Longitudinal and Transverse Dimensional Changes During Heat Treatment of the Nb_3Sn Cables for the Graded Research Racetrack Dipole Demonstrator (R2D2)

E. Fernandez Mora, M. Durante, J. C. Perez, E. Rochepault, and F. Rondeaux

***Abstract*—The Research Racetrack Dipole Demonstrator (R2D2) is a Nb_3Sn graded magnet developed in the framework of the CEA-CERN collaboration with the goal to assess key technologies for future high field accelerator magnets. This demonstrator magnet features two 1.7 m long racetrack coils, designed in the graded configuration needed for compact and efficient high field magnets. Each coil is made of two different Nb_3Sn cables wound around each other and submitted together to the high temperature heat treatment needed for Nb_3Sn compound formation. The experience on Nb_3Sn coils has taught us that the management of the deformations undergone by the Nb_3Sn cable during its formation must be a priority in the definition and the dimensioning of the tools and the manufacturing processes of the coils. This paper reports the results of the test campaigns carried out at CEA Saclay to study the behavior of R2D2 cables during heat treatment. The first campaign consisted of reduced-coils made of a few turns of each cable, with representative lengths. For each coil, the winding is performed with gaps in the components, and the gaps are measured before and after the heat treatment to quantify the coil length variations. A second campaign consisted in measuring the thickness variations of cable stacks in various configurations. The results allowed validating the choices made for the final R2D2 coils and heat treatment tooling to manage the longitudinal contraction and the transverse expansion.**

***Index Terms*—Conductor dimensions, heat treatment, Nb_3Sn conductors, rutherford cables, thermal contraction, thickness expansion, winding contraction.**

I. Introduction

TWO different graded cables will be used in the manufacturing of the R2D2 racetrack coils to maximize the current density and to minimize the size of the magnet. A high field (HF) conductor and a low field (LF) conductor will be wound, reacted and impregnated together in the same coil layer [1].

During the heat treatment process of Nb_3Sn cables, several dimensional changes can occur due to the transformation of the material's structure as it goes through the critical steps of forming the superconducting compound. Specifically, the Nb_3Sn cables experience first, a longitudinal contraction due to the relaxation of the Nb sub-elements when the Cu matrix is annealed after exceeding 150 °C in the thermal cycle of Nb_3Sn cable formation [2]. Then, the material typically experiences a significant increase in volume. After tin transformation in CuSn phases, the temperature is raised further to initiate the reaction that forms Nb_3Sn. During this reaction, tin diffuses into the niobium to create the Nb_3Sn crystal structure. This phase change, together with the creation of voids, results in the formation of the superconducting compound and an increase in volume, translated in an increase of cable section and length [3].

For the validation of the tooling designed for the fabrication of the R2D2 coil, a new test campaign has been carried out at CEA in collaboration with CERN to have a first information about the behavior of these two Nb_3Sn cables during the winding process and the heat treatment, and avoid cable damage.

For this purpose, cable bending tests, dimensional change tests in reduced coils, and conductor stacks during heat treatment have been performed.

II. R2D2 Cables

Both R2D2 cables, provided by CERN, are rectangular Rutherford type cables, insulated with S2 fiberglass. The main cable parameters are listed in Table I.

III. Cable Bending Tests: Easyway Tests

The necessity to assess the R2D2 minimum easyway bending radius on the cable windability is an important step for the validation of the components and the manufacturing procedure of the R2D2 coil.

