Test Results of HD1b, an Upgraded 16 Tesla Nb₃Sn Dipole Magnet

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Abstract— The Superconducting Magnet Group at Lawrence Berkeley National Laboratory has been developing high-field, brittle-superconductor, accelerator magnet technology, in which the conductor's support system can significantly impact conductor performance (as well as magnet training). A recent H-dipole coil test (HD1) achieved a peak bore-field of 16 Tesla, using two, flat-racetrack, double-layer Nb₃Sn coils. However, its 4.5 K training was slow, with an erratic plateau at ~92% of its un-degraded "short-sample" expectation (~16.6 T). Quench-origins correlated with regions where low conductor pre-stress had been expected (3-D FEM predictions and variations in 300 K coil-size). The coils were re-assembled with minor coil-support changes and re-tested as "HD1b", with a 185 MPa average pre-stress (30 MPa higher than HD1, with a 15-20 MPa pole-turn margin expected at 17 T). Training started higher (15.1 T), and quickly reached a stable, negligibly higher plateau at 16 T. After a thermal cycle, training started at 15.4 T, but peaked at 15.8 T, on the third attempt, before degrading to a 15.7 T plateau. The temperature dependence of this plateau was explored in a sub-atmospheric LHe bath to 3.0 K. Magnet performance data for both thermal cycles is presented and discussed, along with issues for future high-field accelerator magnet development.

Index Terms—Dipole, High-Field, Nb₃Sn, Superconducting Magnets, 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. Present model magnets utilize state-of-the-art Nb₃Sn superconducting cable, and require strong, rigid, predictable mechanical support systems, able to protect the brittle conductor from large Lorentz loads, while providing good magnet training. While the highest-field Nb₃Sn efforts have thus far utilized wind-and-react technology [1-5], react-and-wind technology is also being pursued [6]. Earlier efforts explored the dual-bore, common-coil geometry, with flat racetrack coil modules [3-5], and successfully achieved its associated "undegraded short-

sample" bore field (14.5 T), i.e., no evidence of any conductor degradation. A recent effort achieved a bore field of 16 T (~95% of "short-sample"), with two double-layer racetrack coils, in a small single-bore H-dipole magnet [12-13]. For all models, extreme care was taken to avoid conductor damage from excessive pre-stress (even at the risk of slow training), in order to determine how well the conductor and structure responded to such large Lorentz loads. While many flux-jumps were recorded with the high-Jc conductor that made these fields practical, only conductor movements appeared to initiate quenches, whenever performance fell short of the "undegraded short-sample" limit.

HD1's quench initiations below 16 T clearly showed conductor-movement voltage-spikes ~1 ms before quench-onset [13]. Furthermore, time-of-flight training-quench origins [7] were strongly correlated with regions where either coil-size variations [7,8] and/or frictionless 3D FEM analysis [8] had predicted conductor displacements (from insufficient pre-stress). The coil movement hypothesis was strongly supported by visual inspection of the disassembled coils [7, 8]. This generated proposals to significantly decrease all known pre-stress deficiencies, and retest the coils (to improve training, obtain a higher field plateau, or encounter conductor degradation). Primarily a pre-stress change, this test was labeled "HD1b". Its performance, as well as, its subsequent thermal cycle (HD1b-2) are presented and discussed.

II. Magnet Features and Test Set-up

A. Coil Inspection and Changes

HD1's 2-layer coils had been wound with 36-strand Rutherford cable, 35 turns in the inner layer, 34 turns in the outer layer, using 0.8 mm strands of Oxford's best "restacked-rod processed" Nb₃Sn conductor (Jc > 3000 A/mm² @ 12 T) [9]. Additional details can be found elsewhere [10-13]. When the coils were disassembled after the HD1 test, they were systematically measured and visually inspected for evidence that correlated with HD1's quench-origins. A crescent shaped region of crazed epoxy was easily visible at the outer tip of all eight hard end-spacers, near "turn-6" (6-turns from the pole) [7], which correlated with the shape and location predicted by the pre-test 3D FEM analysis [8] (albeit a larger size). Elsewhere, excepting the high-pressure surface impressions left by the G-10 coil-face insulation sheets, the coils appeared as virginal as before HD1's initial assembly

(transparent epoxy, no visible cracks). Detailed coil-size measurements of both coils confirmed that coil-A was undersized in locations consistent with HD1's post 16 T quench-origins, and post-test low pre-stress Fuji-paper measurements [7, 8]. Further examination revealed that irregularities in the coil-edge support elements were responsible. They were corrected by applying Araldite-1580 (a glass-loaded "green-putty"), and machining the coil to match its mate (coil-B).

