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Test Results for HD1, a 16 Tesla Nb3Sn Dipole Magnet

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***Abstract*— The Superconducting Magnet Group at Lawrence Berkeley National Laboratory* has been developing the technology for using brittle superconductor in high-field accelerator magnets. HD1, the latest in a series of magnets, contains two, double-layer Nb_3Sn flat racetrack coils. This single-bore dipole configuration, using the highest performance conductor available, was designed and assembled for a 16 tesla conductor/structure/pre-stress proof-of-principle. With the combination of brittle conductor and high Lorentz stress, considerable care was taken to predict the magnet's mechanical responses to pre-stress, cool-down, and excitation. Subsequent cold testing satisfied expectations: Training started at 13.6 T, 83% of "short-sample", achieved 90% in 10 quenches, and reached its peak bore field (16 T) after 19 quenches. The average plateau, ~92% of "short-sample", appeared to be limited by "stick-slip" conductor motions, consistent with the 16.2 T conductor "lift-off" pre-stress that was chosen for this first test. Some lessons learned and some implications for future conductor and magnet technology development are presented and discussed.**

***Index Terms*— Superconducting magnets, Dipole, High-Field, Nb_3Sn, Test Results.**

I. INTRODUCTION

Lawrence Berkeley National Laboratory (LBNL) is continuing a vigorous development program for providing cost-effective, high-field magnet options for "next generation" particle accelerators and storage rings. These magnets utilize state-of-the-art Nb_3Sn superconducting cable, and require strong, rigid, predictable mechanical support systems, able to protect the brittle conductor from large Lorentz loads. While all successful high-field Nb_3Sn efforts have thus far utilized wind-and-react technology [1-5], react-and-wind technology is being pursued elsewhere [6]. Recent efforts have explored the dual-bore, common-coil geometry, using flat racetrack coil modules, whose major proof-of-principle tests included RT1 [3] (a 2 layer coil module test at 12 T with excellent training), RD3b [4] (a 3-layer high-field structure test at 14.5 T), and RD3c [5] (a 3-layer field quality test at 11 T). In all cases, extreme care was taken to avoid conductor damage from excessive pre-stress. All prototypes exceeded 90% of "short-sample" (albeit sometimes with labored training), and all, being common-coil magnets, had large stored energy, and up-down asymmetric field harmonics. This led to a desire to explore side-by-side dipoles, in which each bore's return flux augmented its neighbor's, and many features that can be tested in less costly single-bore models. While a 1983 attempt by the LBNL group to utilize block-style Nb_3Sn coils in a single-bore test encountered difficulties [7,8], the recent successes, along with experience from the sub-scale technology development program [9], encouraged a re-exploration of this coil geometry. As a result, HD1 (Helmholtz-Dipole #1) was designed to cost-effectively explore the limits in Nb_3Sn magnet technology, design, materials, and fabrication processes for magnets with this geometry and bore fields above 16 Tesla.

II. MAGNET FEATURES AND TEST SET-UP

A. Conductor and Coils

Thirty-six 0.8 mm strands of state-of-the-art, "restacked-rod processed" Nb_3Sn conductor ($Jc > 3000\ A/mm^2$ @ 12 T, Oxford Superconducting Technology) [10] were Rutherford cabled with a compaction of 88.5% (1.361 mm x 15.75 mm). This cable was insulated with an S-glass sleeve, and wound onto an iron winding-pole, according to previous 2-layer coil procedures [4,5], excepting seven changes: 1) The inter-layer ramp, being near the maximum field, was moved as close as practical to the lead-end to take advantage of the local field reduction produced by locally recessing the iron in the Y-pads. 2) One turn was removed from the outer (lower field) layer, allowing the simplest possible, inter-layer ramp, as well as unequal turns/layer (potentially required in future field-quality magnets). 3) The radius of the pole-island ends was significantly decreased (until the pole-end turn began to de-cable). 4) Extra glass cloth was used between coil layers (to compensate for the cable swelling of the tight pole-end turns. 5) A thin (8 mm thick) horseshoe was used to contain and protect the outer turns during reaction and assembly. 6) Voltage-taps (11/layer) were installed wherever the conductor appeared vulnerable to slippage or damage. 7) Conducting skins were no longer used to protect or pre-stress the coils during assembly and operation. These changes were necessary to produce a "maximum measurable field" proof-of-principle test, with the fewest turns/layer (35 inner, 34 outer), and a

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peak current within our PS range. After winding, the coils were reacted "to size", according to the "RRR = 15" prescription: 210 C for 100 hours, 340 C for 48 h, and 650 C for 200 h [5]. The voltage-tap and protection heater traces were then attached, and encapsulated in the usual manner [4,5].

