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Cable Testing for Fermilab's High Field Magnets Using Small Racetrack Coils

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Abstract— **As part of the High Field Magnet program at Fermilab simple magnets have been designed utilizing small racetrack coils based on a sound mechanical structure and bladder technique developed by LBNL. Two of these magnets have been built in order to test Nb_3Sn cables used in cos-theta dipole models. The powder-in-tube strand based cable exhibited excellent performance. It reached its critical current limit within 14 quenches. Modified jelly roll strand based cable performance was limited by magnetic instabilities at low fields as previously tested dipole models which used similar cable.**

***Index Terms*—Accelerator, Magnet, High Field Dipole, Nb_3Sn**

I. Introduction

Fermilab is working on a new generation of superconducting magnets for present and future accelerators. These magnets utilize several different Rutherford-type cable designs made of state-of-the-art Nb_3Sn strands. Strand and cable tests are important aspects of the magnet R&D program. Fermilab has designed small two-layer racetracks arranged in common coil configuration which were packaged into subscale racetrack (SR) magnets based on a sound mechanical structure and bladder technique developed by LBNL[1]-[2]. The main goal of this work is to test full-size Nb_3Sn cables using compact coil systems that implement Nb_3Sn magnet technology and real cable operating conditions. With such coils, two types of cable, including those used in Fermilab's cos-theta dipole models, were successfully tested in two subscale magnets (SR01 and SR02). These cables were made out of powder-in-tube (PIT) and modified jelly roll (MJR) strands 1.0 mm in diameter featuring high critical current density and an ample range of effective filament sizes (50 and 110 microns respectively). This paper describes the design and fabrication of the two racetrack magnets, as well as their instrumentation and the test procedures applied at the Fermilab's Vertical Magnet Test Facility. The results of these tests are reported and discussed.

TABLE I
Magnet Design Parameters

Parameter	Value
B MAX, T	11.06
I max, kA	28.12
Aperture, mm	2
Coil area, cm^2	6.05
Number of turns per coil	13
Iron yoke OD, mm	215
Stored energy @ 11 T, kJ/m	19.05

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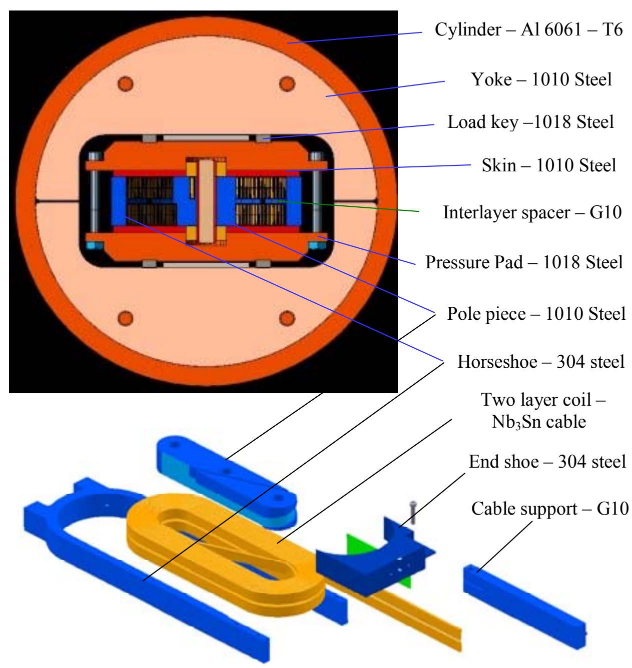

Fig. 1. General layout of the Subscale Racetrack magnet.

II. SR01 and SR02 Magnet Design and Fabrication

A. Racetrack design and parameters

The design of small racetrack magnets SR01 and SR02 developed at Fermilab is based on the mechanical structure developed at LBNL for subscale models, but utilizes full-size cables used in Fermilab's high field magnets which have approximately twice the width. A general layout, showing the internal magnet components, is shown in Fig. 1. Table I contains the magnet general design parameters.