A. Setup

The setup of the installation is shown in Fig. 1. The winding post is composed of two separated 3D printed ABS plastic

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TABLE I
MAIN PARAMETERS OF R2D2 CABLES

Parameter	Unit	HF cable	LF cable
Strand type	-	DEM-1.1	DEM-0.7
Strand layout	-	RRP® 162/169	RRP® 60/91
Strand diameter	mm	1.1	0.7
Number of strands	-	21	34
Cable mid-thickness	mm	1.969 ± 0.010	1.253 ± 0.010
Cable width	mm	12.579 ± 0.050	12.579 ± 0.050
Twist pitch	mm	84 ± 3	79 ± 3
Core	-	No core	No core
Keystone	°	0	0
Insulation thickness	mm	0.150 ± 0.005	0.150 ± 0.005

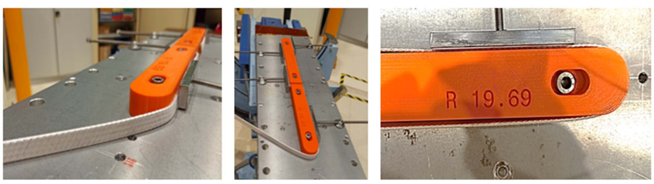

Fig. 1. Easy way bending test on Nb_3Sn HF cable.

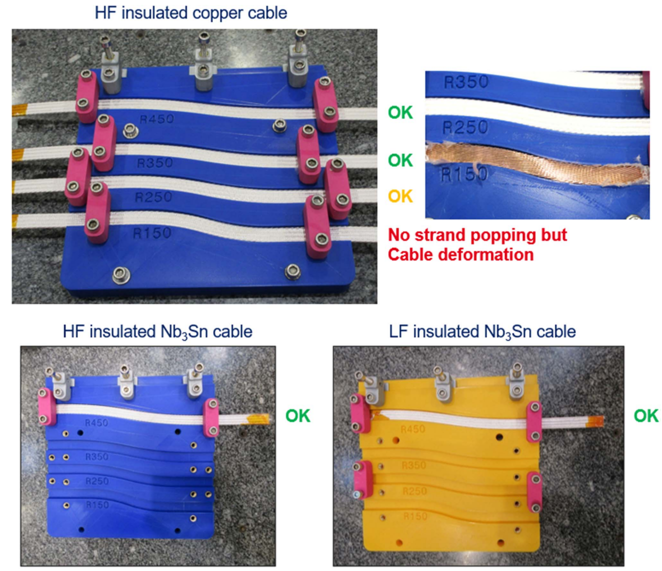

Fig. 2. Hardway tests on HF and LF insulated copper (top) and Nb_3Sn (bottom) cables.

mandrels with a radius of curvature equal to the one of the High Field coil first turn (19.69 mm). These two mandrels are mounted on the plate of the winding machine and the cable is tightly fixed to be able to apply a winding tension up to 30 daN. Once the single turn is wound, it is clamped laterally to maintain the cable in position.

B. Tests on HF Unreacted Insulated Cables

Because of the limited amount of the first Nb_3Sn trial cable run, tests have been carried out firstly on copper HF cable to probe the behavior of the cable. This behavior has then been validated on the actual Nb_3Sn HF cable. The initial applied tension of 15 daN, has been increased to 20 daN at the beginning of the bending, and the up to 30 daN to close the bending.

A slightly different braid was observed in the two cables. Note that only the thickness is specified, and all other braid parameters are left free for the manufacturer. Despite this, no particular differences both in cable positioning and in the behavior of the two cables were found.

IV. CABLE BENDING TESTS: HARDWAY TESTS

Checking the hardway bending radius in the cable exit areas must be carried out to ensure that the leads can be properly guided towards the output of the R2D2 coil.

A. Setup

R2D2 coil grooves with different radii have been 3D printed for use as a test bench. A test bench for HF cables and a test bench for LF cables have been produced. Both tools are 220 mm wide and have a groove with a radius of 450 mm, as the hardway bending of R2D2 coil. The radius of the rest of the grooves decreases by 100 mm up to a radius of 150 mm.

For these sets of tests, it is not necessary to apply any tension.

B. Tests on Copper HF Unreacted Insulated Cables

Tests with copper HF cables have been carried out in a first step to evaluate all the radii of the different grooves. Four samples of 350 mm long copper HF cables have been tested.

