Test Results for a Nb₃Sn Dipole Magnet

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Abstract--A cosine theta type dipole magnet using Nb₃Sn conductor have been designed, built and tested. D19H is a two-layer dipole magnet with a Nb₃Sn inner layer and a recycled NbTi outer layer. Coil-pairs are connected with two of the four Nb₃Sn splices in a high field region, and compressed by a ring and collet system. The ramp-rate sensitivity and the splice resistances were pleasingly low; and the 4.4K training was rapid. At 1.8K, however, the unusually high frequency of outer-coil fast-motion events increased with current, effectively creating a training-ceiling at 90% of the expected outer-layer limit (10.2 T). A low end-load applied to a relatively fluffy outer layer is believed to have caused this training limit. The end-load was increased; but a retest was aborted after the magnet failed a precautionary hipot test.

I. INTRODUCTION

A major goal of the Superconducting Magnet Program at the Lawrence Berkeley National Laboratory is the advancement of magnet technology for accelerator magnets. As it is presently necessary to work with brittle materials for $B > 10$ T, Nb₃Sn is currently being investigated as a prototypical brittle superconductor. Two different Nb₃Sn, 50 mm (bore), 1 meter long dipole designs are being evaluated.

A four-layer Nb₃Sn design (D20), is under construction, in an attempt to explore the 12-14 Tesla range. Its details have been published previously (2,3). The magnet has the following principal goals: (1) reach a significantly higher B-field, (2) validate the technology required to reliably achieve these field levels, (3) provide a facility to test insertion coils made with other high-field superconductors.

A second magnet (D19H) was constructed to provide a faster test-bed for the new Nb₃Sn magnet technology. It utilized the two-layer "D19" design that had been previously developed at the Lawrence Berkeley National Laboratory to reach 10T using NbTi at 1.8 K. This design was modified to replace the inner layer conductor with a Nb₃Sn cable. Its details are published elsewhere in these proceedings[1]. This magnet has the following goals: (1) demonstrate efficient production of Nb₃Sn magnet coils (once the tooling and magnet structure have been developed), (2) evaluate the feasibility of ring and collet precompression of Nb₃Sn coils, (3) evaluate the ramp-rate sensitivity of Nb₃Sn coils, and (4) validate new magnet assembly technologies before more complicated and expensive magnets are attempted.

The first training results for D19H are reported below.

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II. EXPERIMENTAL DETAILS

A. Instrumentation

Each Nb₃Sn coil had 15 voltage-taps, positioned in a manner to monitor four anticipated trouble regions: the pole turn (highest B-field), each of the three wedges (highest discontinuity-related strain), the mid-plane turn (highest stress), and each splice (joint resistance). The outer coil had only full-coil taps. All voltage-tap signals were processed by analog-derivative amplifiers (1V output for 100V/s input). "Fast-Imbalance" signals were produced by nulling a coil section against its closest neighbor. These signals assisted the determination of quench onset.

Each Nb₃Sn/NbTi splice was soldered under pressure with a eutectic solder for a distance of 100 mm. A twisted pair of wires was attached across each joint and monitored with an HP3458A voltmeter. A thermometer was also embedded within each splice-block to monitor any temperature rise.

Four strain gages (one/coil/layer) monitored the pole-turn pressures; and load-cells (six/end) monitored the end-force applied by each of twelve end-load loading-bolts.

B. Test procedures

The temperature and resistance of each coil was monitored during cool-down and warm-up. The strain gages were also monitored to determine the timing of the cool-down loading losses. When 4.4K was achieved, the magnet was ramped to quench at a slow rate (5A/s), until we later discovered that 20A/s was equivalent for training purposes. After establishing the existence of a thermally-limited plateau, the ramp-rate sensitivity was measured. After cool-down to 1.8K, the above sequence was repeated.

After warming the magnet, both end-loads were increased substantially, in preparation for another round of tests. Testing was aborted when the magnet failed a standard 700V hi-pot and quickly degraded to 210V (considered inadequate to safely extract energy from the magnet during quenching).

