Design and Construction of a Hybrid — Nb$_3$Sn, NbTi — Dipole Magnet

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Abstract—A two layer superconducting dipole magnet — D19H, with a Nb$_3$Sn inner layer and a NbTi outer layer was designed, constructed and tested. The 50mm bore inner layer of an existing NbTi dipole magnet (D19A), has been removed and replaced with a Nb$_3$Sn coil. The outer NbTi coil, collars, iron yoke, ring, collets and outer skin from the disassembled D19A magnet have all been reused. Employing glass insulated cable with aluminum-bronze poles and end spacers the Nb$_3$Sn coil was reacted at 660°C for 240 hours and fully epoxy impregnated. The design and construction of the magnet are described and test results reported elsewhere in these proceedings[1].

I. INTRODUCTION

The High Field Magnet Group at Lawrence Berkeley National Laboratory (LBNL) has been involved in R&D of superconducting accelerator magnets and cable, for over 25 years. In the early 1990’s following the successful test of a 7.63 T (4.35K), 10 T (1.8K) NbTi dipole, the group assumed an increased R&D effort on Nb$_3$Sn superconductor technology by constructing a high field, 13T, dipole magnet (D20)[2]. Experience with the D20 magnet made clear the differences between NbTi and Nb$_3$Sn technology and has shown that sufficient engineering details that may be acceptable with NbTi magnet R&D are insufficient with the brittle Nb$_3$Sn conductor. Areas where NbTi magnet construction have been left for the technicians to fill in are no longer acceptable and the design of a Nb$_3$Sn magnet can only be effective if it is fully engineered and completed to its last three dimensional detail. While the D20 effort is still underway, the group has decided to demonstrate its revised concept of Nb$_3$Sn technology by investing into a fully 3D CAD package (ProEngineer), and demonstrate the D20 experience and advanced software tools in the construction of revised dipole D19H with a hybrid of Nb$_3$Sn inner layer and a NbTi outer. Magnet D19A[3] has been disassembled and its inner NbTi layer replaced with a similar Nb$_3$Sn coil, while reusing the outer NbTi layer and slightly modified collars with identical yoke and skin. The details of the design and some test results are described in this paper.

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II. MAGNET DESIGN

A. Magnetics

D19H is a two layer “cosine-theta” dipole magnet very similar to a high field 50mm bore magnet D19A built as a possible alternative for the SSC main dipole. The concept was to replace the inner NbTi layer with a Nb$_3$Sn test coil and reuse the outer NbTi layer. Winding, reacting and epoxy impregnating the Nb$_3$Sn coil and assembling it with the old D19A NbTi outer layer, collars yoke and structural components was an effort that took about nine months to complete. The revised magnetic design of the inner layer (Fig.1) had to accommodate the increase in the cable insulation thickness as well as the reduction in keystone angle. As a result, the number of turns was reduced from 20 to 18 and the pole angle reduced from about 74.5° to 70.5°. Minor changes in the radial build up between the two layers were also required especially in the high field region where splices between Nb$_3$Sn and NbTi had to be made.

Based on short sample values of $J_c$ (Table I) the magnet was designed to be layer two limited. The central field was expected to reach 7.73T at 4.3K and 9.96T at 1.9K with a current of 7285A and 9903A respectively. The field in the end and splice joint regions was calculated and sufficient iron surrounding such areas was removed to reduce the local field and insures extra margin. The total Lorentz force on the midplane, expected to reach 22 MPa at 10T, will be taken care
of by prestressing the coils. The total axial force of 246KN will be taken care of by end plates. The magnet is about 1m long and has an inductance of 0.006 H/m.

