Mechanical Validation of the Support Structure of the Nb_3Sn Magnet FRESCA2

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***Abstract*— FRESCA2 is a dipole magnet dedicated to upgrade the present CERN cable test station FRESCA to a nominal bore field of 13 Tesla (T) in a 100 mm clear aperture. This paper reports on the assembly process and the three cool-down tests to cryogenic temperature of the support structure of FRESCA2. This structure is based on an aluminum alloy shrinking cylinder pre-loaded through the use of water-pressurized bladders.**

In order to verify the assembly and loading processes, this structure was assembled using full block aluminum alloy "dummy coils" standing for the Nb_3Sn coils. Then, the whole assembled structure was cooled-down to 77 K with liquid nitrogen in a dedicated facility at CERN. The mechanical behavior was monitored at all stages by strain gauges located on different components of the structure. Three cryogenic tests were made by increasing the loading gradually up to values corresponding to the ultimate field of 15T.

The expected stresses within the structure after assembly, loading and cool-down were determined from the 3D finite element model of the support structure. A comparison of the model predictions with the strain gauge data is presented.

***Index Terms* — Dipole, superconducting magnet, accelerator, Nb_3Sn.**

I. Introduction

EuCARD [1], the European Coordination for Accelerator Research and Development completed in 2013, aimed at developing new concepts and technologies for upgrading accelerators. Within this framework, the High Field Magnet task focused on designing, building and testing a 1.5 m long dipole magnet, with operational flux density of 13 T in a 100 mm bore, in order to upgrade the FRESCA test facility at CERN, used to qualify conductors at higher fields. The mechanical support structure was based on the bladder and key concept, approach developed at LBNL [2] and successfully used in a number of magnets, and on the shrinking shell and longitudinal pre-compression system concept [3] as well. A description about the conductor and magnet design is given in [4] and an overview of the fabrication process and cable characterization is given in [5].

The present paper reports on the results of the mechanical characterization of FRESCA2 support structure; after assembly and pre-loading with aluminum alloy dummy coils.

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The whole assembled structure was cooled down three times to cryogenic temperature. The dummy coil loading was gradually increased for each test up to values corresponding to the ultimate field of 15 T. Strain gauge data measurements were systematically obtained at all stages of the tests and compared with the expected stress values calculated with Ansys®.

II. Assembly and Loading of the Support Structure

A. Cross-section

For the assembly and cooling-down tests, the coil-pack was assembled with full block aluminum alloy "dummy coils" replacing the brittle Nb_3Sn coils with the aim of testing mechanically the structure and not to represent the behavior of superconducting Nb_3Sn coils. There is one dummy block per pole.

The cross-section of FRESCA2 with dummy coils is shown in Fig. 1. Both vertically and horizontally, the coil is surrounded by pads which transfer forces to the iron yoke through keys mostly in the perpendicular direction. The yoke is made of 5.8 mm thick iron laminations maintained by stainless steel end-plates. Two lateral keys per side are used in order to align the forces with the coil, especially around the ends. The forces on the iron are contained by a 65 mm thick aluminum alloy cylinder (shell). The total mass of the magnet structure is around 10 t; the yoke mass is more than 5 t and the shell less than 1 t. During the very first assembly and cool-down test, the experimental strain data was coherent with the expected stress values from the finite element model as reported in detail in [6].

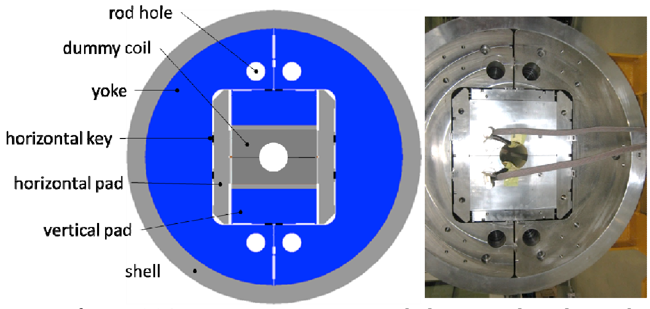

Fig. 1. Left: FRESCA2 magnet cross-section with dummy coils replacing the brittle Nb_3Sn superconducting coils for the mechanical tests of the magnet support structure only. Right: end of the magnet showing the main components: the shell, the two yoke halves, and the horizontal and vertical pads around the dummy coils.

