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Author

Gourlay, S.A.

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Design and Fabrication of a 14 T, Nb_3Sn Superconducting Racetrack Dipole Magnet*

S.A. Gourlay, P.Bish, S. Caspi, K. Chow, D.R. Dietderich, R. Gupta, R. Hannaford, W. Harnden, H. Higley, A. Lietzke, N. Liggins, A.D. McInturff, G.A. Millos, L. Morrison, M. Morrison, R.M. Scanlan

Lawrence Berkeley National Laboratory, Berkeley, California, USA

Abstract – **Most accelerator magnets for applications in the field range up to 10 T utilize NbTi superconductor and a cosine theta coil design. For fields above 10 T, it is necessary to use Nb_3Sn or other strain sensitive superconductors and other coil geometries that are more compatible with these materials. This paper describes our recent efforts to design a series of racetrack coil magnets that will provide experimental verification of an alternative magnet design philosophy, with the near-term goal of reaching a field level of approximately 14 T. The conductor and fabrication issues relevant to building high field, racetrack dipoles utilizing Nb_3Sn superconductor and a wind and react approach will also be discussed.**

I. Introduction

The ongoing program for the development of high field superconducting accelerator magnets at Lawrence Berkeley National Laboratory (LBNL) is centered on a simple racetrack coil geometry. In particular, we are concentrating on the common coil approach [1,2] for its potential simplicity of construction and consequent cost effectiveness. The design concept consists of a pair of racetrack coils shared between two apertures, producing fields in opposite directions. Our development program involves producing a series of tightly integrated model magnets with the eventual goal of achieving a field of 14 – 15 Tesla. Our first step towards this goal, a 6 Tesla magnet (RD-2) using Nb_3Sn conductor, has been successfully built and tested [3]. The next major step in our program is the construction of a magnet with a bore field of approximately 14 Tesla [4]. Designated RD-3, it will be the focus of this paper. As an interim project, the outer coils for RD-3 will be assembled in a support structure similar to that used for the 6 Tesla magnet and operated up to 12 Tesla, generating stresses that are a factor of 4 greater than the 6 Tesla magnet. This test configuration has been designated as RT-1 (Racetrack Test) in order to differentiate it from an actual magnet.

This next series of tests will be used as a means of exploring the design and fabrication issues relevant to progress towards higher field levels. Optimal field quality will be addressed later in the program.

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II. Design

A cross section of RD-3 is shown in Fig. 1. It contains nominally 3 coil layers; a double pancake outer coil and an inner coil, which consists of a full layer plus a 5-turn coil block. The virtue of the double-layer pancake coils is that the leads exit straight out the end of the magnet, allowing all splices to be external. The general magnet parameters are given in Table 1.

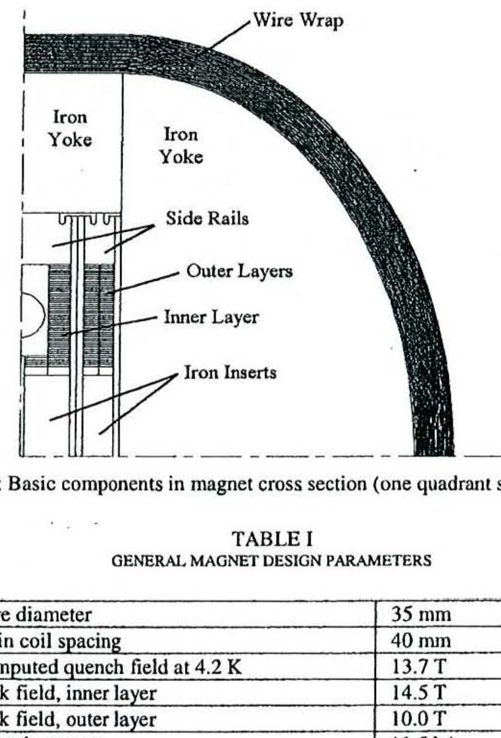

Fig. 1: Basic components in magnet cross section (one quadrant shown).

TABLE I
GENERAL MAGNET DESIGN PARAMETERS

Bore diameter	35 mm
Main coil spacing	40 mm
Computed quench field at 4.2 K	13.7 T
Peak field, inner layer	14.5 T
Peak field, outer layer	10.0 T
Quench current	11.5 kA
Number of main coil layers	1 + 3
Straight section length	500 mm
Number of turns (half magnet)	5+50+49+49
Nominal height of each main coil	80 mm
Minimum coil bend radius	70 mm
Vertical bore spacing	220 mm
Yoke outer height and width	300 mm
Total wire wind thickness	30 mm

At the highest field ranges, conductor performance is one of the key issues. The conductor for the next magnet has been produced and tested. Table II lists the primary conductor and cable parameters.