B. Strand and cable

The cable was manufactured at Fermilab, using two different types of stand: 1mm diameter PIT strands manufactured by Shape Metal Innovation and 1mm diameter MJR strands manufactured by Oxford. Both cables were rectangular in cross section (no keystone), contained 28 strands, and had overall dimensions of 14.2 mm x 1.84 mm for the PIT cable and 13.95 mm x 1.95 mm for the MJR cable, respectively. Before insulating, the cable was heat-treated at 200^{o}C for 30 minutes to reduce residual stresses incurred during the strand and cable manufacturing processes.

Cable insulation consisted of 0.250 mm thick and 13 mm wide S-2 Fiberglass tape, spiral wrapped onto the cable with a 3.3 mm overlap. To improve the stiffness of the insulation, an inorganic binder, CTD-1008®, was applied to the tape and cured at 80^{o}C for 30 minutes before wrapping onto the cable.

TABLE II
STRAND PARAMETERS

	SR-01		SR-02	
MANUFACTURER	SHAPE METAL INNOVATION		Oxford	
PROCESS METHOD	PIT		MJR	
Strand diameter, mm	1.00		1.00	
Cupper content, %	53.6		47.1	
Effective filament diameter, um	34		110	
FILAMENT PITCH AND DIRECTION	20mm, right		13mm, right	
Ic and N-VALUE @ 12 T	696*A*	45	832*A*	40
provided by manufacturer	728*A*	53	803*A*	35
			810*A*	42

TABLE III
CABLE PARAMETERS

	SR-01	SR-02
MATERIAL	PIT	MJR
Cable type	Rutherford	Rutherford
Dimensions, mm	14.20 x 1.84	13.85 x 1.95
Strand diameter, mm	1.00	1.00
Number of strands	28	28
Strand Jc by design (12 T 4.2 K)	2000	2000
Cu/Non_Cu by design	0.85	0.85
Keystone angle	0	0

Strand and cable parameters are summarized in Table II and Table III.

C. Coil fabrication

Both PIT and MJR coils were fabricated using the same procedures. To determine an estimate of the coil size after winding, stacks of both bare and insulated cable were measured at a range of pressures. These measurements were then used to determine the cavity size to be used in the reaction fixture during the coil heat treatment. The reaction fixture cavity size was shimmed to a thickness based on the insulated cable data taken at a pressure of approximately 14 MPa.

The two-layer, 26-turn (13 turns in each layer) racetrack coil was wound around an iron pole piece (as shown in Fig. 1.) with winding tension of 30 kg. Each coil layer required 6.5 m of cable.

Interlayer insulation, consisted of 2 layers of 1 mm thick spacer of S-2 glass. The spacer was fabricated at Fermilab by compressing 10 layers of thin S-2 glass cloth, filling with inorganic binder, and curing at 150^{o}C for 30 minutes.

Ground insulation was applied in a two-step process. First, a temporary layer of ceramic cloth was used during the coil reaction. This cloth filled the area between the coil and the reaction fixture and provided tiny channels for Argon flow during reaction. This layer was removed after reaction and replaced with a combination of sheets of S-2 fiberglass material and G-10 that covered the coils during the epoxy impregnation and became a permanent part of the magnet.

Heat treatment was performed inside a reaction retort at Argon atmosphere at 660^{o}C for both MJR and PIT coils. Specific reaction cycles varied for the two materials. For the PIT coils, the temperature was increased from room temperature by 25^{o}C/hour to 660^{o}C and remained at 660^{o}C for 170 hours. For the MJR coils, a multistage reaction cycle was used. The temperature first was increased from room temperature by 25^{o}C/hour to 210^{o}C and remained at 210^{o}C for 100 hours, then it was increased by 50^{o}C/hour to 340^{o}C and remained at 340^{o}C for 48 hours, and finally it was increased by 75^{o}C/hour to 660^{o}C and remained at 660^{o}C for 72 hours before cooling.