III. EXPERIMENTAL RESULTS

A. Coil Resistance and Strain-Gage Histories

Two different superconducting transitions were easily visible at the expected temperatures (Fig. 1). Both outer (NbTi) coil resistances decreased ($RRR = 75$) from their initial values (each 136 mohms). The inner coils differed by 4% at 300K (100 mohms, 96 mohms). This relative difference increased during cool-down to 0.33 mohms and 0.24 mohms, prior to transition. This yielded significantly different RRR-values (300 and 400, respectively).

Fig. 1. Superconducting transitions: the inner (Nb₃Sn) coils were clearly differentiated from the outer (NbTi) coils during initial cool-down.

The strain-gages also changed during cool-down (Figs. 2, 3), showing an anticipated relaxation everywhere. The lead-end almost completely unloaded. During training, the outer-layer pole pressures decreased (Fig. 4), while the inner-layer pole-pressures and the end-loads (Fig. 5) increased. After warm-up, all strain-gages indicated higher stress-states than before cool-down. Two end-load increases were made in preparation for further testing. Testing was aborted when the magnet failed a standard hi-pot test.

Fig. 2. Pole-pressure history: Initial creep, cool-down loss, training shifts, warm-up, and creep during two end-load increases.

Fig. 3. End-force history: Initial creep, cool-down loss, training shifts, warm-up, and two end-load increases.

B. Magnet Ramping

During ramping, the magnet transfer function slope was measured to be 1.13T/K.A initially, reducing to 0.81 T/K.A above 6T. The outer poles (Fig. 4) unloaded symmetrically and nearly linearly with the square of the magnet current (excepting the first ramp where some jumps were observed). The inner poles were also symmetrical, decreasing non-linearly above 8 Tesla. The end-loads increased non-linearly (Fig. 5) at approximately 15% of the total Lorentz end-load.

Fig. 4. Pole Pressures: The I^2 dependencies were more linear for the outer layer than the inner layer; and all pole-pressures decreased more rapidly above 8 K.A. Although the inner layer did unload the fastest, it did not unload as fast or as much as expected.

Fig. 5. End Forces: These four end-load-cell signals illustrate the axial asymmetry of the pre-load (RE=Return-end, LE=Lead-end) and the relative axial symmetry of the nonlinear I^2 dependence. The rate of total end-load variation accounted for only 10-20% of the calculated Lorentz end-load.

The first 4.4K quench (Fig. 6) occurred at 7.4T (90% of plateau). Plateau was achieved after six outer-layer (NbTi) quenches, one of which fell-back. The 1.8K training began at current-ramp #26, with inner-layer (Nb₃Sn) quenching at 80% of the expected maximum ($B > 10.2T$). The rate of improvement was significantly slower, and was eventually dominated by outer-layer (NbTi) quenching after ramp #46. The frequency of "fall-backs" was also high. Training was aborted in order to measure the 1.8K ramp-rate sensitivity.

Fig. 6. Quench History: Training and ramp-rate studies at 4.4K and 1.8K. Testing was aborted to warm the magnet and increase the end-load.

Quench onsets were most easily identified with the “Fast-Imbalance” signals (Fig. 7, 8). The early, 1.8K, inner-layer training quenches (# 26-46) seldom showed the fast-motion signatures normally observed at quench onset during training. They also showed significantly (10x) slower quench propagation speeds than the training-limiting outer-layer quenches (Fig. 8).

Fig. 7. A Nb₃Sn quench: Most of the first twenty 1.8K training quenches originated in the Nb₃Sn layer. Large “fast-motion” imbalances at quench-onset were usually absent, and the average quench propagation speeds (7 m/s) were much slower than for NbTi.

Fig. 8. A NbTi quench: The 1.8K training-limiting, outer-layer quenches typically showed large fast flux-imbalances, immediately before quench propagation. TI-TO = Top(inner-outer) and BO-BI = Bot(outer-inner).

The number of Fast-Imbalance events increased rapidly with current during ramping (Fig. 9). At 4.4 K, most of them occurred shortly before the quench, the number reducing with training. At 1.8K, the rate of increase was more linear, starting at 5 KA. No decrease with training was observed above 7 KA.

Fig. 9. Number of “Fast-Imbalance” Events: vs. Current. The 4.4K ramps Q1, 2 (5 mV threshold) showed reduction with training at all currents. The 1.8K ramps Q59, 71 (10 mV threshold) showed no improvement with training.