B. Magnet Assembly and Support Structure Changes

The coils were reassembled in the same (HD1) structure (Fig.1), in which a 45 mm thick, 740 mm OD aluminum shell pre-stressed the coils transversely, via the iron yoke. Four axial aluminum "Z-rods" pre-stressed the coil-ends [12-13]. As with previous LBNL high-field magnets [4-5, 12-13], a modest 300K pre-stress was provided by pressurized bladders, and captured by keys, enabling the operational pre-stress to be approached from below, via differential thermal contraction.
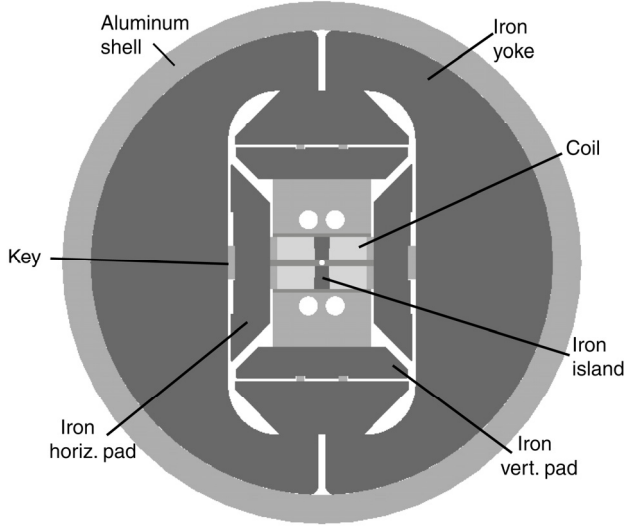

Fig. 1. HD-1 cross-section: Two horizontal, double-layer pancake coils were separated by a thin bore-plate, and compressed on all sides by compression pads, bridges, and iron yokes. Transverse compression was provided by a, 45 mm thick, 740 mm OD aluminum shell. G-10 sheets electrically insulated all coil surfaces, and cushioned irregularities at high-pressure interfaces. Iron interference-keys allowed the removal of internal 300K pre-stressing bladders, with only a small loss of pre-stress. Operational stresses were approached from below during cool-down, and relieved during warm-up.

HD1b's assembly, discussed in detail elsewhere in these proceedings [8], differed from HD1 in five distinct ways: 1) The 3-D FEM's inter-element friction was increased (from frictionless) in a manner to best reproduce HD1 measurements. This reduced the (pre-HD1) calculated coil-end conductor displacements, peaking near "turn-6" (6-turns from the pole-island). 2) HD1b's 300K shell tension was increased in a manner to increase the cold pre-stress against the long edge of each coil to ~185 MPa (~20% above HD1's 155 MPa). This "17 T" pre-stress margin (~20 MPa, conductor lift-off at ~17 T), was presumably sufficient to eliminate HD1's performance-limiting pole-turn quenching, without producing excessive conductor degradation. 3) All coil end-support systems were modified in a manner to significantly reduce the calculated, Lorentz-induced, coil-end

displacements [8], which had slowed HD1's training [7]. While failing to eliminate the "turn-6" gap at 16 T, it was believed sufficient for a cost-effective proof-of-principle. 4) The cold end-load force (provided by four "Z-rods" [12,13]) was increased 15% above that its HD1 level. 5) All 300K Z-load increases were applied before corresponding shell adjustments (to reduce coil "end-fluff" before it was trapped by transverse-load friction).

C. Diagnostic and Test Set-up

Coil protection and diagnostics were as before [13]. Eleven voltage-taps divided each coil-layer into 10 segments, with primary attention on the inter-layer ramp, pole-turn, end-spacer (turns 5-6), outer-turn (turn-35), and its Nb_3Sn/NbTi lead-in splice. Average coil pre-stress was inferred from temperature-compensated strains in the aluminum shell, and two of the four axial "Z-rods". A cold Hall-probe measured the peak bore-field, with the same (HD1) calibration.