The splices were made after reaction. Each Nb_3Sn lead was sandwiched between two NbTi cables. Leads from both layers were soldered simultaneously in a special fixture made for this application. The splices were insulated with 0.05 mm Kapton. After the splices were made, six voltage taps were attached. One voltage tap was added at the coil midpoint later, after impregnation.

The coil was impregnated in an aluminum fixture with CTD-101® epoxy at a vacuum of approximately 75 µbar. The combined thickness of the iron pole, the coil, the end shoe and the horseshoe needs to be controlled to prevent the brittle conductor from over-compression. This was achieved by shimming the coil and the horseshoe with Kapton® sheets. Before shimming, tests on the assembly were done by bolting it together with Fuji film applied to the critical surfaces to check the pressure distribution. Results show that the pole island and the horseshoe are the most heavily loaded parts.

The area of maximum stress concentration was near the inner to outer layer transition at the pole. Due to the deformations created by bending the cable from inner to outer layer, a wave forms in the cable in the transverse direction, which continues to be evident for several turns. Where the wave crests, the cable tries to move out of its designated layer, causing intermittent high loading along the thin edge.

D. Racetrack assembly and mechanical measurements

After impregnation, the completed coil block was placed into a pre-assembled yoke structure with a bladder positioned between the coils and the yoke. The inflated bladder stretched the aluminum cylinder and compressed the coil block. Keys were inserted, which maintained load on the coil after the bladder had been deflated and removed. The coil stress was approximately 30 MPa when the cylinder was loaded to 270

MPa. Maximum stress in the various magnet components at different stages calculated with ANSYS is shown in Table IV.

TABLE IV
STRESSES IN DIFFERENT COMPONENTS (MPA)

	Bladders	300 K	4.2 K	Bmax
Al Cylinder	270	170	420	420
Nb3Sn Coil	30	16	20	40
Iron Yoke	360	160	480	480

A total of eight resistive strain gauges were installed on the aluminum cylinder for the purpose of measuring coil preload, as shown in Figure 2. Six of them were located at the middle of the magnet. Four are positioned to measure azimuthal stress: 1A-a, 1B-a, 1D-a, 1E-a. Two are positioned to measure longitudinal stress: 1G-l and 1H-l. 1A-a and 1D-a are the midplane-azimuthal gauges, and 1B-a and 1E-a are the pole-azimuthal gauges. Gauges 1C and 1F were located on the edge to measure the average stress across the cylinder thickness.

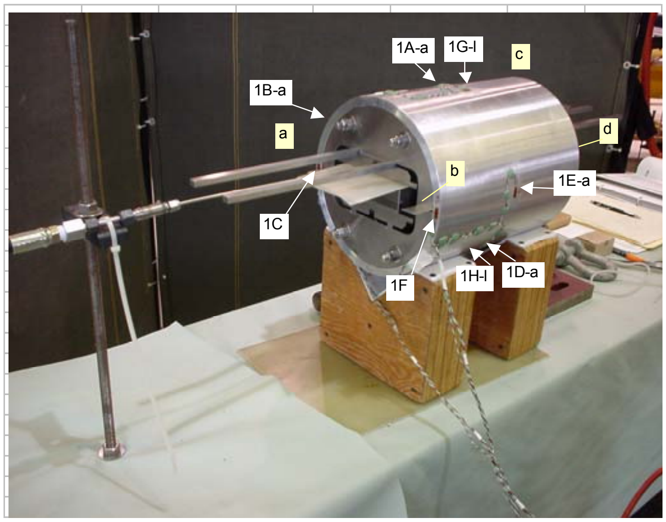

Fig. 2. Strain gauge locations are shown.