The Fast-Imbalance history (Fig. 10) also illustrates the opposing trends of the two trainings. At 4.4K, the total number generally decreased, even though the current increased, while at 1.9K the total number increased with the current (and fell back when the current fell-back).

Fig. 10. “Fast Imbalance” Training-History: The total number/ramp generally decreased with training at 4.4K, but increased with current at 1.8K. The detector was desensitized 2x, (5 mV to 10 mV) after the 1st 1.8K quench

The pole-turn (high-field) splice resistances were equal (1.0 n-ohm), nearly independent of current ($I < 9$ KA), and three times the average mid-plane (low-field) splice resistance. Embedded thermometers in their copper splice blocks showed only small splice temperature rises (0-15 mK, during the 0-9 KA ramp shown in Fig. 11). One mid-plane splice showed a small ramp-rate dependence, while the other mid-plane splice showed no heating at all. One pole-splice showed a steeply rising current dependence prior to magnet quenching, while the other pole-splice, using a germanium resistor, gave unreliable temperatures in the magnetic field.

Fig. 11. The temperature history of three of the four Nb₃Sn/NbTi splices: One pole-splice showed a small ramp-rate sensitivity. One mid-plane splice showed a dramatically increasing current dependence starting 20% before quench. The other mid-plane splice only showed the quench.

The 4.4K ramp-rate sensitivity (Fig. 12) was weaker than anticipated from other reports[4]. It exhibited an anomalous peak at 180 A/s and a rapid fall at 200 A/s to a plateau that was flat out to at least 1200 A/s. The 1.8K dependence showed an even larger fall to a nearly identical plateau at a slightly higher ramp-rate. The 1.8K, slow-ramp data (<200 A/s) should only be considered as lower-bounds because the associated quenches exhibited simultaneous outer-layer, fast imbalances at quench onset (implying outer-layer, motion-triggered quenching). The fast-ramp quenches originated in an interior multi-turn section of the inner coil, not a splice.

Fig. 12. Both ramp-rate sensitivities showed a rapid drop to a flat plateau.

The voltage break-down discovered after warm-up was localized near the lower coil's inner-to-outer-layer high-field splice. Testing was terminated until this condition could be corrected.

IV. DISCUSSION

The early 1.8K inner-layer mid-plane training quenches, with several showing simultaneous upper and lower coil quench-starts, suggests the possibility of some mid-plane slippage and/or mismatched mid-plane surfaces.

The fast-motion-initiated outer-coil training-ceiling and the persistently high frequency of outer layer fast-imbalances is strong evidence for inadequately restrained outer layer coils. This is believed to have been aggravated by the failure to stretch the outer layer during collaring (as was done for D19A), in addition to the conservatively low total end-load

that had been rigidly applied to two coil-layers having markedly different stiffness[1]. The un-potted outer coil appears to have been so loose as to preclude fast-motion training, a prerequisite for increasing the quench-current.

The radial loading from the outside shell apparently provided enough friction that only a fraction of the Lorentz load is delivered directly to the end-structure. The non-linear end-gage response suggests that some of this friction was increasingly overcome as the Lorentz load increased. The larger relative cool-down loss of the lead-end is believed to have resulted from its relatively larger plastic fraction, caused by epoxy-filling twice as many end-part/cable gaps.

The low ramp-rate dependence suggests fairly good inter-strand isolation, until a 200-250 A/s punch-through occurred.

The extremely slow Nb₃Sn quench propagation speed supports the existence of a large relative margin.

V. CONCLUSION

A Nb₃Sn/NbTi hybrid magnet was tested to validate several portions of our growing body of Nb₃Sn magnet technology. The pleasingly low ramp-rate sensitivities and low splice resistances validated the coil-reaction and splice technologies used for the upcoming magnet D20. The low Nb₃Sn quench velocities support the high, anticipated margin of the inner conductor. A NbTi outer-coil "training-ceiling" unfortunately limited our ability to extend our observations to the 10.2 Tesla outer-coil limit. An unusually high frequency of outer-layer fast-motion events did not decrease with training (as usual). This leads us to suspect that looseness in the weakly loaded outer coil-ends limited the stress-range of this test. This could be corrected by substantially improving the packing and loading of the outer coils. However, the cost/benefit ratio of this change alone does not look very attractive with our present commitments.

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