Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

FABRICATION AND TEST RESULTS OF A NB$_3$SN SUPERCONDUCTING RACETRACK DIPOLE MAGNET*

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Abstract

A "proof-of-principle" Nb$_3$Sn superconducting dual-bore dipole magnet was built from racetrack coils, as a first step in a program to develop an economical, 15 Tesla, accelerator-quality magnet. The mechanical design and magnet fabrication procedures are discussed. No training was required to achieve temperature-dependent plateau currents, despite several thermal cycles that involved partial magnet disassembly and substantial pre-load variations. Subsequent magnets are expected to approach 15 Tesla with substantially improved conductor.

1 INTRODUCTION

Economical, high-field magnets are needed to reduce the overall cost of the next high-energy collider. Flat "racetrack" coils are believed to facilitate a reliable, cost-effective utilization of the brittle, high performance superconductors that are currently required to achieve high magnetic fields. The "Common-Coil" racetrack design (schematically shown in Fig.1), with two bores that share coils, has been proposed as a cost-effective design for future colliders [1,2]. Consequently, LBNL's high-field Nb$_3$Sn accelerator magnet development effort has shifted to the "Common-Coil" racetrack geometry. The ultimate goal of the program is to develop accelerator quality dipoles with fields up to 15 Tesla (T). This was approached by first building a lower field magnet (6T) to demonstrate the feasibility of the design, develop fabrication techniques and understand relevant performance parameters. Ultimate success will depend upon the development of high-quality, low-cost, high-field superconductor.

2 DESIGN

The design and early fabrication stages have been described elsewhere [3]. The physical parameters are briefly summarized in Table 1.

The conductor was manufactured by Teledyne Wah Chang Albany (TWCA) for the ITER project. Short sample measurements of single strands predicted a bore field of 6.6 T at short sample. A single measurement of a bifilar cable sample gave a lower value of 5.8 T. Additional measurements are in progress to verify the conductor performance, but as the quench data described below show, the magnet performance was more in line with the cable measurement.

The basic component of this design is the coil module, which consists of a double-layer, 40-turn coil contained in a support structure. The preliminary design was for a 10 mm aperture magnet (40 mm coil spacing) with emphasis on maintaining the simplicity of the racetrack geometry.

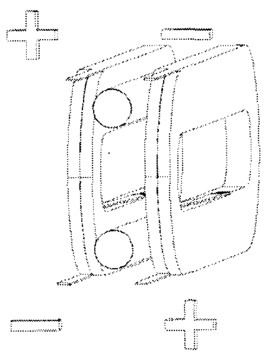

Figure. 1: Schematic of "Common-Coil" Magnet

Table 1: Racetrack Coil Specifications

Coil Geometry	Two, double-layer pancakes
Number of turns	40 turns/coil
Coil Inner-Radius	40 mm
Straight Length	500 mm
Coil-Coil Spacing	40 mm (Max. bore diam.)
Bore-Bore Spacing	150 mm
Transfer Function	0.71 T/KA (linear, no iron)
Cable	30 strand, Rutherford
Cable Size	1.45 x 12.34 mm
Strand	0.808 mm (ITER)
Manufacturer	TWCA
Jc (TWCA)	610 A/mm^2 at 12 T (4.2 K)
B_0 (Max, strand)	6.6 T
B_0 (Max, cable)	5.8 T
B_0 (Max, achieved)	5.9 T

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*This work is supported under contract #DE-AD03-76SF00098 by Director, Office of Energy Research, Office of High Energy Physics, U.S. Department of Energy

0-7803-5573-3/99/$10.00@1999 IEEE.

The coil-support system (Figure 2) permitted independent adjustment of each orthogonal pre-load, and easy modification of any coil module. Coil forces were supported within the coil module. A coil-edge pre-load was applied to the straight section via 50 mm thick Al-bronze rails running the full length of the coil package. The end-load was applied using a series of set-screws that loaded the coil end-shoes. The coil-face pre-load was applied via multiple tensioning rods, whose forces were transmitted via thick, side-by-side stainless steel bridging beams.

