TEST RESULTS OF HD2, A HIGH FIELD NB$_3$SN DIPOLE WITH A 36 MM BORE *

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Abstract

The Superconducting Magnet Program at Lawrence Berkeley National Laboratory (LBNL) has developed the 1 m long Nb$_3$Sn dipole magnet HD2. With tilted (flared) ends to avoid obstructing a 36 mm clear bore, HD2 represents a step towards the use of block-type coils in high-field accelerator magnets. The coil design has been optimized to minimize geometric harmonics and reduce the conductor peak field in the end region, resulting in an expected short sample dipole field of 15 T. The support structure is composed by an external aluminum shell pre-tensioned with pressurized bladders and interference keys, and by two stainless steel end plates compressing the coil ends through four aluminum axial rods. We report on magnet design, assembly, and test results, including training performance, quench locations, and strain gauge measurements

INTRODUCTION

The Superconducting Magnet Program at Lawrence Berkeley National Laboratory (LBNL) is continuing the development of Nb$_3$Sn high field magnets for the next generation of HEP colliders. The superconducting dipole HD2, recently fabricated and tested at the LBNL test facility, represents the first application of block-type coils to accelerator-quality dipole magnets. The conceptual design of the magnet was described in [1], whereas the mechanical analysis of the structure and the magnet fabrication were respectively reported in [2] and [3]. In this paper, after a brief overview of the magnet design and parameters, we present the results of two magnet tests, including strain gauge measurements (recorded during assembly, cool-down and excitation), training curve and quench locations.

MAGNET DESIGN

The HD2 magnet design (Fig. 1, left) features two block-type coils wound around a titanium alloy (Ti 6Al-4V) pole. The pole includes a round cutout to provide room for a 3.65 mm thick stainless steel (Nitronic 40) bore tube with a clear aperture of 36 mm. The coils are supported by horizontal and vertical pads. Vertical pushers and horizontal rails transfer the load from the pads to the coils. Two yoke halves, made of 50 mm thick iron laminations, and a 41 mm thick aluminum shell provide the external coil pre-load through vertical and horizontal interference keys. The diameter of the cold mass is 705 mm. The structure is pre-loaded with water pressurized bladders.

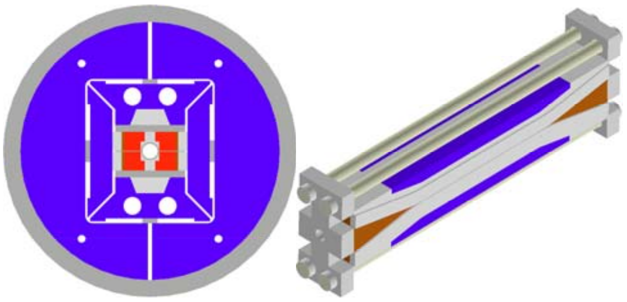

Figure 1: HD2 cross-section (left) and coil end support system (right)

The coil has a straight section of about 481 mm and it tilts up (flares) at a 10° angle in both ends through hard-way bends. After the hard-way bends, the flared region features a short straight section. The tilted ends are supported vertically by aluminum-bronze wedges surrounding the bore tube and axially by two end-plates pushed against the coil by four aluminum rods (Fig. 1, right).

CONDUCTOR AND MAGNET PARAMETERS

The two coil modules of HD2 are composed of two layers wound from a continuous length of cable made of 51 RRP strands with a 0.8 mm diameter. The cable is 22.008 mm wide and 1.401 mm thick. Three coils were fabricated: assuming strand properties from coil 1 (Fig. 2), the magnet has a maximum bore field of 15.1 T (4.2 K), with a conductor peak field of 15.9 T at a current of 17.4 kA. Coil 2 and 3 feature a short sample peak field about 0.6 T higher than coil 1.