Fig. 2 shows the tests. It was observed that the cables in the 450 mm and 350 mm radius grooves did not experience any strain. The cable in the 250 mm groove was slightly deformed. However, for the 150 mm groove, although the cable did not have any strand popping, it showed a significant deformation (collapsing).

C. Tests on Nb_3Sn HF and LF Unreacted Insulated Cables

In a second phase, Nb_3Sn HF and LF cables have been tested to evaluate their deformation in the groove of the 450 mm radius, corresponding to hardway cable exits in R2D2 coil, and to compare their behavior with the tests previously carried out with copper HF cables. A sample of 300 mm long Nb_3Sn HF cable and a sample of Nb_3Sn LF cable have been tested.

Fig. 2 summarizes these tests. The two cables were shaped without difficulty. No deformation of any kind was observed. Due to the limited length of available Nb_3Sn cables, it was decided to test later the behavior in the other grooves (useful for future designs), once all preliminary tests have been completed.

V. LONGITUDINAL CHANGES DURING HEAT TREATMENT: REDUCED COILS

In order to measure the longitudinal behavior of the Nb_3Sn cables, reduced coils using HF and LF conductors have been wound and reacted at CEA Saclay.

Heat-treatment parameters for the R2D2 cables are not completely fixed yet. An RRP standard heat-treatment cycle of

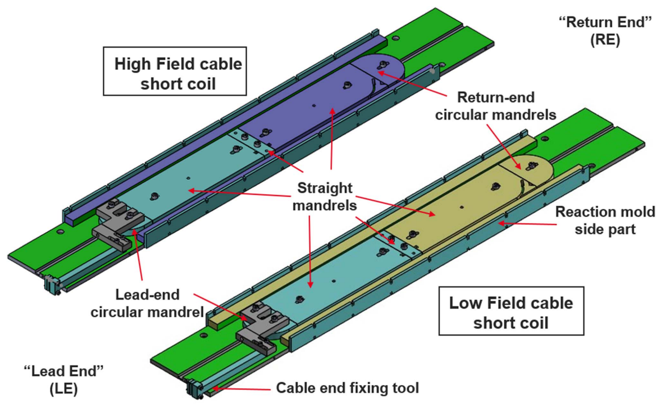

Fig. 3. HF and LF reduced coil set-ups for the measuring of the longitudinal changes during heat treatment. Reaction mold top plate, defining reaction cavity for cable width, is not shown.

48 hours at 210 °C, 50 hours at 400 °C, 50 hours at 665 °C has been applied. If the final heat-treatment cycle has to change, the tests will be repeated once.

A. Setup

The setup used for both HF and LF short coils is similar to the one used to characterize FRESCA2 cable [4]. It consists of a 690 mm long mandrel, with a straight section of 600 mm and a width of 90 mm. The height of the mandrel, as well as the lateral part of the mold, are adapted to HF and LF R2D2 cables dimensions. To evaluate the dimensional changes in the longitudinal direction of the cables, each mandrel is divided into five parts as shown in Fig. 3: one lead-end circular mandrel, three straight mandrels and one return-end circular mandrel.

The winding process carried out is as follows: initially, one end of the cable is fixed in a groove of the straight mandrel of the return end side. The five parts of the mandrel are also fixed to the winding plate, and two and a half turns of cable are wound at a constant tension of 30 daN. When winding is finished, the coil is blocked laterally with the side parts of the reaction mold and the other end of the conductor is fixed to the lead-end circular mandrel. Then the central part of the mandrel is removed (leaving a central gap) and the winding tension is relaxed. Screws are tightened anew, and gap reduction is measured. The top part of the reaction mold is fixed. Finally, just before and during the heat treatment, screws are left untightened, leaving the mandrel and the winding longitudinally free.

The tooling has been dimensioned to leave a cable expansion of 1.3% in width and 4.6% in thickness.

B. Tests on Nb_3Sn HF and LF Short Coils

Two coil manufacturing campaigns have been carried out. A total of two reduced HF coils and two reduced LF coils have been wound and heat-treated as shown in Fig. 4.