TABLE II
CONDUCTOR AND CABLE PARAMETERS

Strand	Inner	Outer
% Cu	51.3	59.5
I_c (12 T) amps	485	446
J_c (12 T) A/mm^2	1981	2190
I_c (15 T) amps	250	230
J_c (15 T) A/mm^2	1021	1129
Length/pieces	9035 m/16	5000 m/14

Notes: Both inner and outer strand wire are 0.8 mm diameter. Manufacturer: Oxford Superconducting Technology. Jc refers to non-copper area.

Cable	Inner	Outer
Strand Number	40	26
Thickness (mm)	1.418	1.408
Width (mm)	17.159	11.338
Length (m)/coil	210	387

A. *Quench Protection*

Quench protection of the coil is accomplished by heaters located on each side of the double pancake winding. These heaters raise part (~90%) of the turns' temperature over $T_c(H)$ for most (~80%) of their length. In this scenario, large voltages to ground are minimized because of the distributed nature of the effective heater pattern, circuit and thermal time constants and the resistance ratios. Within 40 ms or less after the heater firing, the magnet is driven normal, essentially due to eddy current heating, as the ramp down exceeds the critical rate. This process should limit the temperature excursion to < 200 K (adiabatic calculation) and probably < 150 K with the resulting voltages < 400 V.

III. MECHANICAL CONSIDERATIONS FOR HIGH FIELD MAGNETS

The construction of magnets at higher fields requires careful consideration of mechanical support structure issues. Relative to the 6 Tesla magnet (RD-2) the 14 Tesla magnet will have forces 5 times higher. The support structure must be designed to minimize coil movement and shear stress at conductor/support structure interfaces. Magnetic field considerations require as little material as possible between the bore and the conductor in order to have a more efficient cross section. Cross sections which have good magnetic field quality are intrinsically more complex. The 5-turn block on the inner coil of RD-3 simulates a possible field quality structure. It is subject to various shear forces during fabrication, cooldown and excitation. Thus the composite coil strength becomes very important.

IV. COIL MODULE PRELOAD SCHEME

To maximize the bore field and provide a more efficient cross section, the amount of material in the support structure between the bore and the inner conductor and adjacent coil layers, must be minimized. This requires the use of thin sheets of stainless steel "skins", replacing the thick aluminum bronze plates used for RD-2 [3]. The previous method of using fasteners screwed into the aluminum bronze plates will be replaced by welding these skins to the module while being loaded hydraulically in the vertical and axial directions.

A. *Vertical Preload*

New procedures present the greatest uncertainty in the fabrication process. The preload scheme was considered the critical new step in the construction of RD-3. To gain familiarity with the new preload scheme, a simple half scale test was performed in January 1999. A small one-layer racetrack was wound and epoxy impregnated using standard procedures. After potting, a support structure was assembled around the coil and its skins. Both cold worked Nitronic 40 skins were instrumented with four resistive strain gauge bridges to measure the strains during the procedure (see Fig. 2)

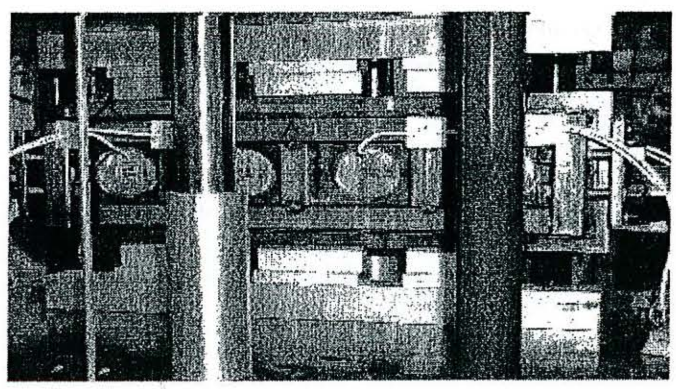

Fig. 2 Skin weld test setup.

The computed skin strain is plotted in Fig. 3.