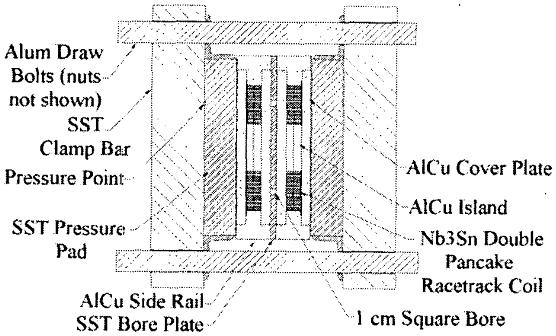

Figure 2: Magnet Cross Section

3 FABRICATION

The cable was insulated with a nominal 0.13 mm thick sleeve of woven S-2 glass. To reduce carbon deposits during reaction, the factory sizing is baked out and replaced with a palmitic acid sizing. However, there is still a minor problem with low resistivity of the epoxy. Alternatives are being considered.

Each double-layer coil was wound around a central island on a flat plate, with an inter-layer ramp to avoid an internal splice. Narrow strips of stainless-steel foil contact the cable at the intended voltage-tap locations. A 10 mm thick end-spacer was inserted after the 6th turn, to reduce the peak field in the coil ends.

After winding, the coil straight section was compressed to a predetermined size by bolting spacer-bars and side-rails onto the coil-face support-plates. End-shoes were installed, and the leads were carefully insulated and supported in their final positions. The coils were placed in a stainless-steel retort under positive Argon atmosphere and reacted according to the manufacturer's recommended reaction cycle (~2 weeks).

The reacted conductor is quite strain-sensitive, and must be protected from excessive strain. In preparation for supporting the conductor with an epoxy-glass matrix, each Nb$_3$Sn lead was carefully spliced to a pair of NbTi cables, and immobilized. The stainless steel side-rails and face-plates that were used during reaction were replaced with similar Al-bronze pieces that were designed to closely fit the post-reaction coil dimensions. A 1 mm thick shim was inserted between each side-rail and corresponding face-support plate that would permit post-potting coil loading via a thinner shim. Mica paper was added between the outer turn of each coil and the associated support pieces. This improved the electrical insulation and provided a potential shear plane away from the conductor. To further facilitate shearing, all coil support pieces were mold released before potting. These shear planes were intended to reduce shear stresses while coil-face and coil-edge pre-loads were independently adjusted.

The completed coil assemblies were vacuum impregnated to provide good internal conductor support, and produce robust coil modules for insertion into the coil support structure. All surfaces in contact with the coil during potting were left undisturbed, in order to provide good surface matching, without the stringent machining tolerances that were encountered with previous Nb$_3$Sn magnets, another potential cost saving feature of this design. The coil modules were stacked and aligned via pins. All loads from the adjustable external loading elements were transferred through the use of bearing rods or balls. This technique greatly reduced the need for high tolerances. Minor variations in coil module thickness and uniformity were accommodated with Kapton shims under the pressure pads.

3.1 Test Configurations

One philosophy in magnet design maintains that the coils should have sufficient preload such that under Lorentz loads the conductor maintains contact with the support structure. In order to satisfy this design requirement at fields over 12 T, the required room temperature preloads approach levels that could damage the conductor. Taking advantage of the flexibility of the RD-2 design, we have performed a series of tests with reduced horizontal and vertical preload. Three pre-load combinations (Table 2) were tested.

Table 2: Tested Coil Pre-Loads

Magnet	300K Horiz.	300K Vert.	4K Horiz.	4K Vert.
RD-2-01	14 MPa	50 MPa	30 MPa	30 MPa
RD-2-02	6 MPa	50 MPa	6 MPa	30 MPa
RD-2-03	6 MPa	21 MPa	6 MPa	7 Mpa

The initial test configuration (RD-2-01) was loaded sufficiently to maintain contact between the coil and all support surfaces (although insufficient to stop slippage during high excitation).