III. TEST RESULTS

A. Training Preparations

Operational pre-stress was approached from below during cool-down, increasing from the 300K assembly values to 150 MPa in the shell, and 290 MPa the Z-rods (Fig. 2). Test preparations were similar to HD1 [13].
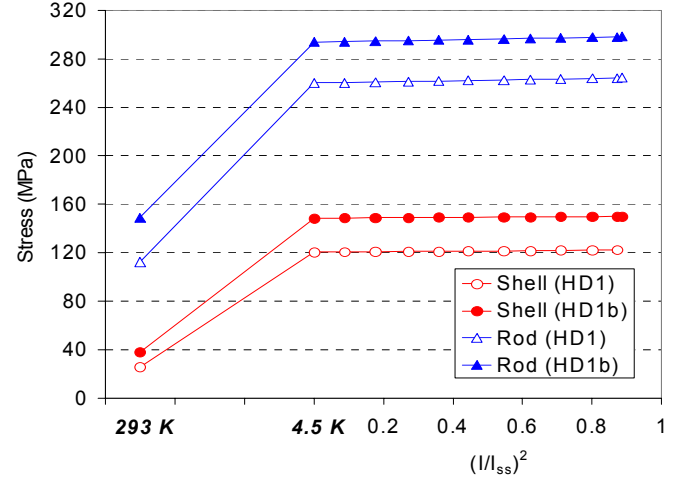

Fig. 2. The calculated absolute shell and axial Z-rod tensions for HD1 and HD1b, under the following conditions: "293K" (relaxed onto the keys), "4.5 K" (cold), and various fractions of the "short-sample" Lorentz level. The relative linearity vs. Lorentz-loading indicates sufficient pre-stress to maintain conductor contact with its supporting structure.

B. HD1b Training (1st Thermal Cycle)

The initial ramp to quench was changed from our standard stair-step ramp to an ascending series of complete triangle ramps, with peaks at 10%, 30%, 50%, 70%, 90% of I_{ss}^2, to differentiate between competing "causes" for the strain-gauge offsets after HD1's first quench, while affording observation of slip-stick training-retention and flux-jump repeatability. Most of the observed fast-flux-changes were labeled "flux-jumps", because they were relatively slow (5-10 ms duration), had no "deceleration" (negative second time-derivative), or mechanical "ringing", and recurred predictably every ramp.

HD1b's first training quench (15.1 T, 10.2 kA) occurred while attempting the "90%" triangle ramp. Subsequent

training was relatively rapid, reaching a 16 T plateau after the 8th quench (Fig. 3). As during Huench-origins were at the same coil-end locations as HD1's (near an end-spacer apex), and had a similar relative distribution. One was on turn-5 (5-turns from the pole island, inside the end-spacer); the remainder started on turn-6 (outside the end spacer). One was in the lead-end; the others were in the return end. Two were observed in coil-B's inner layer-1; the others were in coil-A's outer layer-2.
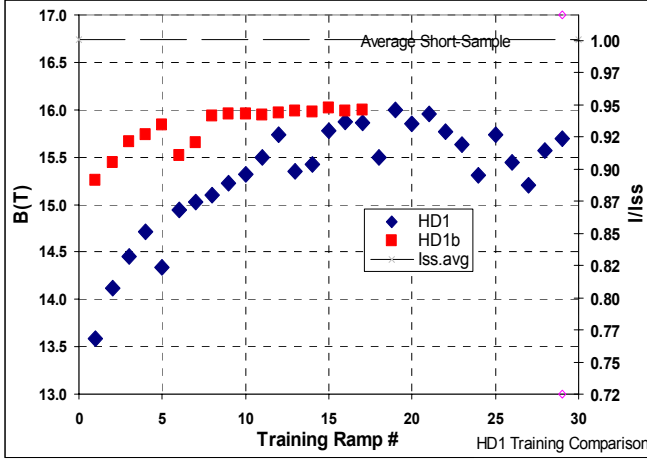

Fig. 3: Compared to HD1, HD1b's training started higher (15.2 T) and quickly (9th attempt) reached a stable plateau slightly below HD1's 16 T peak.

