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Performance Comparison of Nb3Sn Magnets at LBNL

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Performance Comparison of Nb_3Sn Magnets at LBNL

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***Abstract*—The Superconducting Magnet group at Lawrence Berkeley National Laboratory has been successfully developing Nb_3Sn high-field dipole magnet technology for the last ten years. Noteworthy magnet tests include D20 (50mm bore, 4-layer cosθ, 12.8 T, accelerator quality dipole), and recent racetrack dipoles: 1) RT1 (2-layer, 12 T, no bore, no training), 2) RD3b (3-layer, 14.7 T, 10mm bore), 3) RD3c (3-layer, 10 T, low-harmonics 35mm bore), and 4) some small Nb_3Sn magnets that utilized new technology. The performance of these magnets is summarized, comparing 1) cable and magnet geometry parameters, 2) training behavior, 3) ramp rate sensitivity, 4) RRR measurements, 5) peak temperatures and voltages, and 6) fast flux adjustments that occur during ramping.**

***Index Terms*—Superconducting Magnets, Nb_3Sn, Cosθ, Racetrack, Comparison.**

I. Introduction

THE superconducting magnet group at the Lawrence Berkeley National Laboratory has been developing high-field, superconducting Nb_3Sn magnet technology for future accelerators. Over the last ten years, improvements in conductor properties resulted in a significant increase of the maximum dipole field. At the same time new design concepts and fabrication techniques allowed reducing the magnet cost. D20 demonstrated that Nb_3Sn conductor could be used in an accelerator quality cosθ dipole [1]. A desire for more cost effective magnets motivated the exploration of flat racetrack common coil magnets. Recent efforts have focused upon assessing their ability to achieve higher fields, at less cost, while retaining the reliability and field quality of cosθ magnets. RT1 showed exceptionally fast training in a 12 T test of reusable racetrack modules with improved conductor [2], [3]. RD3b [4]-[6] verified that a high field insert-coil could be made with this conductor and used at 14.7 T without degradation. RD3c utilized a larger bore insert module with a flat racetrack coil for field quality improvement [7]. Meanwhile, a Subscale Magnet Test Facility has been developed to investigate innovative approaches to mechanical, conductor and fabrication issues in the 10-12 T field range before applying them to a full-scale magnet [8], [9]. In this paper, several important features of these Nb_3Sn magnets, and the results that have been achieved thus far are compared. Recently, interest has developed in Nb_3Sn cosθ quadrupoles for the LHC upgrade [10].

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II. Magnet Designs

A. General Features

The magnets were all assembled from vacuum-epoxy-impregnated coil modules. To avoid an internal splice, all modules were wound as double-layers. Table I shows the parameters for all magnets.

TABLE I
GEOMETRIC FEATURES AND GENERAL PARAMETERS

MAGNET	D20	RT1	RD3b	RD3c	SM-01
Geometry	Cosθ	Race-track	Race-track	**Race-track**	Race-track
Ncoils	2	2	3	**3**	2
Lcoil (m)	1.6	1	1	**1**	0.3
Dbore-hole (mm)	50	-	9.5	**35**	-
Dsc-free (mm)	50	9.5	24.3	**39.5**	3.8
Imax (kA)	6.3	10.5	10.9	**10.9***	9.8
Bbore (T, 4.3K)	12.8	12.2	14.6	**10.0***	11.9
Bpeak (T, inner)	13.1	-	14.8	**13.1**	-
Bpeak (T, outer)	10.3	12.36	11.5	**11.3**	11.9
Nturns (inner)	16+26	-	50	**16**	-
Nturns (outer)	40+56	49	49	**49**	20
Inductance (mH)	45.6	10	17	**15**	0.3
Energy (MJ)	1.1	0.6	1	**1.1**	< 20kJ

* Calculated values considering no degradation are 11.9 kA and 10.9 T. Training was aborted to assess further training improvements with a later thermal cycle.