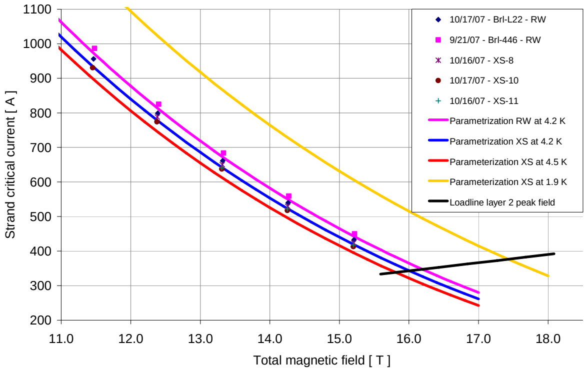

Figure 2: Critical current (A) vs. applied field (T) measurements and parameterization curves of virgin (round) and extracted strands used for coil 1.

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*Work supported by the U.S. D0E (No. DE-AC02-05CH11231)

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MAGNETIC ANALYSIS

The conductor peak field of 15.9 T is located in the pole turn of layer 2 along the straight section (Fig. 3), where the pole turn of layer 1 has a margin of 0.6 T. In the end region (Fig. 4), the field decreases from 15.8 T at the beginning of the ramp to 14.8 T in the end pole turn.

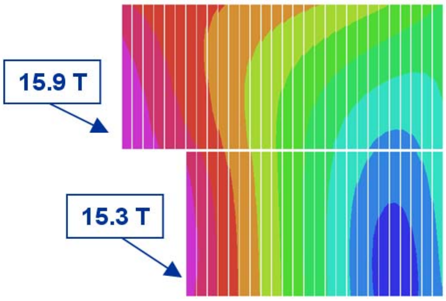

Figure 3: Maximum conductor field (T) in the straight section.

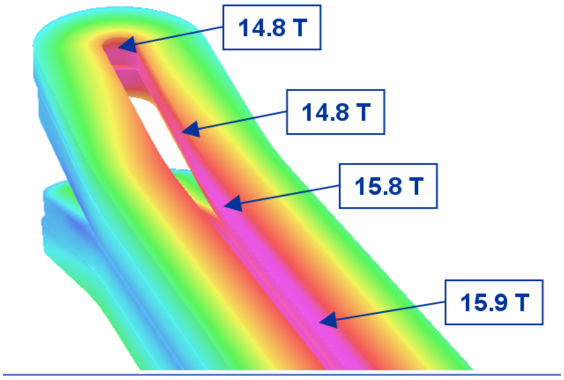

Figure 4: Maximum conductor field (T) in the end region.

MECHANICAL ANALYSIS

Straight section

The main component of electro-magnetic force in HD2 is horizontal and directed outwardly. In order to prevent the pole turn to separate from of the Ti pole, the coil is pre-compressed after cool-down to an average stress of 150 MPa (Fig. 5, right).

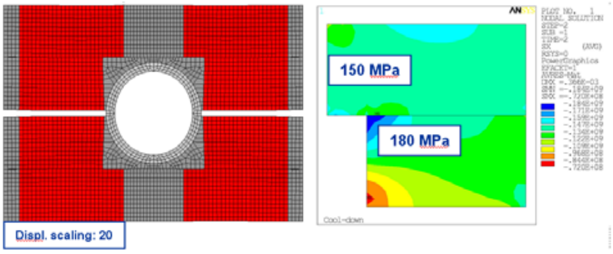

Figure 5: Coil stress conditions after cool-down: deformed shape of a 2D finite element model with displacements enhanced by a factor 20 (left) and horizontal stress (MPa) in the coil (right).

Because of the deformation of the bore tube, depicted in Fig. 5 (left), the coil area next to the square corners in layer 1 does deflect as much as the mid-plane area, generating a high stress point of 180 MPa in the coil.