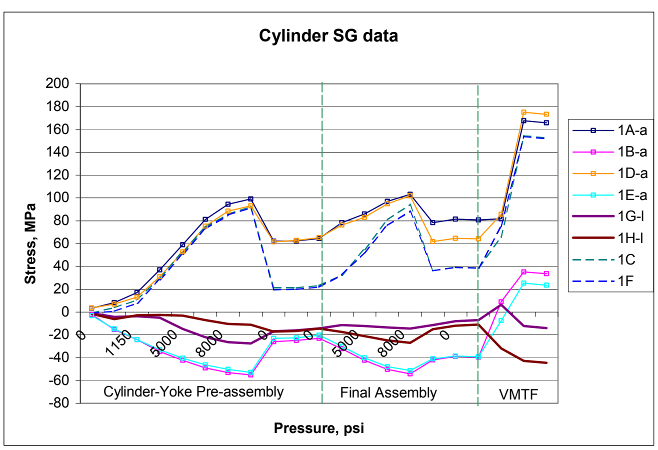

Fig. 3. Summary of the stress analysis is shown (better plot).

There were two assembly steps: cylinder-yoke pre-assembly and final assembly. During these steps, strain gauge data were taken and the outside diameter of the aluminum cylinder is monitored using a micrometer and pi-tape. Strain Gauge data are shown in Fig. 3. Gauges 1A-a and 1D-a were chosen as the main process indicators since they are located in the area which has the most uniform cylinder deformation. The maximum load reached on the shell was 103 MPa. Spring back after the keying process is completed is 25-30%.

III. TEST RESULTS

SR01 with PIT cable and SR02 with MJR cable were tested at Fermilab's Vertical Magnet Test Facility (VMTF) [3] which is capable of testing up to 4.5 m long superconducting magnets at 0-30 kA current range. These racetracks were instrumented with a minimal number of voltage taps. Two voltage taps were soldered to the leads and one of them to the center of the magnet to make two half coil voltage segments for protection. Two additional voltage taps were soldered right next to the NbTi side of the splices so splice measurements could be made. In order to be able to initiate a quench, a spot heater was installed on one of the coils. This heater was useful to check that the magnet protection circuits were functional before the magnet was fully energized.

A. *SR01 quench history*

SR01 was tested in February – March 2004. After the magnet was cooled down to 4.5 K a quench test was performed. The history of the quench test is summarized in Fig. 4. The first quench of the magnet occurred at relatively high current of 19292*A*. This current was already much higher than any previously built Nb_3Sn magnet at Fermilab. It took 14 more quenches at 20A/sec ramp rate to train the magnet. The maximum current value was at 23713*A*. This value is consistent with the calculated critical current value estimated by measuring critical current of strands at the Fermilab Short Sample Test Facility (SSTF) taking into account additional degradation of PIT cable due to its sensitivity to transverse pressure [4].

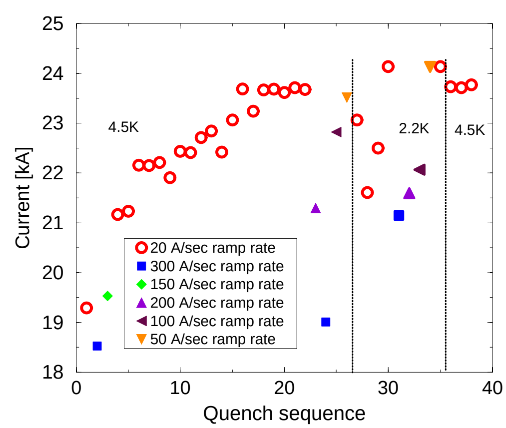

Fig. 4. Quench history of SR01.

In order to expose the magnet to larger Lorentz forces the magnet was cooled down to 2.2 K and quenched several times. Both low and high ramp rate quenches exhibited erratic behavior showing no sign of any training. Although the magnet quench current was much lower that what one would expect from any reasonable temperature parameterization of the quench current, we were able to increase the Lorentz forces within the magnet. So if the magnet was not trained at 4.5 K we should have accelerated its training. On the other hand if the magnet reached its critical limit value the quench current should not show any improvement once it is warmed up again to 4.5 K. From Fig. 4. one can conclude that the magnet quench current remained the same consequently the magnet reached its critical current limit.