D20 is a cosθ dipole, assembled from two double-layer coil modules. Wedge-shaped spacers were utilized to provide accelerator field quality and compensate for the partially keystoned cable. In contrast, in the RD (Racetrack Dipole) and SM (Subscale Magnet) magnets, the coil modules were all constructed with (double-layer) racetrack windings. No spacers were used in these coils, until the attempt to improve the field quality with an insert in RD3c.

The magnets also differed in their bore diameters (Dbore-hole), and conductor-free distances near the bore (Dsc-free), parameters that influence the bore's field magnitude and field quality. D20 and RD3c had bores that were large enough to insert a warm rotating coil field probe. While the Roman arch geometry of D20's coils was self-supporting, the racetrack coils required bore-plates that were rugged enough to keep the bore holes from yielding under the coil pre-stress.

There were also large variations in stored energy and inductance. Stored energy for the D20 and RD magnets is of the same order, despite a factor three difference in the inductance, due to the difference in short sample current. For the subscale magnets (SM series), the stored energy is much lower, allowing fast quench recovery during the test with low helium consumption.

B. Cable Parameters

Table II summarizes the strand and cable parameters of these magnets. In all cases, the cable packing factor was around 85%. The cable insulation (about 0.125mm/turn) was a woven fiberglass sheath around the bare cable that was epoxy impregnated after winding and reaction.

TABLE II
STRAND AND CABLE PARAMETERS

MAGNET	D20	RT1	RD3b	RD3c	SM01
Jc (A/mm^2)	960, 1600	-	2043	2014	-
(12T, 4.2K)	1627	2143	2143, 1754	2143, 1754	2260
Jcu (A/mm^2)	2240, 1481	-	2270	2319	-
(12T, 4.2K)	1535	1367	1367, 1329	1367, 1329	2774
No. strands	37	-	40	31	-
	47	26	26	26	20
No. turns	16+26	-	50	16	-
	40+56	49	49	49	20
Cu/SC	0.43, 1.08	-	0.90	0.90	-
	1.06	1.64	1.64, 1.35	1.64, 1.35	0.81
Strand diam.	0.753	-	0.800	0.800	-
(mm)	0.482	0.800	0.800	0.800	0.710
Thickness	1.356	-	1.386	1.396	-
(mm)	0.873	1.408	1.408	1.408	1.270
Width (mm)	14.45	-	17.20	13.32	-
	11.63	11.34	11.34	11.34	7.80
Pitch length	93.50	-	119.80	93.40	-
(mm)	81.28	81.28	81.28	81.28	54.88

* Cable values are an average of the known strand values.
** When two rows exist, the upper row is associated with the inner module (if it existed). The bottom row indicates outer module values.
*** The second of two values separated by comma refers to an identical coil with a different conductor.

Note that RD3b and RD3c used the same outer coils, one of which was also used in RT1, demonstrating the reliability of Nb_3Sn coils. There was a significant improvement in J_c between D20 and RD3c's strand. The ultimate J_c target for the Conductor Development Program is 3000 A/mm^2 (12 T, 4.2 K) [11]. Another goal is to enhance the overall current density by reducing the copper to superconductor ratio and decreasing insulation thickness.

C. Magnet Protection

The magnet protection system is triggered when the half-magnet voltage imbalance exceeds a preset threshold (about 0.5-1.5 V). Two quench protection heater power supplies were fired shortly after (25-40 ms). The heater geometry was determined by the desire to keep the peak coil temperature below 200 K, and the peak internal voltage difference less than 400 V. The heater efficiency depends on how fast the voltage threshold is reached by the quench front, and on heat diffusion from the heater into the cable through the kapton insulation. After a delay, sufficient to observe the heater effect, the current extraction power supply is fired to accelerate energy removal. This delay varied according to the experimental need (quench propagation studies, or protection).

In full scale magnets, each coil layer had an actively heated, Kapton-encapsulated quench-heater foil that was potted, and in intimate contact, with the coil. This foil had a geometry that could directly heat more than 70% (average) of the turns in the straight section. Being a distributed heater, the active part was only 40% for D20 and 35% for the RD series (average). With sufficient applied energy, this could initiate a global quenching within 10ms. The set of heaters were wired in two series circuits to minimize the internal magnet voltage differences in case of failure of one PS circuit. The energy dump resistor was adjusted to keep the magnet's terminal voltage below 500 V. In order to reduce cost and assembly time the subscale magnets did not have quench heaters and the short L/R decay times made their elimination reasonable.