The second configuration (RD-2-02) had the coil-face pre-load reduced enough to insure that each coil would separate from its inner (bore) face-plate during excitation. This was done by replacing the aluminum tensioning rods with stainless steel, and reducing the room temperature pre-load.

The third configuration (RD-2-03) had its coil-edge preload reduced enough to insure that the inner turn would separate from the island during excitation. This was accomplished by changing the straight edge shim thickness, and re-adjusting the end load.

4 TEST RESULTS

4.1 Quench Behavior

RD-2-01 required no training and achieved a thermally dependent 4.4 K plateau current of 8.29 kA on the first ramp. The mechanically modified versions of the magnet (RD-2-02 and 03) performed identically to the original load configuration, despite the sizable differences in loading and loading histories. During the initial cooldown, 18 high current quenches were used to establish training, ramp rate, and temperature dependencies. Figure 3 shows the spontaneous quench history of the RD-2 series.

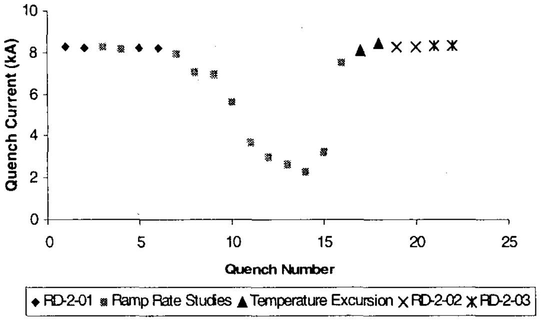

Figure 3: RD-2 Quench History

Initial ramp rates were 12 A/s. All quench initiations showed a thermal start characteristic, i.e. a gradual start with no evidence of a fast flux change, as was observed in previous Nb$_3$Sn magnet (D19 and D20) tests [4,5]. All quenches originated in the same area in coil-2, with the exception of the highest ramp rate, which occurred in coil-1. The quenches started simultaneously in both the high-field and low-field layers, within the multi-turn segments that spanned the coil's highest field region, at the approximate axial location of the inter-layer ramp, on the ramp side of the coil. Fast flux changes (probable motion voltage spikes) were monitored during the current ramps on the half-magnet balance (coil 1 – coil 2). Compared to the other Nb$_3$Sn magnets the number and magnitude of the voltage spikes were very small, exhibited unusually high frequencies and did not appear to be associated with the initiation of a quench. The magnet exhibited a monotonic-decreasing quench current as the ramp rate increased. No plateau was visible either at low ramp rates or the highest measured (540 A/s, 0.386 T/s), in contrast to the behavior of both D20 and D19. The temperature dependence at the quench current was measured at two additional operating points, 4.68 K and 3.88 K, shown in Figure 3.

4.2 Quench Propagation

Voltage-tap signals, and signal sequences, were very similar for all quenches (neglecting current-dependent amplitude and speed variations). At any current, the propagation speeds were similar with previous Nb$_3$Sn experience (6-10m/s), but varied considerably (5 – 21 m/s) with location, indicative of sizable variations in operating margin, ohmic power density, and/or heat capacity. Propagation speeds around the island-ends appeared to be considerably (1.5-2x) faster than in adjacent straight sections.

5 DISCUSSION AND CONCLUSIONS

A 6 Tesla, Nb$_3$Sn racetrack dipole magnet has been built and systematically tested under varying preload conditions. In every configuration the magnet reached the conductor short-sample limit without training and validated the simple fabrication features of this particular magnet design. A 14 T racetrack dipole magnet, utilizing the experience gained on the 6 Tesla magnet, is currently being designed [6,7] and is scheduled for completion later this year.

6 ACKNOWLEDGEMENT

We wish to thank our group of talented technicians for their indispensable contributions to the design and fabrication effort in this project – Bob Benjegerdes, Paul Bish, Doyle Byford, Hugh Higley, Roy Hannaford, Greg Hay, Nate Liggins and Jim Smithwick.

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