M. Husistein, F. Roth, F. Oberle, R. Smith, M. Jenni, C. Müller und M. Holenstein for their careful and dedicated sample preparation and SULTAN operation.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] G. Federici *et al.*, "Overview of the design approach and prioritization of R&D activities towards an EU DEMO," *Fus. Engin. and Design* 109-111, 2016, pp. 1464-1474.

[2] P. Bruzzone et al., "Design, Manufacture and Test of a 82 kA React&Wind TF Conductor for DEMO", *IEEE Appl. Supercond.* 26, 4801805 (2016).

[3] K. Sedlak, P. Bruzzone, X. Sarasola, B. Stepanov and R. Wesche, "Design and R&D for the DEMO Toroidal Field Coils Based on Nb_3Sn React and Wind Method," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 2017, Art. no. 4800105.

[4] P. Bruzzone *et al.*, "A Prototype Conductor by React&WIND Method for the EUROfusion DEMO TF Coils," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, 2018, Art. no. 4202705.

[5] K. Sedlak et al., "DC Test Results of the DEMO TF React&Wind Conductor Prototype No 2", *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, 2019, Art. no. 29011305.

[6] K. Sedlak, P. Bruzzone, B. Stepanov and V. Corato, "AC Loss measurement of the DEMO TF React&Wind Conductor Prototype No 2", *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, 2020, Art. no. 2961067.

[7] P. Bruzzone, B. Stepanov, K. Sedlak and V. Corato, "A new test method of AC loss measurement for fusion conductor", *Fus. Engin. and Design* 146 PartA, 2019, pp. 928-931.