III. TEST RESULTS

A. Training History

Fig. 1 shows the 4.4 K training histories of all the magnets.

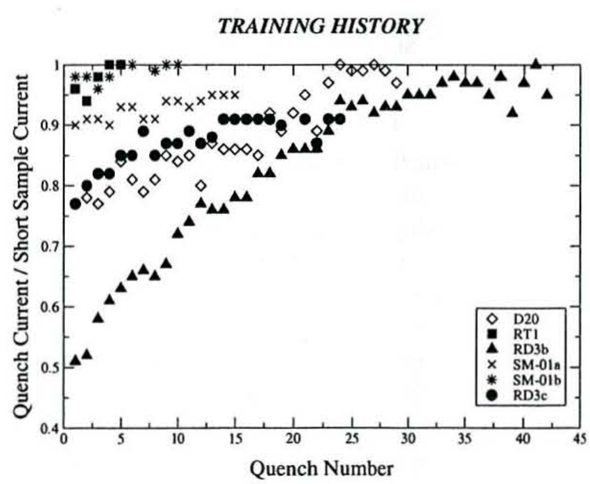

Fig. 1. Training history: normalized quench current vs. quench number.

All but two of the magnets (RT1 and SM-01b) exhibited slow training, requiring between 25-40 quenches to reach the expected conductor limit. D20 required several quenches at 1.8 K to achieve its 4.4 K conductor limit [1]. RD3b reached its short sample after 40 quenches, but not consistently. Below 13.7 T, RD3b experienced most of its training quenches in the virgin inner module. Above this value, most of the quenches started in the previously tested outer coil modules and the highest field of 14.7 T was recorded. Most of RD3c's quenches were also in these same outer coils, while its virgin insert coil experienced only two quenches. This module was only welded and no vertical and axial pre-stress was applied. On the inner module of RD3b the pre-stress was 56 MPa vertically and 25 MPa axially. RD3c reached a plateau at 90%

of its short sample during its thermal cycle. SM-01a experienced trouble exceeding 95% and its thermal cycle was aborted to change the pre-stress. SM-01b was assemble using the same coils and lower pre-stress [8]. Only RT1 and SM-01b performed well and reached their short sample limit within a few quenches. Both magnets had low horizontal pre-stress so that coil-coil separation occurred at 50% of maximum field.

B. Ramp Rate Sensitivity

The 4.4 K ramp rate sensitivity of these same magnets (Fig. 2) shows a relatively weak dependence at low ramp-rates [1], [3], [6], followed by a "cliff-like" drop to a flat plateau as the ramp-rate increases. The full-scale coils experienced their drop-off between 3-5 T/min in the bore-field. In the small-scale coils, the drop-off was less clearly defined.

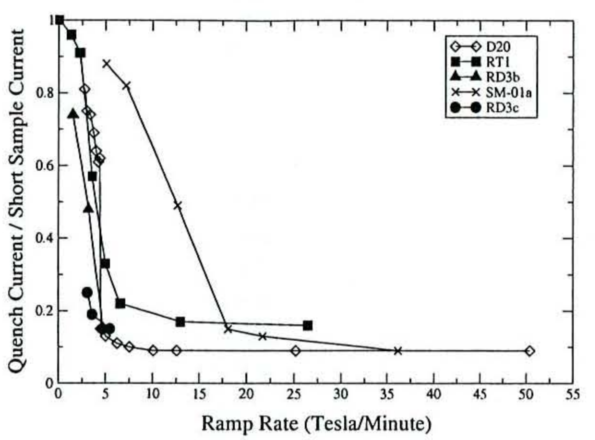

Fig. 2. Ramp-rate sensitivity of the maximum magnet current. Normalized quench current is plotted as a function of the ramp rate of the bore field.