B. Magnet assembly and Support Structure

The resulting coils were assembled, one on each side of an insulated bore-plate. RD3's aluminum shell and yoke [4,5,11,12,13] were re-used to reduce costs, and allowed a monotonic approach during cool-down, to a stress level (~150 MPa) where conductor degradation might occur [14]. This system significantly exceeded the structural requirements for such small coils, and resulted in two consequences: 1) The outer diameter was disproportionately large. 2) The increase in cool-down pre-stress was significantly larger than before [4,5]. The resulting cross-section (Fig. 1) is discussed in considerable detail in an earlier paper at this conference [13].

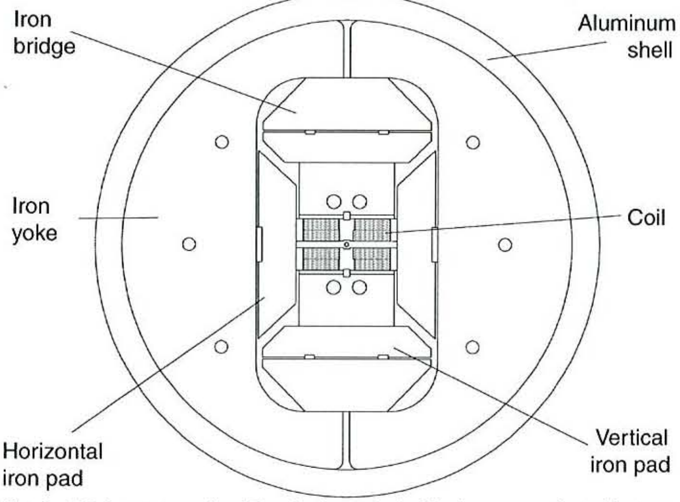

Fig. 1, HD-1 cross-section: Two horizontal, double-layer pancake coils were separated by a thin bore-plate, and compressed on all sides by compression pads, bridges, and iron yokes. Compression was maintained by a 45 mm thick, 740 mm OD tensioned aluminum shell. G-10 strips electrically insulated the coil surfaces, while simultaneously cushioning irregularities in the high-pressure interfaces. Iron interference keys permitted removal of internal pre-stressing bladders. Most of the final pre-stress resulted from cool-down.

To compensate for the increase in Lorentz conductor stresses, the previous bladder and key pre-stress technology [4,5,9,11,12] was extended to 3-D [13]. Shell tension supplied the X & Y pre-stress, while four, tensioned high-strength (2219-T85) aluminum "Z-rods" provided axial compression. All stresses (Fig. 2) were expected to increase significantly during cool-down. While friction against the coils' hard components would provide a relatively stiff containment boundary, it created uncertainty about the fraction of the yoke compression that was transmitted to the conductor. To reduce potential damage on the first cool-down, 100% transmission was assumed, with a 16.2 T lift-off (despite negative training consequences).

C. Diagnostic and Test Set-up

Eleven voltage taps divided each layer into 10 segments, with primary attention to the inter-layer ramp, the pole-turn, the end-spacers, the outer turn, and the splices. The average coil pre-stress was inferred from temperature-compensated strain gauges that measured the tension in the aluminum shell [4-5], and two of the four axial rods.

A Hall probe was installed in the bore, to measure the central field's axial profile. Its cold calibration, measured last year to 15 T at the University of Wisconsin, was extended to 16 T by sinusoidally extrapolating the first and second derivative of the nearest Shubnikov-deHass sensitivity oscillation.