B. Components of the Support Structure

The two dummy coils are shown in Fig. 2 up-left one over the other with the corresponding vertical pads bolted and stacked together. The central straight section is 728 mm long and the end-regions are tilted up at an angle of 17°. Each vertical pad is made of two parts: a stainless steel plate in contact with the coil, and an iron insert along the straight section contributing to the magnetic field. The coil-pack is shown in Fig. 2 up-right which is composed of the two vertical pads and two horizontal pads around the dummy coils. The horizontal pads are made of stainless steel blocks.

The assembly process was performed in a similar way as to other magnet support structures for Nb_3Sn coils [7]. The shell was slid around the two yoke-halves vertically as shown in Fig. 2 center-left. Two bladders inserted in the slots between the yoke-halves were pumped to spread apart the yoke-halves until contact with the internal surface of the shell. Then the yoke-halves were aligned and locked with temporary keys in between them.

The coil-pack was inserted horizontally in the yoke as shown in Fig. 2 center-right. Then, a clearance is generated in between the coil-pack and the yoke by inflating bladders next to the key-slots and sliding permanently keys in to control the pre-stress of the surrounding structure in order to compress the coil. Vertical keys are mainly for centering the coil pack while the proper preload of the coil pack is achieved by different shimming for the horizontal keys. The steps of the loading procedure were similar to other Nb_3Sn magnets [8] resulting in a magnet with key interference at room temperature.

The Fig. 2 down-left shows the longitudinal pre-compression system similar to the system used for SMC [9]: four Al alloy rods are pre-tensioned in order to compress the coil-pack by a high resistance steel end-plate. All components assembled together are shown in Fig. 2 down-right.

Fig. 2. Components of the FRESCA2 support structure. Up-left: dummy coils and vertical pads. Up-right: the coil-pack composed of dummy coils and vertical and horizontal pads. Center-left: the shell sliding around the two halves yokes. Center-right: the coil-pack. Down-left: the longitudinal compression system; four rods and two end-plates. Down-right: the whole assembled structure.

C. *Instrumentation*

The support structure was instrumented with 56 strain gauges in total. Half-bridge strain gauges were placed on 10 points along the straight section and end-regions on the outer diameter of the shell measuring both azimuthal and longitudinal direction. A similar distribution of 7 stations was used in the inner radius aperture of the dummy coils. Thermal compensation was performed for all points by gauges mounted on stress-free aluminum elements. Full-bridge strain gauges thermally auto-compensated were mounted on the rods in opposite azimuthal locations to compensate bending effects, measuring in the longitudinal direction only.

III. Cool-down tests

In order to perform the cooling-down of such a structure, a test facility was specially built outside the magnet test facility of CERN. This facility is composed of a cryostat (4.57 m high and 1.2 m large) placed in a mechanical steel trellis (5 m high and 1.102 m wide) to support the magnet weight effectively. This facility is now used for cooling other magnets. The support structure was cooled with liquid nitrogen (LN_2), with a cooling-speed regulated automatically with a maximum allowable gradient of ΔT = 100 K in between top and bottom of the structure with the aim of minimizing thermal stresses because of the differential shrinkage of the different materials. The temperature was monitored by carbon-ceramic sensors mounted at different locations of the support structure. An overview of these sensors is given in [10]. One cool-down operation takes about 2 days and the warm-up process takes 4 to 6 days.

The procedure was exactly the same for each one of the three tests as follows: 1. bladder-operation, 2. rod-pretension, 3. cool-down to 77 K, and 4. warm-up to 293 K (room temperature).

The key-interference values, which is the total thickness of shimming and keys stacks to tight the components together by blocking the generated clearance, was gradually increased for each test during bladder operation in order to tune the pre-stress the surrounding shell with the aim of pre-compressing the coil-pack. The pre-tension of the four rods of the longitudinal compression system was gradually increased as well. The strain in the shell, the two dummy coils and the four rods was monitored during all room-temperature pre-loading operations, during the cooling-down to cryogenic temperature and warm-up to room-temperature.