Table I Measured current density of Nb$_3$Sn layer 1 conductor

| $J_c$ (A/mm$^2$) | Twente U$^*$ (cable) | BNL (cable) |
|-----------------|---------------------|-------------|
| 6T              | 4350                | 4350        |
| 8T              | 750                 | 2917        |
| 10T             | 517                 | 1950        |
| 11T             | 410                 | 1580        |
| 14T             | 480                 |             |

B. Magnet design

Although many of the magnet components have been recycled from D19A, the inner layer had to be fully engineered. A cable with dimensions similar to the old SSC inner cable was made from 30 strands of IGC wire. To avoid possible leakage of tin during reaction, about half, 0.6°, of the D19A keystone angle was used. The cable and copper wedges were all insulated with a sleeve of S2 glass, 0.117mm thick. End spacers machined from solid round bars of aluminum-bronze (bronce C64200) were plasma sprayed with alumina (0.127mm thick) for extra insulation. Bronze pole spacers were plasma sprayed along the conductor side only. During winding, a constant tension of 133N was applied and cable was carefully guided around the end spacers to avoid strands from popping out. Initial winding tests have shown that the plasma spray and cable insulation are insufficient in preventing shorts, therefore, an extra wrap of glass, 0.10mm thick, was placed around all turns adjacent to bronze spacers. Special tooling had to be made to position the cable around the ends and maintain a good fit between cable and spacers. Following the winding operation midplane stainless steel bars were used to compress the coil azimuthally and a glass tape under tension (90N) was wrapped over the coil and mandrel, keeping them radially in contact. The coil and mandrel assembly were then placed inside a reaction cavity in a manner that radially confined the coil between the mandrel and cavity walls while azimuthal pressure was applied by the side bars. The ends were free to move axially (this was proven later to cause the end shoes to move out and open a gap with the coil). Finally, the coil and cavity were placed inside a retort which was then installed inside a reaction oven. The magnet final radial build up and overall parameters are listed in table II and III.

C. End spacers

The end spacers were designed using the program Bend[4] in a process outlined in Reference[5]. The connecting points between the outer and inner edges of a surface were sent electronically to the shop and prepared for use on a 6-axis Electro Discharge Machine (EDM). Out of a single prefabricated aluminum bronze cylinder with dimensions that match the conductor radii of layer 1, several end spacers could be made. Since the overall process required very little human intervention and was proven to be cost affective the pole spacers of both layer 1 and 2 were made that way as well.

III. REACTION

With the coil secured in the cavity and placed inside a retort and into a reaction oven a supply of liquid argon was connected to the retort and constant flow was applied during
the 3 weeks of reaction in a process described in Table IV below.

| Operation                        | Temperature °C | Time (hr) |
|---------------------------------|----------------|-----------|
| Ramp to Cu and Sn conversion into CuSn alloy | 210           | 100       |
| Stabilization                   | 340            | 48        |
| Reaction                        | 660            | 20        |
| Cooldown                        | 200            | 43        |

**IV. MAGNET ASSEMBLY**

With the impregnation completed, each half of the inner layer appeared as a solid cylinder. The original outer coil, formed with B-stage epoxy, had no poles. For ease of assembly, bronze pole pieces were inserted into the pole space of layer 2 replaced and the pole tabs on the stainless steel collar were removed. A special slot was machined into the poles to support the high field joint. The final NbTi to NbTi splice between layers, was made in the “hockey stick” region similarly to the way it was done in D19A.

**D. Splice joints**

Layer to layer splice joints were made in the high field region and lead splices were made just outside the coils near the end. In the high field region the cable of the inner layer was ramped radially outwards from the pole region forming an S shape bend approximately 100mm long (see Fig. 2). The cable in the ramp region was secured within a bronze cavity and was extended axially an additional 100mm to make room for the splice. A NbTi cable placed along each side of the reacted Nb3Sn was soldered inside a copper box assembly. To assure a more uniform joint and maintain temperature control during splice soldering we have developed a resistance-soldering system that uses carbon electrodes above and below the conductor. The temperature is controlled and a chart recording is made. A typical joint is 12mmX80mm and takes one to two minutes to fuse. Resistance measurements made on several typical joints indicated an average resistance of less than 0.6nΩ at 6T. The low field splice joints to the leads were made in a similar fashion.