C. RRR measurements

Table III lists the 20K Residual Resistivity Ratios (RRR = R(300K)/R(20K)) that were measured for these magnets. D20 had higher RRR's than most of the RD-series, with one that was extremely high whose conductor was produced from a different manufacturer (IGC) than the other three (TWC). The high J_c conductor in the RD-series exhibited lower RRR's.

TABLE III
20K RRR MEASUREMENT

MAGNET	Coil	RRR
D20	upper inner	201.0
	upper outer	44.9
	lower inner	47.5
	lower outer	51.6
RT1	outer 1	13.0
	outer 2	11.6
RD3b	outer 1	13.4
	outer 4	15.8
	inner 3a	3
	inner 3b	21.0
RD3c	outer 1	13.2
	outer 4	16.1
	inner 6	92.0
SM-01	SC-01	39.7
	SC-02	36.9

This was due to the duration of the high-temperature reaction cycle, which was cause of poisoning of copper with tin that penetrated the diffusion barrier. The relatively low RRR's appeared to have no serious effect on performance but some changes were observed. In particular, larger quench voltage signals, shorter turn-turn delay times, decreased L/R current decay times, and no significant effect on the peak coil temperature. The larger RRR's in recent racetrack coils have correlated with shorter high-temperature reaction times.

D. Peak Temperatures and Voltages

Peak temperatures have been determined for D20, RT1 and RD3b, using the coil segment resistances, and the T(R) calibration measured during cool-down. The highest temperature observed in D20 was 205 K. For RT1 and RD3b the highest measured temperature was 215 K. The measured peak voltages did not reach values higher than 250 V. This voltage is well below the critical threshold of 400 V since in all the quenches both heaters and dump resistors were used.

E. Fast Flux Changes(FFC's)

The time-derivative of the voltage developed by some portion of a magnet circuit provides a frequency-weighted view of the flux changes experienced by that circuit. During short sudden movements of a current-carrying conductor, it provides an easy way to visualize and quantify the relative acceleration experienced by the conductor and the size of its movement. Assuming the Lorentz force always moves a current-carrying conductor toward a larger net enclosed flux, the polarity of a signal produced by electrically nulling one part of a magnet against another allows the search for movement locations with a signal that is relatively insensitive to external noise sources. A detection threshold allows collecting only those events above a preset level of motion. An examination of signals collected while ramping a magnet often reveals two distinctly different classes of signals. The most frequent signal has a sudden pulse onset, followed by a reverse swing and a rather slow decay of the excited spectrum (Fig. 3).

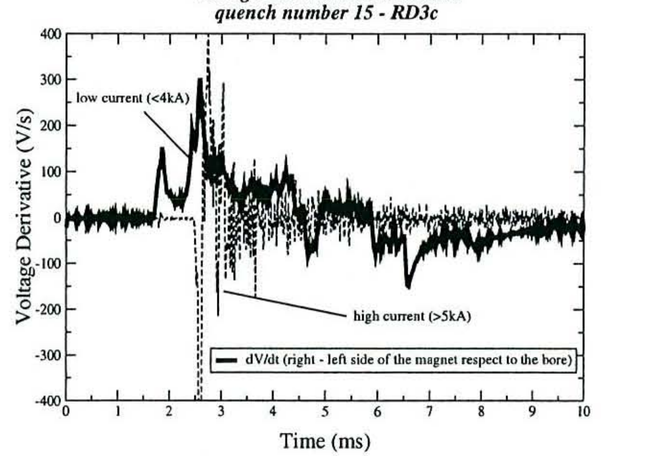

Fig. 3. One of several thousand half-magnet-imbalance, Fast-Flux-Changes (FFC's) that were recorded during RD3c's training. In bold, a low frequency imbalance observed at 10% of calculated short sample during ramp Q15 of RD3c's training.