Each coil-layer had a protection heater (R = 3 ohm/heater), which covered 65% of the exposed cable edges (to reduce internal quenching voltages). The cryostat pressure was carefully regulated to avoid temperature-dependent training plateau fluctuations, and the fast flux-change data acquisition sampled more frequently (200 kHz). All other systems operated as previously [1,3,4,5].

III. TEST RESULTS

A. Cool-Down and Training Preparations

Cool-down supplied most of the pre-stressing tension, as expected (Fig. 2), in both the shell (30 to 110 MPa) and the Z-rods:(125 to 230 MPa). Coil resistance measurements revealed a 20 K RRR = 15, consistent with the heat-treatment target. Inter-coil insulation and diagnostic signal integrity were verified at maximum stress (4.3 K). The magnet-imbalance signals were nulled, appropriate PS and fault-system responses were confirmed before both protection heaters were adjusted to produce magnet quenching at 30% I_{ss}.

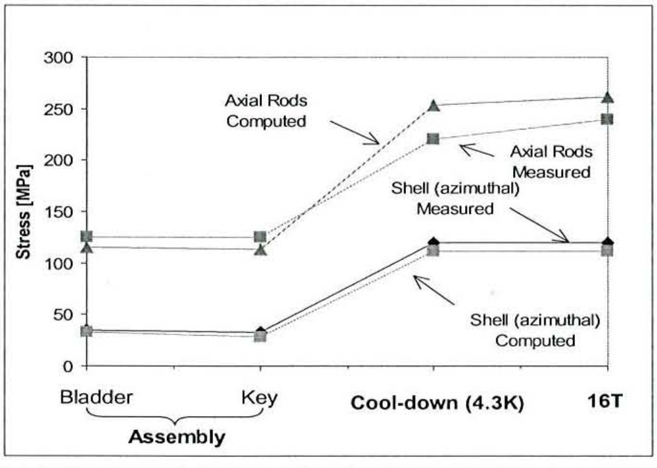

Fig. 2. The measured absolute shell and axial Z-rod tensions were close to predictions for the following four conditions: a) 300K ("Bladder) pre-stress, b) relaxing onto the keys ("Key"), c) 4.3 K, and d) 16 T Lorentz excitation.

B. Ramping and Training

An unexpectedly large number of transient flux imbalances were recorded while ramping the magnet: 128 events exceeded 12 mV before reaching 550 A (~10 times that observed in RD3c [5] in the same current range). Most were labeled "flux-jumps", because they were slow (5-10 ms duration), had no ringing, and recurred repeatedly every ramp. Several large ones triggered protection quenches, after which false alarm, the responsible trip-level (or integration time) was increased until only training quenches triggered protection responses. The final threshold (1.5 V) resulted after an 8.5 kA false alarm.

The first training quench (13.6 T, 8.7 kA, 83% of I_{ss}) (Fig. 3) occurred on the following ramp: It originated in coil-A's return-end, 6 turns from the pole, at the outer tip of field-reduction "end-spacer", 0.6 ms after a relatively violent (>2000 V/s) stick-slip motion (10 mV peak). The resistance propagated at a relatively slow 40 V/s/front (8 m/s).

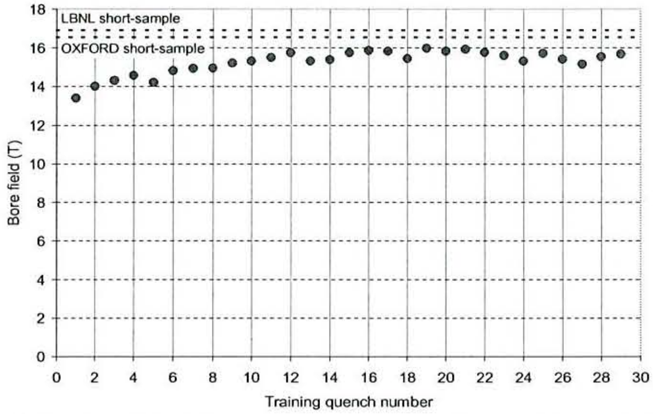

Fig. 3. HD1's training history relative to two scaled "short-sample" (OST and LBNL) strand measurements. I_{ss} and B_{ss} were defined as the average of the two measurements. Training started at 83% of I_{ss} and peaked at 95% (19th try). Stick-slip flux signatures were successfully captured before most quenches.