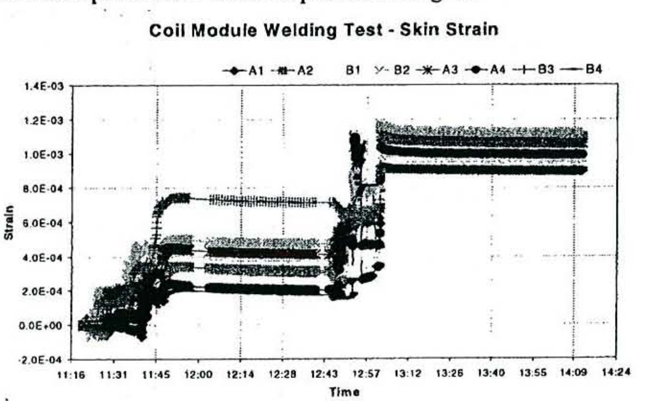

Fig. 3 Skin strain during welding procedure.

The first jump in strain occurred when the skin was skip welded to position it. The second increase was due to the final welding step. Upon removal from the press the final strain on the skins was about 0.1 percent. The strain gauge output was also used to calculate the final vertical preload on the coil module. Table III summarizes the test results. The difference in final measured preload to theoretical preload is about 30%. The large difference in stress between the original state in the press and the final stress can be attributed to the very thin 1.25-mm skins used in the experiment. The stress difference will be lower in the RD-3 magnet since the skins will be twice as thick (when scaled).

TABLE III

SKIN STRESS IN VARIOUS FABRICATION STAGES

Stress	Value in MPa
In Press	-151
Theoretical Final Preload	-52
Final (Measured) Preload	-39

B. Axial Preload

Integrated Lorentz forces at the magnet ends act to stretch the coil axially. Additionally, the local force distribution acts to compress the coil ends. A preload scheme is used to preload the coil axially to minimize the coil stress at the ends. The preload is accomplished using a methodology similar to that for the vertical preload: the end shoes are pressed towards the magnet center and welded to the skins. The axial preload operation is performed simultaneously with the vertical preload operation.

To minimize the coil stress, the axial preload must provide enough support when the coil is energized. Since the end is circular in shape, a preload level that is too high results in bending of the coil end and subsequent high cable tension at the innermost turn and high compression at the outermost turn. A preload level that is too low results in bending in the opposite direction (high compression at inner turn, high tension at outer turn). Coil stress is minimized when the preload is adjusted to yield stress contours that are similar to stress contours in solenoids: the contour lines are constant azimuthally. Fig. 4 shows stress contour plots for stress normal and parallel to the cable for the outer module when the magnet is energized. The maximum compressive stress normal to the cable occurs at the end of the straight section near the center turns. The innermost turn maintains contact with the island at the ends—following the same philosophy as for vertical preload. To provide the correct axial preload, the axial preload applied at room temperature is half that of the vertical preload. Since the axial and vertical room temperature preloads are at different levels, the end is placed in some bending at room temperature. The room temperature coil stress due to this bending is not an issue because they are substantially lower than levels when the magnet is energized. During cooldown, the differential contraction between the different components (iron island, coil, skin, side rails) results in an increase in the axial preload. A study of the coil modules through all stages of magnet assembly provides assurance that the coil stress peaks during magnet energization (and not preloading) and overall stress levels are minimized.

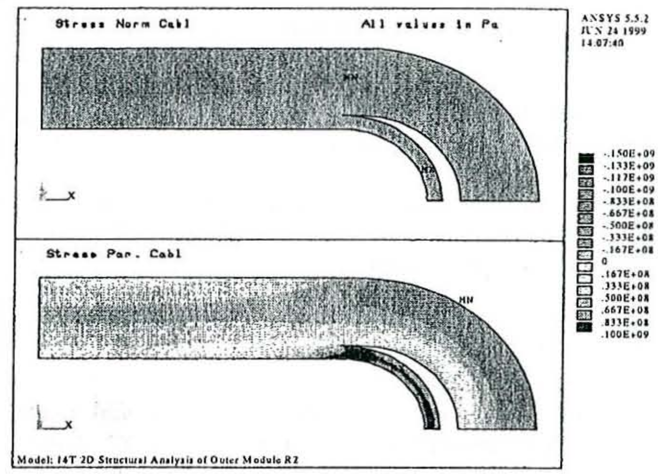

Fig. 4: Contour plot of stress normal and parallel to cable at coil ends for outer coil module.