**E. Epoxy impregnation**

After the splice joints were made, temperature sensors were added and all connections to the voltage traces completed. The coil was ready for epoxy impregnation. Sealed within an encloser and pumped on for approximately 12 hours the coil temperature was raised and maintained at 55°C for an additional 18 hours. A mix of CTD-101 epoxy (Composite Technology Development, Inc.) was prepared and the coil was impregnated over a 10 hour period. At that point a curing cycle began that followed the manufacture schedule shown in Table V.

| Operation   | Temperature °C | Time (hr) |
|-------------|----------------|-----------|
| Ramp to     | 55 to 110      | 3         |
| Hold        | 110            | 5         |
| Ramp to     | 110 to 125     | 3         |
| Hold        | 125            | 16        |
| Ramp to     | 125 to 50      | 8         |

Both layers were assembled with the aid of collars. A series of assembly tests were made to establish the proper amount of shimming between layers and between layer 2 and collars. It was realized that in order to achieve the required prestress on the coils and in particular on the Nb3Sn inner layer, a radial interference needs to be introduced between both layers. This is in opposition to the use of azimuthal shims usually placed between pole turns and collars. With the help of strain gauge blocks installed inside the pole pieces of both layers and the use of pressure sensitive paper, a combination of radial shims including ground plane insulation on all coils (including midplane) were experimentally determined. After collaring, the azimuthal prestress on layer 1 was 7Mpa and that of layer 2 16Mpa.

A final prestress of 66Mpa and 76Mpa on layer 1 and 2 respectively was reached after ring and collets were assembled outside the yoke halves. In the same way as it was done during the D19A assembly, the yoke halves were placed around the collared coil and aligned to both collars and aluminum bars. Ring and collets were then placed around the yoke and axially pressed, exerting a final prestress on the coils. At the point were the rings were fully situated a control gap of about 0.178mm remained between the yoke halves.

A cylindrical shell 6.35mm thick, was welded around the rings and a special weld made to the flanges on both ends.
Special plates were installed between flanges and coils and a small axial pressure of 4.5MPa was applied to both layers.

V. MAGNET TEST

The magnet was tested both at 4.35K and 1.7K. At 4.35 it reached a plateau of 7.56T, 7360A on quench number 7. All quenches originated in layer 2 and there were no detectable quenches in the Nb$_3$Sn layer. The magnet had low ramp rate sensitivity and a rate of 20A/s was used throughout most of the test. At 1.7K the magnet started training at 7949A and after about 40 quenches has reached a central field of 8.99T at 9092A. When the test was terminated there was no sign that short sample performance has been reached in any of the layers. Many quenches seemed to start in both layers almost simultaneously (within 1 ms). Few quenches originated along the pole and none started in any of the joints or the ramps. When quenches started in the NbTi coil it usually was preceded by a fast motion event detected on the data acquisition system, quenches associated with the Nb$_3$Sn coil have shown no fast motion events and usually seemed to propagate slowly. Strain gauge measurements have indicated that both coils have retained their azimuthal prestress, however there was evidence that the original low axial prestress on the lead end had just about vanished during cool-down. In addition over the training period there was evidence of a ratchetting effect on the ends and small increase in axial prestress was measured. Farther interpretation of the results concluded that the very low axial prestress may be the cause of slow training.

In Figure 4 below data of the measured central field is plotted together with its calculated values. As previously mentioned many of the test results are presented in another paper in these proceedings[1].

At the time the paper was written the axial end load has been increased to 25MPa and the magnet was prepared for another test.

VI. CONCLUSION

The technology for winding, reacting and potting of Nb$_3$Sn coils combined with manufacturing techniques of magnet components and splices will considerably improve future R&D of such complicated magnets.

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