Training proceeded monotonically upward for four quenches, exceeding 0.86 I_{ss} on the second ramp, and, after a fall-back, exceeded RD3b's (14.5 T) record on the sixth ramp. Training essentially stalled after the 12th ramp (15.8 T), with an erratic "plateau" between 14.9 T (89%) and 15.9 T (95%). After achieving the peak field (19th ramp), quench origins predominantly switched from the outer tip of an end-spacer, six turns from the pole (usually the return-end), to the peak field region of the pole-turn. "Stick-slip" flux signatures [3,4,5] were captured 0-1 ms before most training quenches.

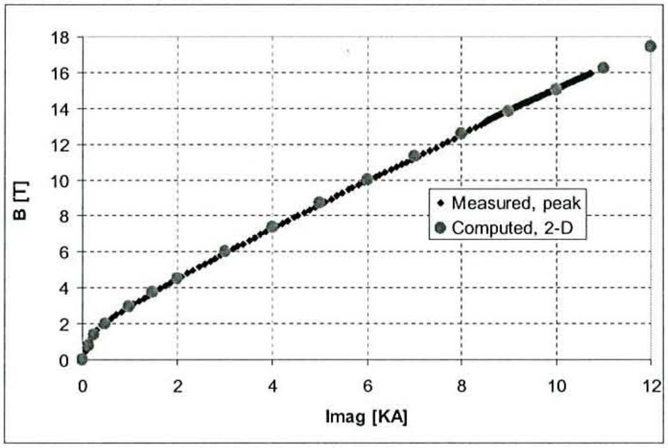

Fig. 4. 2-D central-field prediction, and measured peak bore-field: Both the rapid saturation of the iron winding-pole and the gradual saturation of the pads correlated well with predictions, and are expected to be relatively easy to correct.

The peak B-field dependence was close to 2-D expectations (Fig. 4), with no clear strain-gauge evidence of conductor separation from a pole. Splice resistances were very low (≤ 1.2 n-ohm), and a ramp-rate "cliff" (Fig. 5) was observed, which was considerably softer, at a faster ramp-rate (~0.1 T/s, 75 A/s), and higher plateau than previously observed [4,5].

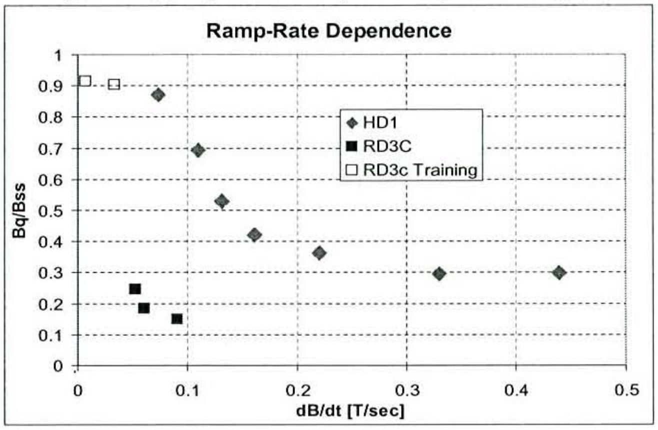

Fig. 5. Ramp-rate comparison. The highest two points were training quenches; as both RD3c and HD1 trainings stalled with "stick-slip" triggered quenches.

IV. DISCUSSION

A. Peak Performance Protection Efforts

Degradation-free performance of brittle Nb_3Sn dipole coils, up to 96% of short-sample predictions, under a maximum average compressive coil-stress of 150 MPa, is the single most important outcome of HD1. We therefore conclude that a combination of efforts to mitigate known performance limitations, was successful: 1) The (~150 MPa) pre-stress was sufficient to permit training to 16 T. 2) This pre-stress did not result in significant conductor degradation (less than 5% below the un-degraded I_{ss}). 3) Two vulnerable high-field conductor regions were adequately protected by local B-field reduction at: a) the tight bending radius associated with the small radius pole, and b) the inter-layer ramp and its "hard-way" bends. 4) Extra interlayer glass was added to avoid crushing the swelled pole-turn ends.