V. Composite Material Strength Tests

Finite element modeling can estimate the stresses in proposed magnet designs. However, empirical data on material strengths, especially on new composites, is required to identify problems. As a complement to computer simulations, material tests have been performed to determine the strength of the interface between layer 1 and layer 2. As can be seen in Fig. 5, the shear stress between these layers could exceed -35 MPa while the module is in the vertical press in preparation for the welding of the skins. Testing determined that the strength of the interface at room temperature ranged between -24 to -32 MPa. At 77 K, the strength of the interface increased to -61 MPa. Concerns about possible failure during preloading of

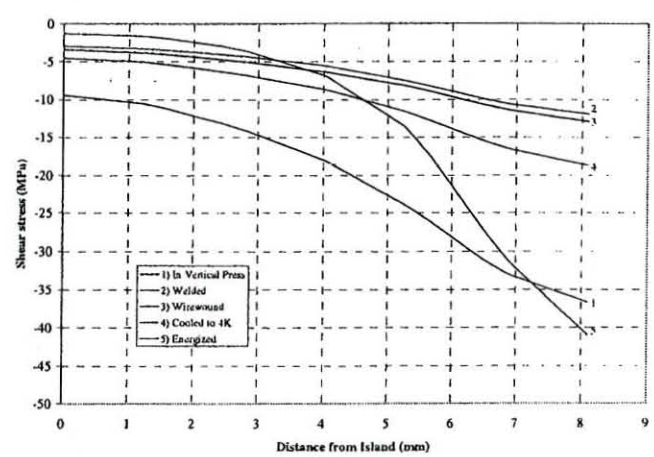

Fig. 5 chart of shear stress at interface between layer 1 and layer 2.

Some things to note about the shear stress chart:

- Values are obtained from an ANSYS analysis
- "in vertical press" means the inner coil module is placed in the press and a preload of 72 MPa is applied.
- "welded" means the thin skins are attached and module is released from press. Springback of thin skins after welding is not included.
- "wirewound" means the coil module is assembled with the outer module and yokes and 30 layers of wirewinding is applied.
- "cooled to 4K" means the complete magnet assembly is cooled to 4 K from 293 K.

the interface prompted a series of new tests with modified structures. Both proposed designs (see Fig. 6) included a sheet of S2 glass across the shear interface for increased strength.

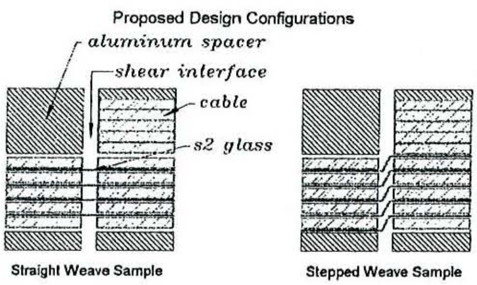

Fig. 6 Shear test samples

The results proved encouraging as both samples failed at much higher stresses. These designs are now being considered for the inner coil modules. Table IV lists the results for some of the samples tested.

TABLE IV

SHEAR SAMPLE TEST RESULTS

Sample	Failure Shear Stress (Mpa)
Standard Sample - set #1	-32
Standard Sample - set #2	-24
Standard Sample - LN_2	-61
Straight Weave Sample	-44
Stepped Weave Sample	-50

IV. Fabrication

The fabrication steps differ in only a few instances from those used on the previous magnet [3]. The cable, insulated with woven glass sleeving is wound around an iron island or "pole-piece". A 3 mm gap in the island is used to allow for differential contraction during the high temperature heat treatment of the coil. All metal surfaces in contact with the coil or support structure are covered by binderless mica paper to help prevent shear build-up between the coil and support structure that might cause premature quenching during excitation. The coil is then sized to a dimension determined via 10-stack measurements and enclosed in a stainless steel reaction fixture consisting of two 25 mm plates and side rails, fastened with Inconel 718 bolts, preferred because of their high strength at elevated temperatures. The coil package goes through a heat treatment schedule to form the Nb_3Sn, which reaches a maximum temperature of approximately 680 ^{0}C for 2 weeks. Following reaction, a pair of NbTi cables are spliced to the fragile Nb_3Sn leads. The splice regions are later impregnated into the coil package. The stainless reaction fixture is replaced with stainless steel side and end bars and a pair of 4.75 mm thick Nitronic 40 "skins". The assembled coil package is then vacuum impregnated. All surfaces in contact with the coil are mold released and covered by mica paper. The coil module is then placed in a preload fixture and the skins are welded. The completed coil modules are then assembled with the iron yokes and wire wound to obtain the necessary horizontal preload.

VI. Summary

The engineering design of a Common Coil geometry dipole magnet with a predicted bore field of approximately 13.7 Tesla has been completed. Mechanical tests have been performed with some of the new design features, such as the new preload scheme that uses thin "skins" to provide both vertical and horizontal prestress. Measurements of the composite indicate that the shear strength at certain critical interfaces needs to be improved.

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