After the 8th quench, slightly below HD1's peak field (16 T), a ramp-rate dependent "plateau" (predictable currents and quench-origins) was observed (Fig. 4).
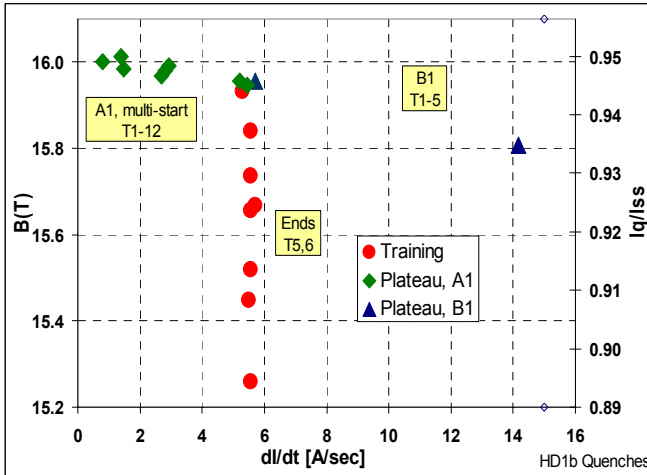

Fig. 4 HD1b's quenches vs. ramp-rate: While all quenches had multi-turn starts, three distinct quench-origins were observed: 1) training quenches started in the coil-ends (turns 5-7); 2) Slow plateau quenches (<6 A/s) started in coil-A's inner layer (A1, turns 1-12); 3) faster plateau quenches started in coil-B's inner layer (B1, turns 1-5). While plateau quenches started more gradually than training quenches, they quickly attained higher speeds.

At low ramp-rates (dI/dt < 6 A/s), all "plateau" quenches exhibited simultaneous starts (Fig. 5) in the first five turns adjacent to coil-A's winding pole, in both the high-field layer (layer-1), and the lower-field layer (layer-2). Turn-6 and some of the outer multi-turn segments started simultaneously ~1.6 ms after quench-onset. Compensating for the multi-turn segment's inductance, applying turn-6's propagating dV/dt to its neighboring (lower-field) turns, and assuming one quench-

origin/turn, at least 8 outer-layer and 9 inner-layer turns had started quenching. Under these assumptions: > 28 turns (~41% of coil-A) had propagating quenches 1.6 ms after onset.

In addition to the multi-simultaneous quench-starts, the plateau quenches also generated propagation signals (Fig. 5) that were near overlays of each other. The axial time-of-flight to the nearest voltage tap, ~9.3 ms to nearest tap "A1R2"(coil-A, layer-1, return-end, turn-2) varied weakly with current. The average dR/dt speed (~19 m/s, assuming uniform 30 K resistivity along the cable), yielded a the quench-origin in the high-field straight-section, ~176 mm from the "A1R2" tap at the start of the return-end. The quench-quench fluctuation was within the time-resolution of the DAQ (+/- 2 mm). Time-of-flight to the second nearest voltage-tap (turn-5's "A1R5") yielded a similar quench-origin for turn-5, suggesting that the quench-origins for neighboring turns may have been as well.
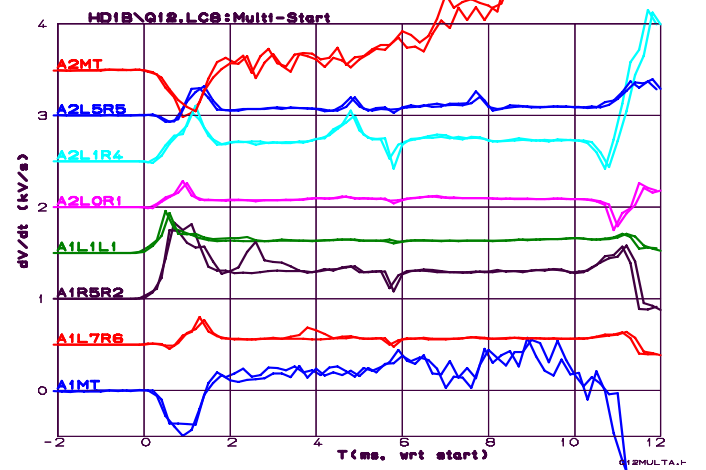