This imbalance has been of intense experimental interest at LBNL since before D20 [1], and interpreted as evidence of stick-slip conductor motion. This signal is frequently observed immediately before the start of a spontaneous training quench (Fig. 4). It was observed that the frequency of these events usually increases dramatically while ramping a magnet into a "virgin" Lorentz-stress range. The same frequency in "non-virgin" regions usually reduces monotonically as the magnet "trains". In addition, the magnet's training rate correlates with the rate of reduction of the "non-virgin" event frequency. At the same time in any "training fall-back" not only the current reduces but also the "non-virgin" event frequency increases.

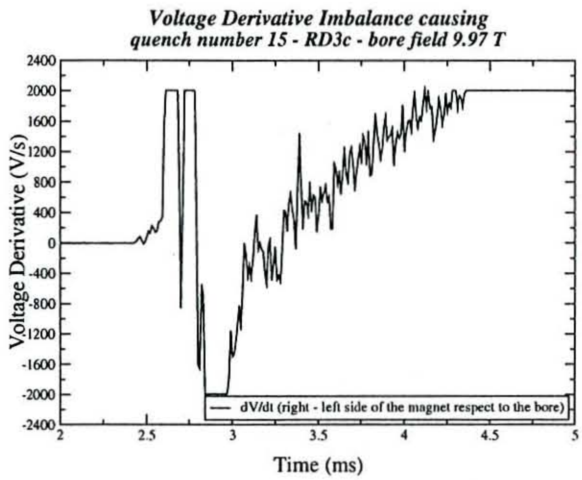

Fig. 4. The massive FFC 1ms before the onset of resistance that terminated ramp Q15 (the highest field observed during RD3c's training).

Low frequency flux changes (Fig. 3 bold curve) have been observed when the magnet current is low (10-50% of the cable's current-limit). The number of these "slow" events is nearly independent from the direction of current ramping, the number of complete ramps since the last quench, and the level of the magnet training. At higher ramp-rates, the number of events decreases, and the magnet imbalance voltage increases. When a half-magnet imbalance asymmetry exists, the asymmetry inverts when the ramp-rate inverts [7].

IV. Discussion

Virgin magnet performance continues to be unpredictable for several reasons, including the large number of parameters that can influence training, and the difficulty in quantifying (and controlling) these parameters. With the new approach for magnet assembly and disassembly achieved with the RD3-style magnet containment of flat racetrack coils, one can imagine inexpensive tests of changes that could affect training. For example, the pre-stress reduction to allow RT1-style coil separation in SM-01 [8] took 2 days (removal to reinsertion in its cryostat). Even if coil separation is intolerable for field quality inside accelerator magnets, low pre-stress currently appears to be a simple means to accelerate the assessment of magnet technology innovations.

The relatively similar ramp rate sensitivity of the large coils is not too surprising, given their relatively similar preparations. Studies of quench propagation on different cables through stimulated quenches could be helpful in studying inter/intra-strand current sharing behavior in the cable, especially for the new cable design such as mixed strand and cored cable [11].

The RRR values appear rather controllable. The present target is RRR >10, with a conductor heat treatment target of less than 200 hours, without losing current density [11].

A small-magnet test is being planned to investigate the relationship between peak conductor temperature and conductor margin degradation, using an integrated ribbon spot heater and local thermometer near the maximum field.

The frequent presence of high-frequency FFC's immediately before spontaneous quenching, and the strong correlation between magnet training rates and FFC training rates, supports the notion that controlling the frequency and amplitudes of FFC's could accelerate magnet training and improve reliability.

Locating these conductor movements could help magnet designers design more reliable magnets and "retro-fix" slow-training magnets more systematically. The slow fast-flux changes are believed to result from flux jumping in excessively large Nb_3Sn filaments, and will likely disappear as the conductor improves.

V. Conclusion

For several years the Superconducting Magnet Group at LBNL has been developing technology for high-field Nb_3Sn accelerator magnets. Dipole magnets with different geometries and characteristics have been successfully tested. Common coil magnets have been explored the past few years. While the cost reductions and record dipole fields have been very encouraging, many issues require further improvements, including: training, conductor movements, ramp rate dependence, and flux jumps. The recently initiated Subscale Magnet Program is expected to address many issues in a more cost-effective manner.

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