In Table II are summarized the results of the longitudinal behavior during the heat-treatment. Surprisingly, the HF coil contracts very little (by the order of 0.05%), while the LF cable contracts significantly (by the order of 0.33%) compared to data in the literature [2], [4], [5], [6]. One explanation for the high contraction of the LF cable could be that the ratio of copper is comparatively high (1.8), causing more stress relaxation during the annealing of copper. Another explanation of the low contraction of the HF cable could be the tightness of the braid, preventing the contraction by providing a confinement to the cable, as highlighted in [5], [7].

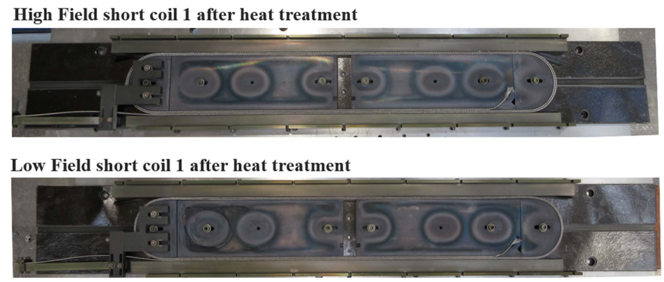

Fig. 4. HF and LF reduced coils after heat treatment.

TABLE II
RESULTS OF THE LONGITUDINAL BEHAVIOR ON REDUCED COILS DURING HEAT TREATMENT

		HF coil 1	HF coil 2	LF coil 1	LF coil 2
Reduced coils before HT	Coil length after winding tension release L_1 (mm)	700.92	700.82	697.32	697.37
Reduced coils after HT	Coil length after HT (mm)	700.52	700.48	695.16	695.1
	Coil length variation (mm)	-0.40	-0.34	-2.34	-2.22
	Central gap variation (mm)	-2.40	-2.05	-3.77	-3.48
	Coil length variation $/L_1$	-0.06%	-0.05%	-0.34%	-0.32%

VI. TRANSVERSE CHANGES DURING HEAT TREATMENT: CONDUCTOR STACKS

For the measurement of the transverse behavior of Nb_3Sn, mechanical compression tests at 5 MPa of stacks of conductors before and after heat treatment have been carried out. These tests have been performed at CERN.

A. Setup

As these series of tests involve heat treatment, two molds with different groove widths have been used for the compression measurements of the stacks. A mold has been designed by CERN, dimensioned for unreacted samples (measurements before heat treatment), and another one has been designed by CEA for the reacted ones (measurements after heat treatment). They have a groove width of 13.08 mm and 13.30 mm respectively.

The device used for mechanical compression is a manual press with four LVDTs to measure the stack height variation.

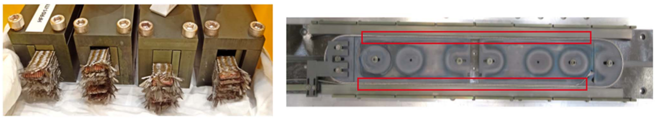

Fig. 5. On the left, molds of the 10 stacks in nominal and free cavity configuration. On the right, straight section of one of the short coils from where the stacks were extracted.

TABLE III
NOMINAL DIMENSION OF R2D2 CONDUCTOR STACKS

Cable	Heat Treatment	Parameter	Unit	HF cable	LF cable
Insulated	Before	Width	mm	12.90	
		Height	mm	22.69	15.53
	After	Width	mm	13.04	
		Height	mm	23.6	16.1

B. Validation Tests

A series of validation tests have been performed prior to the measurements with Nb_3Sn R2D2 cables in order to ensure the correct measurement of this system.

First of all, two aluminum reference blocks of known height were measured. Secondly, a cross check was made of the two molds in order to allow comparisons between them. In both cases, the block measurements results did not differ by more than 10 microns from the nominal values, allowing both the measuring device and the cross-check to be validated.