Fig. 5 A 1000V/s overlay of raw dV/dt voltage-tap signals (2ms/div) for two typical plateau quenches shows nearly simultaneous multi-turn quench-initiation in both the inner (A1) and outer (A2) layers. Upward polarity means increasing resistance or flux. Nearly duplicate quench propagation implies duplicate quench-origins. Subtracting inductive contributions yields signals that primarily depend on (quench-speed) x (number of quench-pairs within the segment). Changes in amplitude reflect changes in conductor margin, average resistivity, and/or number of quench-fronts in a segment.

The quench propagation signals also showed a resistance-growth-rate (~quench velocity) for the initial onset that settled to a (2-4x) slower, nearly steady value by 1.6 ms (Fig. 5). This was most noticeable in the low-inductance turns, and was true for both layers, with the longest lasting transient speeds in the 3-turn segment "A1R5R2", and the largest "speed ratio" in turn-6. Assuming the initial speed transient resulted from "degraded" margin, the largest "degraded" region was estimated to be ~80 mm long (assuming the measured average cable-resistivity at 30K was uniform). Comparing the negative inductive transients in the multi-turn segments (A1MT & A2MT in Fig. 5), with non-quenching "sister" segments in coil-B revealed a small positive signal (flux-increase, diamagnetic collapse?) existed in both "MT" (multi-turn) segments between initial-onset, and its own onset ~1 ms later.

Ramp-rates above ~16 A/s also had simultaneous multi-turn quench-origins, but with several distinct differences: 1) Quenches started in coil-B. 2) Simultaneous quench-origins

were observed only in layer-1, and only in turns 1-5 (from the pole-turn). 3) Simultaneous quenches in layer-2's "MT"-segment involved only the 5-turns with the lowest margin (turns 6-10), and started ~3 ms later than the secondary onset in the slower ramp-rate quenches in coil-A. 4) Quenches propagated into the ramp segment (from layer-2's lead-end pole-turn) after 2.5 ms (estimated to be ~31 mm), placing the quench-origin in the curved lead-end region. 5) A layer-1, turn-6 quench-front passed "B1L6" (lead-end) after propagating 5 ms, implying with a similar quench-origin.

C. HD1b-2's 4.5K Training (2nd Thermal Cycle)

Training during the second thermal cycle produced a distinctly different quench history (Fig. 6). Only the first quench showed a conductor movement "trigger" at 15.4 T (only marginally higher than HD1b). The associated slip-stick flux signal was the largest ever recorded, since their systematic recording began at LBNL (D19H, 1996), and it origin appeared to be near HD1b's plateau origins. The second quench, at ~15.8 T (~10.6 kA, ~0.93% of the average undegraded "short-sample"), exhibited a gradual, "plateau-like" quench-initiation and propagation, with multiple quench-origins nearly coincident with previous plateau quenches. Subsequent attempts generally resulted in lower fields, eventually stabilizing slightly around 15.7 T.
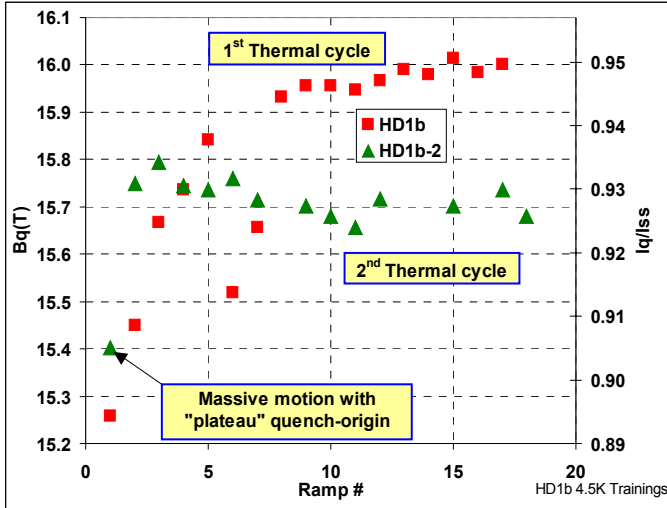

Fig. 6 Compared to Hd1b, HD1b-2's (2nd thermal cycle) training started higher and reached its maximum (~15.8 T, ~1.5% lower than HD1b's plateau) on the third attempt. The peak field degraded with subsequent attempts to ~15.7 T. All plateau quench-origins were nearly identical.