B. SR02 quench history

SR02 was tested in June 2004. Training of this magnet was much longer than SR01. It took more than 20 quenches to reach a quench plateau (see Fig. 5.). However, this plateau was not very smooth indicating that the magnet didn't reach its critical current limit. After ramp rate studies we cooled the magnet down to 2.2 K and quenched the magnet 11 times. The quench current was erratic and lower than what was achieved at 4.5 K. After warming up the magnet again to 4.5 K the magnet quench behavior remained erratic. Magnet quench performance is limited by low field quenches which is consistent with theoretical and experimental studies of magnetic instabilities in Nb_3Sn state of the art strands and cables performed at Fermilab [5-8] .

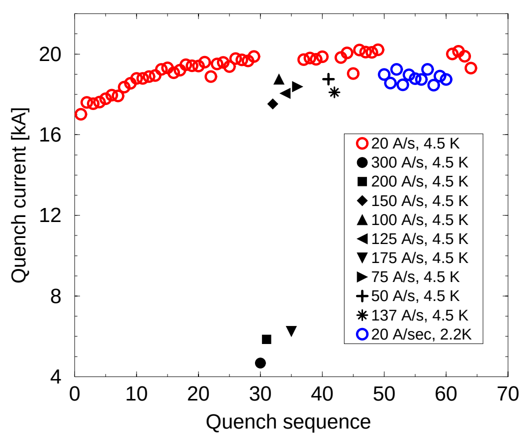

Fig. 5. SR02 quench history.

C. Ramp rate studies

After training ramp rate dependence studies were performed (see Fig. 6.). The quench current as a function of the ramp rate for SR01 follows a smooth curve indicating that the magnet has no other limitation than its critical current value. Quench current as a function of the ramp rate for SR02 however, was not a smooth curve.

TABLE V
SPLICE RESISTANCES AND RRR VALUES

	Lead splice 1 Resistance [nΩ]	Lead splice 2 Resistance [nΩ]	RRR
SR01	0.76	0.80	129
SR02	0.57	0.67	125

The error of the resistance measurement is about ±0.04 nΩ
The error of the RRR value is about ±5

D. Splice resistance measurements

Both SR01 and SR02 splice resistance values (see Table V) are small enough to ensure us that quench current limitation of SR02 is very unlikely to be associated with splice manufacturing issues.

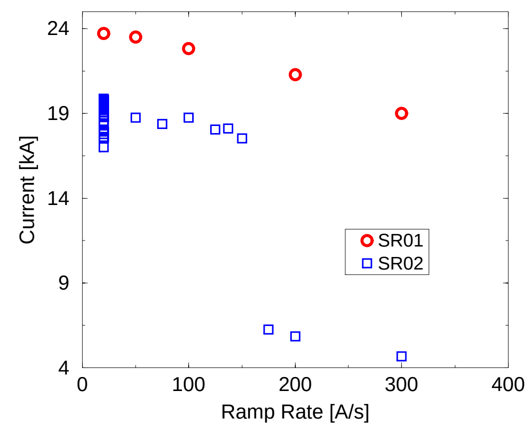

Fig. 6. Ramp rate dependence of SR01 and SR02.

IV. CONCLUSIONS

Two small racetracks were designed, built and successfully tested at Fermilab. SR01, which contains PIT conductor, exhibited excellent performance. It reached its critical current limit within 14 quenches. PIT cable was used in our last cos-theta dipole model HFDA05 with reached its short sample limit at 10 T field [9]. SR02, with MJR conductor had moderately good performance. Its quench current plateau value was much higher than the quench current value of any other MJR based model magnet due to higher RRR value, but it didn't reach its high-field critical current limit, which is consistent with [8].

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