C. Tests on HF and LF Nb_3Sn Unreacted and Reacted Insulated Cables

Two measurement campaigns have been carried out, on both HF and on LF cables. For each type of cable, eight stacks of ten conductors were measured. Four stacks were extracted from the reacted short coils, while the other ones were prepared with non-reacted cables and measured before and after heat-treatment. The reaction mold of the stacks had a length of 100 mm, a width of 13.04 mm, and a nominal height of 23.6 mm for HF conductors, and 16.1 mm for LF conductors. Three stacks were heat treated in nominal cavity, while for the fourth one no height constrain was applied (free configuration) as shown in Fig. 5.

The nominal dimensions of the 10-stacks are shown in Table III, while Table IV summarizes the measured heights values. The results are the average of three pressure cycles at 5 MPa.

Concerning the stacks reacted in the nominal cavity and in the free cavity molds, we see that, for both conductors, stacks reacted in the free cavity expand more than those reacted in the nominal cavity. However, even for the stacks reacted in the free cavity, that dilates more, the dilatation is lower than the cavity chosen for the coil reaction mold.

Regarding the results of stacks extracted from short coils, it is observed that, for both conductors, the stacks expand more than those reacted in the short molds. Stacks extracted from the coils have values very close to the expected nominal values, consistent with the room left in the tooling.

TABLE IV
RESULTS OF THE TRANSVERSAL BEHAVIOR ON INSULATED CONDUCTOR STACKS DURING HEAT TREATMENT

HT	Reaction Cavity	Unit	10 stack average height		Corresponding HT factor (neglecting insulation variation)	
			HF cable	LF cable	HF cable	LF cable
Before		mm	22.6	15.58		
After	Nominal	mm	23.26	15.92	2.90%	3.10%
	Free	mm	23.48	16.03	4.00%	4.00%
	Extracted from coil	mm	23.51	16.11	4.17%	4.70%

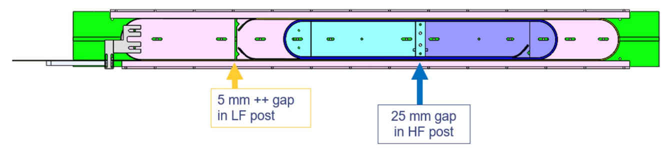

Fig. 6. Scheme of the hybrid coil.

VII. CONCLUSION

Several test campaigns to characterize the behavior of the R2D2 Nb_3Sn cables have been performed. A first campaign consisted in bending the cables in different configurations and allowed validating that the hard-way and easy-way bending radii chosen for the design of the coils are feasible and safe. For the second campaign, length changes of reduced coils before and after heat treatment were measured, and allowed highlighting two different behaviors of the cables: the HF cable contracts by the order of 0.05%, while the LF cable contracts by the order of 0.33%. This difference in the contraction behavior is not yet fully explained and might be better studied using other types of tests described in [3], such as in situ measurements on bare cables and metallographic analyses of sub-elements. These values will be taken into account using different gaps designed in R2D2 coil components. A third campaign consisted in measuring the thickness expansion of cable stacks before and after heat treatment. The values measured in particular on stacks extracted from the reduced coils allowed validating the expansion of 4.5 to 4.6% designed in the heat treatment tooling.

The behavior characterization of the R2D2 Nb_3Sn cables will be completed in the coming months with several campaigns to be performed at CEA Saclay.

Few lengths of HF and LF conductors will be wound and reacted together in a hybrid reduced coil representing the R2D2 coil (Fig. 6), to study more the behavior between them, and to evaluate the dimensional changes they undergo when they are cowound before the heat treatment. The results could be compared with those of the reduced short coils made from each conductor separately, whose results are in Table II, in order to give information on the impact of the friction between the two cables.

It is also planned to perform mechanical tests on R2D2 impregnated cable stacks with compression cycles up to a maximum stress of 150 MPa, at 300 K, 77 K and 4.2 K. In addition, thermal contraction measurements between 300 K and 77 K and between 300 K and 4.2 K could be carried out to complete the whole cable characterization study.

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