For the first time, no turn-6 coil-end quenching was observed. All quenches after the second produced quench propagation signal-sets that were approximate replicas of those during HD1b's "plateau", but with two minor differences: 1) Initial "quench-onset speed transients" (immediately after onset) lasted longer for turns 2-4. 2) Turn-5's quench passed "A1R5" ~1 ms sooner, implying its turn-5 origin was slightly (~20 mm) closer to the return-end (still well within the previously hypothesized "degraded conductor" region) propagation signal sets that were near duplicates every quench. Ramp-rate quench-origins between 20-60A/s were identical to HD1b's at 16A/s (i.e., coil-B, lead-end, multi-turn).

D. HD1b-2's Sub-cooled Training (T < 4.5K)

The temperature dependence of the "plateau" current was explored by ramping the magnet while immersed within a sub-atmospheric LHe bath. The observed temperature dependence was close to a slightly degraded Nb$_3$Sn, "load-line temperature dependence" down to ~4 K, below which the coil leads were no longer immersed in LHe (i.e., the coils could be significantly warmer than the bath). While cooling the bath allowed higher fields (Fig. 7), the 4.5 K plateau current did not increase. All quenches (excepting at 3.0 K) were replica's of HD1b's "plateau" quenches. The 3.0 K quench exhibited simultaneous origins in coil-A, like the others, but originated at the lead-end, in the first three turns (i.e., a new location).
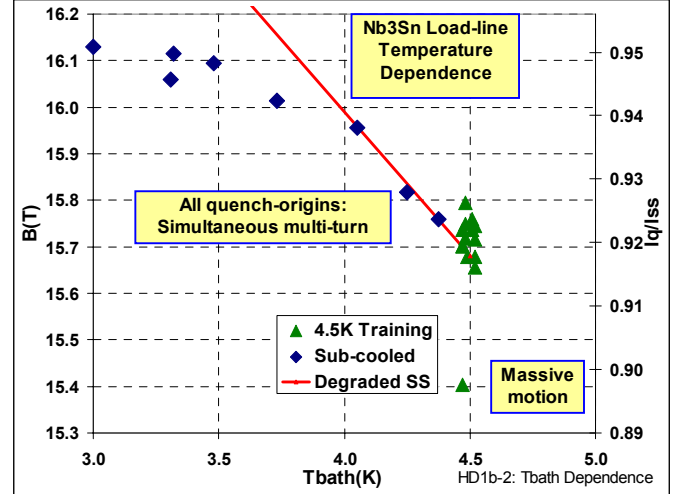

Fig. 7. HD1b-2 quenches vs. LHe bath temperature: The solid line "load-line temperature dependence" resulted from the intersection of the load line with measured short-sample dependences at three temperatures, and offset slightly downward to intersect the average of the final three 4.5K quenches. The conductor was expected to be warmer than the bath below ~4 K, where the coil-leads were no longer immersed.

IV. DISCUSSION

A. Pre-training Observations

Good agreement between structural strain measurements and 3-D FEM calculations continued to raise confidence in our 3-D thermal-mechanical-Lorentz model. The large number and size of flux-jumps, expected from 3000A/mm^2 (12 T, non-Cu) strands, while requiring some desensitization of our quench-detector, failed to limit magnet performance in any manner.

B. Reduction in Coil-End Training Quenches

Hd1b's coil end-support changes were motivated by the correlation between HD1's training quench-origins and the previously predicted Lorentz-induced conductor displacements near the end-spacer tips (turn-6). HD1b was expected to have considerably less conductor displacement and a higher field-onset [8]. For similar conditions, this was expected to result in faster training, with a higher onset current. While the full magnet disassembly, coil handling and reassembly might have failed to fully restore HD1's "virginal" state, the high correlation between performance and expectations raised confidence in the 3-D FEM's ability to

"predict" training performance from calculated conductor displacements.