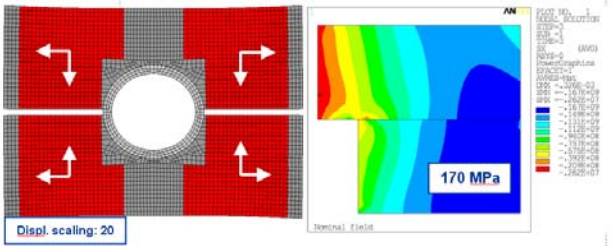

Figure 6: Coil stress conditions during excitation: deformed shape of a 2D finite element model with displacements enhanced by a factor 20 (left) and horizontal stress (MPa) in the coil (right).

During excitation, as the e.m. forces push the conductor horizontally towards the pads and vertically towards the mid-plane (Fig. 6, left), the stress in the coil region next to the pole decreases (Fig. 6, right) and the highest stress of 170 MPa is now located in the low-field area of the coil.

End region

The mechanical conditions of the coil end regions have been simulated by a 3D mechanical model (Fig. 7, left). The axial component of the e.m. force in the ends tends to separate the conductor from the pole.

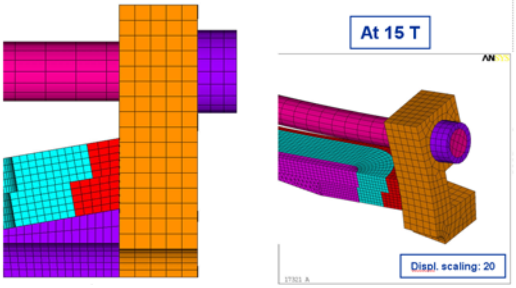

Figure 7: 3D model of the magnet end region (left), and deformed shape during excitation with displacements enhanced by a factor 20 (right).

Following the same principle adopted for the straight section, the end support system is designed to prevent such a separation and minimize conductor motion when the magnet is energized. The computed deformed shape of Fig. 7 (right) indicates that the compression of the end shoes obtained by the end-plate is expected to maintain the pole turn in contact with the pole.

TEST RESULTS

Two tests were carried out: HD2a and HD2b. In both tests coil 1 (limiting coil) and coil 2 were used. The shell was pre-tensioned at 293 K to 35 MPa and reached 140 MPa after cool-down (Fig. 8), corresponding to a maximum expected coil stress of 150 MPa. The average rod tension increased from 35 to 90 MPa during cool-down (Fig. 9).

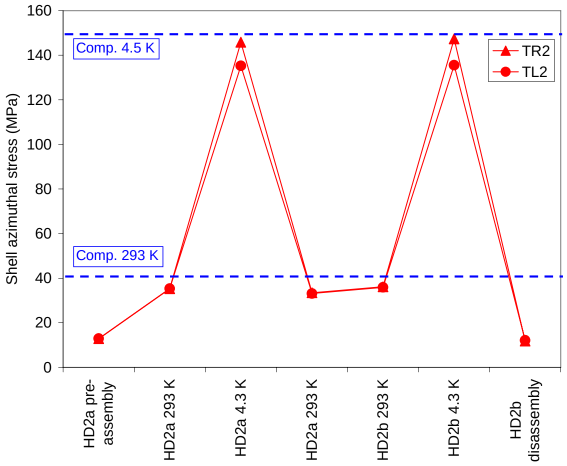

Figure 8: Shell azimuthal stress (MPa) during assembly, cool-down and tests.

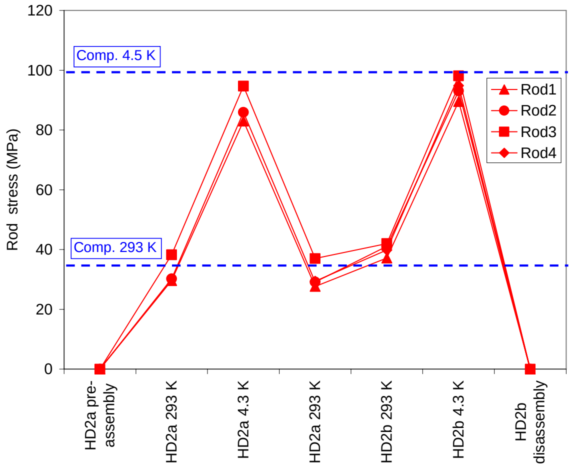

Figure 9: Rod axial stress (MPa) during assembly, cool-down and tests.