IV. Analysis

Finite element modelling was performed on one eighth of the entire geometry in 3D which corresponds to one quarter of the cross-section of the magnet over its half-length as shown in Fig. 3. The model computed the stress of the support structure. Results have been extracted on those points were the strain gauges were mounted. A coefficient of friction of 0.2 was assumed on every contact surface among the components overall the structure.

The average of the experimental strain data, both in azimuthal ε_θ and axial ε_z directions of the shell, the two dummy coils and the four rods of the longitudinal compression system, was converted into the corresponding stress values (σ_θ and σ_z) using the relation:

$$\sigma_{\vartheta,Z} = \frac{E}{(1-v^2)}(\varepsilon_{\vartheta,Z} + v\varepsilon_{z,\vartheta}) \qquad (1)$$

with E the elastic modulus of 79 MPa at 4.3 K; and v the Poisson's ratio of 0.34 for aluminum.

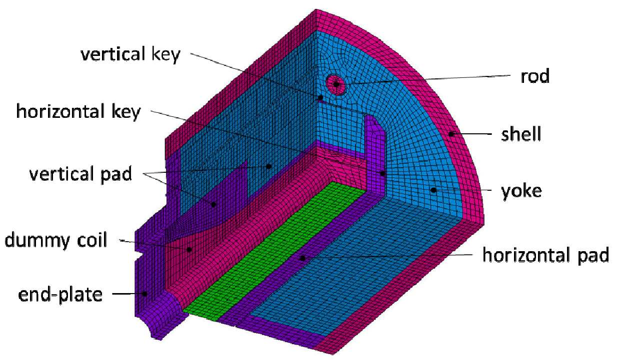

Fig. 3. FEM model of ⅛ of the FRESCA2 support structure with dummy coils replacing the superconducting coils

For the first test, an azimuthal strain value of $\varepsilon_\theta = 495$ µm/m was the target on the middle of the shell for both sides and a very similar strain value for the connections side (CS) and non-connections side (NCS) locations. Experimentally, an average value of $\varepsilon_\theta = 485$ µm/m was measured in both sides of the shell at room temperature. This experimental strain value corresponds to an average expected value of σ_θ = 35 MPa for azimuthal stress in the three longitudinal locations as shown in Fig. 4. The marked lines correspond to experimental data measurements at different points of each of the components. The solid lines represent the expected stress values at room temperature of 293 K during both key-interference and rod-pretension, and at cryogenic temperature of 77 K.

Once the structure was warmed-up to room temperature, the interference values were increased in order to obtain a corresponding additional stress of σ_θ = 16 MPa for the second test after bladder operation and this was again incremented of σ_θ = 16 MPa for the last test.

Similarly, the evolution of the stress values at +/- 45° from the mid-plane of both sides of the shell during the three tests is shown in Fig. 5. The shell has reached about 10 MPa lower after every warm-up of each one of the tests, a not fully reversible process usually attributed to friction. But this difference decreased for the second test and disappeared completely for the last one. Also an excellent symmetry of the values on both sides of the shell was observed. The experimental values are in good agreement with the model expected results.

The evolution of the stress values in the straight-section of the dummy coils is shown in Fig. 6. The two dummy coils stress values are in agreement with the finite element model at room temperature but a discrepancy was found just on the straight section of the dummy coils and at cryogenic temperature only; for each one of the tests, lower values than the expectations were found on the azimuthal direction indicating an over compression transmitted from the horizontal pads of the coil-pack, resulting in bending effect of the dummy coils increasing the strain in the inner radius of the aperture. In spite of that, the values were back to the expected values at room temperature for all the tests. A possible cause of this discrepancy at 77 K could be an error of the temperature compensators for these strain gauges. Indeed they were not mounted at the same location of the strain gauges themselves on the aperture of the dummy coils, but at the exterior of the component because of the limited space. This will be verified with an instrumentation check-up after disassembly of the support structure. Similar behavior of much higher compression than predicted was obtained at LBNL in the pole pieces of the Nb_3Sn dipole HD3 [11] and it is still under study.