C. HD1's "Plateau-Degrading" Quench Elimination

Coil-A's dimensional changes, and a larger (180 MPa average) coil-edge pre-stress were implemented to eliminate coil-A's pole-turn plateau-degrading quenches [13]. Their complete elimination was very encouraging. However, the resulting stable ramp-rate-sensitive plateau, ~5% below "undegraded short-sample", slightly below HD1's 16 T peak, with "short-sample-like" quench-onsets in the straight section, suggested this training improvement may have been achieved at the expense of some conductor degradation.

D. HD1b's Plateau Quenches

HD1b's "plateau" quench-origins were at an entirely new (high-field) location, and its quench-propagation signals were significantly different from those observed in HD1 [7,13]: 1) The rate of rise of quench-resistance was gradual and monotonic, without steps, or voltage spikes, very similar to previously observed "short-sample" or ramp-rate margin-degraded quench-onsets [1,3,4]. 2) Nearly simultaneous multi-turn quench-onsets, while somewhat similar to its earlier training quenches, and conductor-motion triggered plateau quenches in RD3c [5], failed to exhibit any evidence of motion-induced flux-change. 3) The replication of signal-sets (and associated time-of-flight's) implied a tight set of repeating, multi-turn simultaneous quench-origins. 4) The repeating initial quench-speed transients (Fig. 5), followed by slow steady resistance growth, could be explained by a local (60-80 mm long) cable margin-degradation.

The plateau's ramp-rate dependence and gradual quench-onsets suggested a degraded margin, and raised questions about the plateau's temperature dependence, and the impact of a 2nd thermal cycle upon training and "plateau" current.

E. 2nd Thermal Cycle and Sub-Cooled Training Lessons

The large size of the "slip-stick" movement that triggered the first training quench of the second cool-down, coupled with the absence of additional motion-triggered quenches (despite eight subsequent increases in peak field), suggested a thermal-cycle-induced loss of "mechanical training" that was predominantly re-established in one large movement. As with HD1b, the plateau's gradual quench-onsets, temperature and ramp-rate dependence, tightly clustered quench-origins, and , the relatively slow quench-speed (after onset) suggested a local margin degradation. However, the degraded-plateau, and the shift in its quench-origins, coupled with the first quench's similar quench-origin, and record conductor motion, raised the specter of thermal-cycle-induced "slip-stick" conductor degradation. Finally, the coil-end quench at 16.1 T suggested a resumption of mechanical training, although not confirmed by any 200 kHz quench-onset data (DAQ malfunction).

V. SUMMARY AND CONCLUSION

The record setting (16.0 T) block-dipole magnet "HD1" was disassembled after motion-triggered quenches suggested inadequate conductor pre-stress. Both coils were examined and modified slightly to increase their end-support (via 3-D FEM guidance), and reassembled with higher coil pre-stress in all regions where HD1 had quenched. The (HD1b) re-test revealed that all previous quench-origins had either been eliminated, or significantly reduced. A stable 4.5 K ~16 T "plateau" was quickly attained ~5% below "short-sample" expectations, which exhibited "short-sample-like" quench-onsets, and ramp-rate dependence. Plateau quenches started simultaneously on 15-30 turns (i.e., over a wide range of field-strength), and appeared to propagate away from regions of locally depleted margin. A 2nd thermal cycle revealed "short-sample" quench behavior on the third quench, at ~1.5% lower field. The peak field degraded another ~1%, after additional quenching. Its plateau quenches were similar to those in HD1b, but started slightly closer to the return-end.

Complete absence of quench-onsets within HD1's interlayer ramp and $Nb_3Sn/NbTi$ splices, plus the elimination of most of HD1's training quenches was very encouraging. However, the plateau quenches raised some questions: 1) Would conductor degradation continue with additional thermal cycles? 2) Could the inferred local degradation be independently verified? 3) Was the degradation reversible? 4) Could it be avoided without harming training performance? 5) Could marginal conductor stability help "explain" the simultaneous plateau quench-onsets over such a large range in B-field? 6) How many "locally degraded" coil-regions might be encountered before reaching HD1's "undegraded short-sample"? 7) What would be the most cost-effective way to develop 18 T accelerator magnet technology?

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