While reversible conductor degradation was not a primary issue in this particular geometry (as the maximum operating conductor stress occurred where the B-field was low), irreversible degradation near the high-field region could have limited magnet performance. The aluminum-over-iron pre-stressing system avoided over-shooting the operational pre-stress .by approaching it monotonically from below. Unfortunately, when most of the operating pre-stress is generated during cool-down (as in HD1), there is some danger of missing the target. The 3-D modeling was very useful in predicting the response of this complex mechanical system, and guided the implementation of step-wise 3-D pre-stressing, using horizontal and vertical pre-stressing bladders, and axial rods. Accordingly, HD1's pre-stress target was conservatively chosen to correspond to (no friction) conductor/pole separation at a bore-field of 16.2 T.

While inadequate to reach a non-degraded I_{ss}, the chosen pre-stress was sufficient to verify the magnetic, mechanical and quench protection design calculations up to 16 T, in the presence of cabling, winding, and high-stress conductor degradation, hard spacers and high-field inter-layer ramps, and allowed the coils to be available for further testing.

B. Sub-scale Magnet Technology Contributions

This test validated the full-scale implementation of some technology that had previously been tested in LBNL's sub-scale magnet technology development program: 1) Horseshoe protection of a coil's edges facilitated coil reaction, potting and assembly processes, by replacing eight heavy side-bars and two end-shoes) [4-5], with two light reaction horseshoes, and one potting horseshoe. 2) Welded coil-skins (previously for stand-alone, 2-D coil-edge pre-stressing) were abandoned to simplify coil fabrication, and increase the coils' J_e and reliability. 3) Sub-width NbTi cable facilitated splice soldering, and required less cryostat real estate.

C. Cool-Down, RRR & Ramping Issues

Good agreement with calculations raised confidence in the new 3-D stress calculations, while the RRR = 15 similarly validated the coil reaction prescription. The changes in ramp-rate dependence are believed to have resulted from the smaller field perpendicular to the flat of the cable. Unfortunately, the number and size of the flux-jumps was disappointing, especially the need to desensitize the quench detection threshold to 1.5 V before training could proceed.

D. Quench-Origins

The pattern of quench-origins, in conjunction with their stick-slip triggering, suggested that the conductor was methodically shearing with respect to (or separating from) two kinds of hard coil-elements. This was consistent with calculations [13], which predicted that these interfaces would separate or be close to separation at 16.2 T (no friction). Friction was expected to have reduced the conductor preload, resulting in a lower threshold for separation. This was encouraging, as training might improve with a variety of pre-stress increases.

No training quench origin was consistent with the large conductor displacements predicted from the frictionless accumulation of Lorentz stress in the most compliant direction of these block coils (normal to the flats of the cable) [13]. This could mean that the friction between conductor and the local Y-pad was either 1) large enough to stop slippage completely, or 2) too small to trigger quenches with the associated conductor margin. If the former case applies, such quenching might start at higher fields. If the latter, the conductor may have separated from the Y-pads at a lower field, or quenching might start when the conductor margin is smaller.

The preponderance of return-end training suggested that the horseshoe, while facilitating coil fabrication, might have shielded the coil from the Z-rod compression. Whether this can be corrected without abandoning its benefits remains an open question. In all cases, HD1's training is expected to improve with pre-stress increases. How much the pre-stress can be increased without degrading ultimate performance also remains an open issue.

V. CONCLUSION

A block dipole magnet was successfully fabricated and tested to 16 Tesla, with a high first quench, followed by relatively rapid training to 95% of the cable's short-sample prediction. Plateau quenches were preceded by conductor motion signals, consistent with the conservatively low pre-stress that was chosen to avoid, permanent conductor degradation. With no observable degradation (from all potential sources), and good performance from all new technology features, the test was extremely encouraging, and left the coils available to potentially establish the maximum allowable Nb_3Sn magnet pre-stress in this geometry.

ACKNOWLEDGEMENTS

This was quite an achievement, albeit only one step along a long development path toward a reliable energy-doubler option. Particular mention goes to the conductor manufacturer (OST), and all the administrators, assistants, and technicians, whose contributions made these results possible.

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