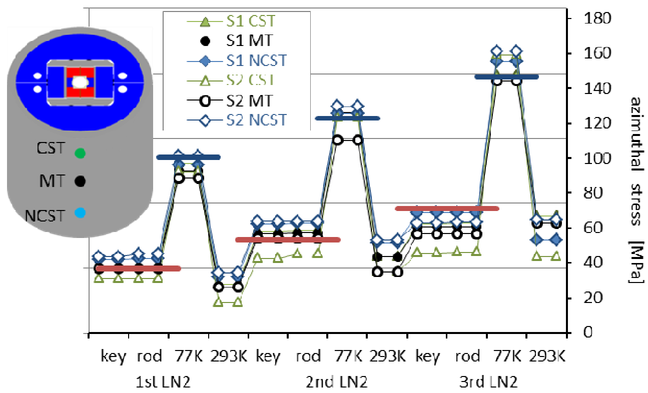

Fig. 4. Evolution of the azimuthal stress for the shell at three longitudinal locations (S1 and S2 correspond to side 1 and side 2 of the shell, respectively): the marked-lines correspond to measurements; the three upper solid-lines represent the expected values 77 K and the three lower solid-lines at room-temperature.

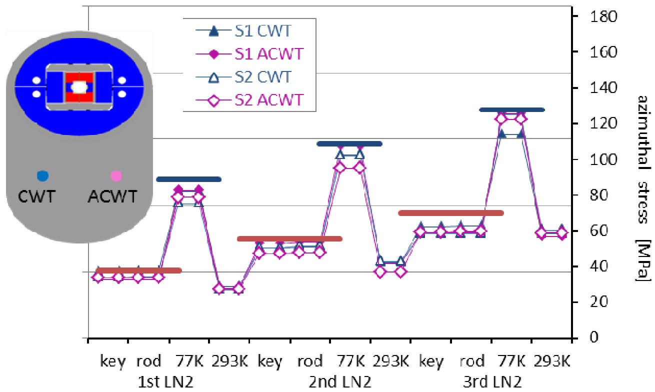

Fig. 5. Evolution of the azimuthal stress for the shell at +/- 45° from the mid-plane (S1 and S2 correspond to side 1 and side 2 of the shell, CWT to clock-wise and ACWT to anti-clock-wise, respectively): the marked-lines correspond to measurements; the three upper solid-lines represent the expected values 77 K and the three lower solid-lines at 293 K.

The evolution of the stress values at the end-regions of the dummy coils is shown in Fig. 7. The two dummy coils stress values are in good agreement with the FEM expectations both at room and cryogenic temperatures.

Although the signal of one of the four rods was lost for the second test and an a second one was lost for the last test, the strain gauges mounted on the rods measuring on the longitudinal direction provided data during the three cooling-down tests consistent with the predictions of the finite element simulations as shown in the Fig. 8.

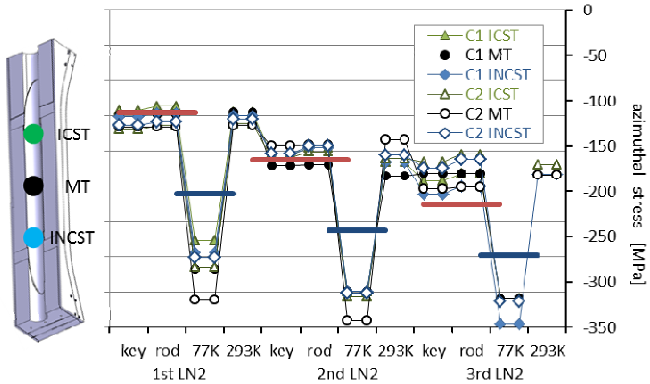

Fig. 6. Evolution of the azimuthal stress for the dummy coils along the longitudinal direction of the straight-section only (C1 and C2 correspond to dummy-coil 1 and dummy-coil 2; ICST to Connections Side, INCST to non-Connections side, and MT middle, respectively. The marked-lines correspond to measurements; the three upper solid-lines represent the expected values at room-temperature and the three lower solid-lines at 77 K.