Training quenches and quench locations

During the HD2a test, the magnet had a first quench at 12.0 T of conductor peak field, corresponding to 73% of the expected magnet limits and to a bore field of 11.4 T (Fig. 10). The highest current was reached at quench #18, with a conductor peak field of 14.0 T, corresponding to 87% of the expected magnet limits and to a bore field of 13.3 T. During the HD2b test the magnet had a first quench at 11.5 T of conductor peak field, corresponding to 71% of the expected magnet limits and to a bore field of 11.0 T (Fig. 10). The highest current, identical to the one recorded during the previous test, was reached at quench #31. Because of a failure of the extraction system, a higher number of MIITS where released after quench #31. As a results, coil 1 exhibit an higher ramp-rate sensitivity. After reducing the ramp rate, the magnet reached the previous maximum current quench at #39.

Out of 14 training quenches of the HD2a test, almost all evenly distributed between the two coils, 12 were located in the layer 1 pole turn, towards the end of the straight section (Fig. 11). During the HD2b test (Fig. 12), before quench #31, 4 (6) quenches occurred in coil 1 (2). After quench #31 all quenches were located in coil 1.

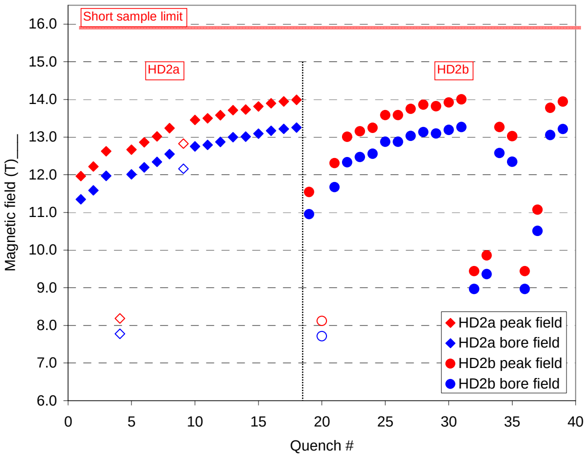

Figure 10: Training quenches of HD2a and HD2b.

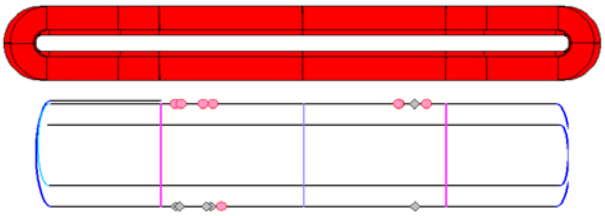

Figure 11: HD2a quench locations: coil 1 (gray markers) and coil 2 (pink markers).

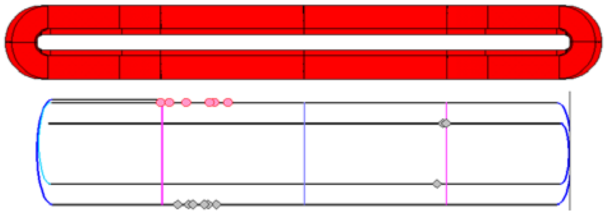

Figure 12: HD2b quench locations: coil 1 (gray markers) and coil 2 (pink markers).

REFERENCES

(1) G. Sabbi, et al., “Design of HD2: a 15 T Nb_3Sn dipole with a 35 mm bore”, IEEE Trans. Appl. Supercond. 15 (2005) 1128.

(2) P. Ferracin, et al., “Mechanical design of HD2, a 15 T Nb_3Sn dipole magnet with a 35 mm bore”, IEEE Trans. Appl. Supercond. 16 (2006) 378.

(3) P. Ferracin, et al., “Development of the 15 T Nb_3Sn Dipole HD2”, IEEE Trans. Appl. Supercond. 18 (2008) 277.