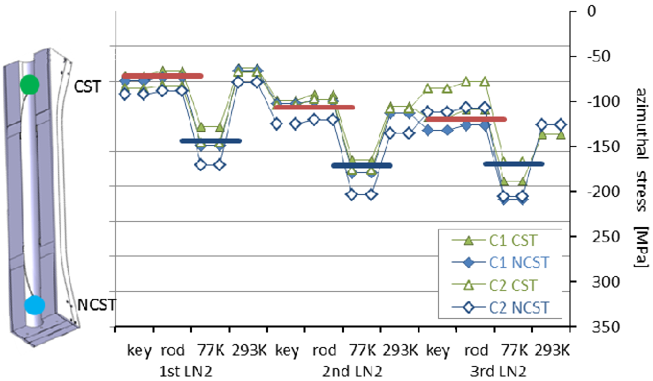

Fig. 7. Evolution of the azimuthal stress for the dummy coils at the end-regions (C1 and C2 correspond to dummy-coil 1 and dummy-coil 2, respectively). The marked-lines correspond to measurements; the three upper solid-lines represent the expected values at room-temperature and the three lower solid-lines the expected values at 77 K.

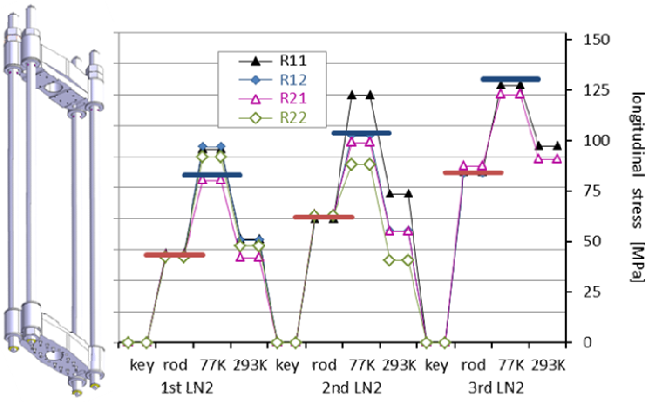

Fig. 8. Evolution of the longitudinal stress for the four rods of the longitudinal compression system. The marked-lines correspond to measurements; the three upper solid-lines represent the expected values 77 K and the three lower solid-lines the expected values at 293 K.

A summary of the data taken during cool-down from 293 K to 77 K is presented in TABLE 1, showing the gradual increment of the loading conditions.

TABLE 1
STRESS VALUES CORRESPONDING TO THE AVERAGE OF THE MEASURED STRAIN IN THE SHELL, DUMMY COILS AND RODS

Component	1st test	2nd test	3rd test
Shell long			
293 K	35 MPa	51 MPa	67 MPa
77 K	100 MPa	120 MPa	145 MPa
Shell mid-plane			
293 K	38 MPa	55 MPa	65 MPa
77 K	90 MPa	110 MPa	130 MPa
Dummy straight			
293 K	-114 MPa	-167 MPa	-217 MPa
77 K	-204 MPa	-245 MPa	-280 MPa
Dummy ends			
293 K	-73 MPa	-107 MPa	-121 MPa
77 K	-147 MPa	-171 MPa	-175 MPa
Rods			
293 K	40 MPa	57 MPa	78 MPa
77 K	77 MPa	103 MPa	127 MPa

V. CONCLUSIONS AND FUTURE PLANS

FRESCA2, a 100 mm aperture dipole magnet aimed at providing a bore field of 13 T, will be used as a superconducting cable test station at CERN. Mechanical and assembly tests with dummy coils made of aluminium alloy have been successfully performed. This validates the design of the mechanical structure of the magnet as well as the pre-loading procedure. For these cool-down tests, an entirely new cryogenic test facility was built at CERN. All stages of the design, assembly process, pre-load and cooling-down have been verified.

The measured strain values are consistent with the finite element model predictions except for a discrepancy observed in the straight section of the dummies after the cool-down only, which will be further verified with an instrumentation check-up after disassembly. It was demonstrated that the structure supports properly the coil during assembly and powering conditions.

Two first superconducting Nb_3Sn coils will be assembled with two copper prototype coils in order to form a magnet that will be inserted in the mechanical support structure. These two copper prototype coils have been wound at CEA-Saclay, then both reacted at CERN and one of these already impregnated successfully at the time of submission of this paper.

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