A LAYER-WOUND, 8.7-TESLA SUPERCONDUCTING DIPOLE MAGNET*

W.V. Hassenzahl, S. Caspi, W. Gilbert, C. Peters, J. Rechen, C. Taylor
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Introduction

The superconducting dipole magnet (D-9B) described in this report is similar in construction to a previous model coil (D-9A) described in detail in Reference 1. In this paper we discuss the features of D-9B that are different from those of D-9A and the results of tests in He I at about 4.3K and in He II between 1.8 and 2.16K. (Because of the space limit here and the extensive references in Reference 1, few references are cited here.) The development of D-9A and D-9B is part of a program at the Lawrence Berkeley Laboratory to establish the technology of 8 to 10T accelerator dipoles. The performance of the magnets D-9A, and D-9B, and D-10B (described in the preceding paper in these proceedings Reference 2) show that dipoles can operate successfully at least at the lower end of this field range.

Summary

A photograph of the completed D-9B magnet is shown in Fig. 1, and a cross section is given in Fig. 2. In construction this coil is quite similar to D-9A. The coil consists of four layers of superconductor in the form of a Rutherford cable. Each layer is composed of two halves that are fabricated separately and are assembled onto a stainless steel bore tube. The straight sections of the coil are self supporting and do not touch the bore tube. A barber-pole wrap of nylon is applied after each layer as an assembly aid and to produce some compressive prestress in the coil. After all four layers are assembled, stainless steel rings and aluminum collets are used to apply a large prestress to the coil.

D-9B Construction

As in the D-9A dipole, one of the goals in fabrication was to produce sufficient precompression in each of the four layers to maintain the first turn of each layer in positive compression against its respective pole island during operation at the highest current. In other words, Lorentz forces would not be able to move the first turn away from its adjacent pole island.

Target values for the precompression (column 4, Table I) were determined for each layer as follows. The calculated change in pressure due to cooldown (column 2, Table I) was added to the uniform circumferential compression required to move the first turn of conductor the same distance as the Lorentz forces (column 3, Table I). The actual compression achieved at assembly, the pressure after the coil had 48 hours of room temperature to relax are also given in Table I. The pressure was also measured after cooldown. These values, which are much smaller than expected are given in the last column of Table I.

The compression was measured using strain gauge instrumented aluminum blocks fitted into slots in the glass-epoxy pole island. One gauge block was used in each layer. The gauge blocks had full bridge circuits and used 4K rated strain gauges. Each gauge block (7.1x6.3x25.4 mm^3) was calibrated in place in the pole island and this calibration was rechecked

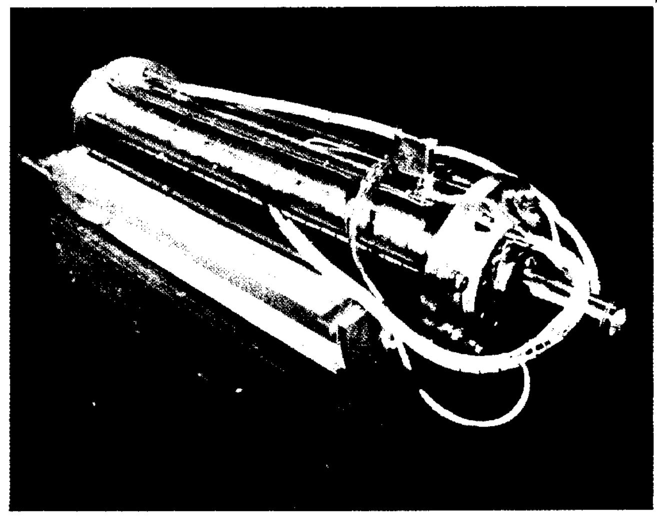

Fig. 1. The completed 4-layer D-9B coil mounted in a cradle for insertion in the test cryostat.

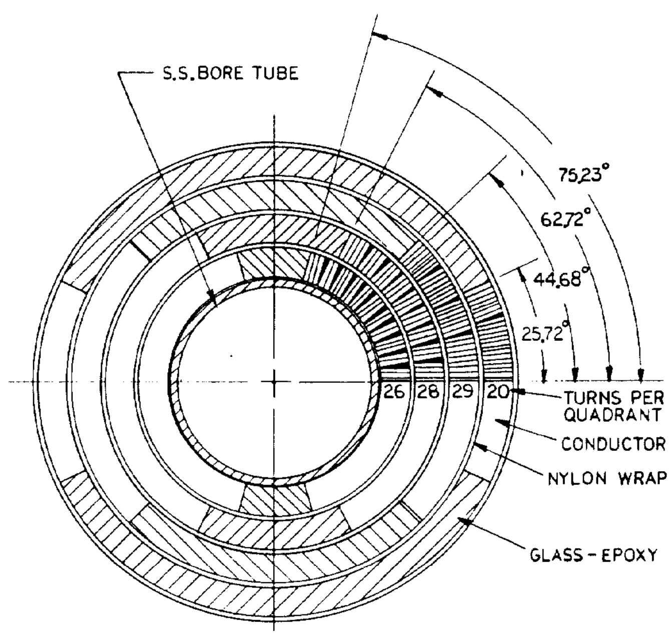

Fig. 2. A transverse cross-section of the 4 layer D-9B coil showing the number of turns and the upper angle for each layer.

*This work was supported by the Director, Office of Energy Resesearch, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

TABLE I

Circumferential Pressure in D-9B During Various Stages of Assembly

Layer	Change at Cooldown (MPa)	Lorentz Equivalent (MPa)	Target Precompression (MPa)	Actual Pressure at Assembly (MPa)	Pressure After Creep (MPa)	Pressure After Cooldown (MPa)
1	20.7	63.7	84.4	100.4	89.8	21.4
2	13.8	60.3	74.1	60.1	54.9	16.1
3	6.9	45.3	52.2	24.1	18.3	0
4	0	11.4	11.4	69.0	-	-

during assembly by applying pressure with a set of assembly clamps.

One point of construction which was different in this model from the former D-9A model was the method of splicing together layers one and two. Formerly, the leads from these two layers were brought radially to the outside of the structural rings and a solder splice made. In this model, the two leads were soldered together and folded into a groove (parallel to the bore axis) in the G-11 end filler piece of layer 3.

The transverse cross section of D-9B is slightly different from that of D-9A. The main reason for the different angles and number of turns is the use of different conductors. The upper angles of each layer and the number of turns in each layer are given in Table II. This configuration produces the loadline given in Fig. 3.

TABLE II

Design angles and number of turns in each layer of coils D-9A and D-9B

	Angles (°) D-9A	Angles (°) D-9B	No. of Turns D-9A	No. of Turns D-9B
Layer 1	75.23	75.23	28	26
2	53.40	62.72	27	28
3	41.00	44.68	26	29
4	23.6	25.72	18	20

III Conductor

The Rutherford cable used in the inner two layers of D-9B is different from that used in the lower-field, outer two layers. The magnet design is based on having the widths of the cables (the thickness of the layer) the same but the thickness of the outer layers' cable some 30% less than that of the inner layers' cable. Thus the current density in the outer layers is increased by this 30%. Fabrication delays in the thinner cable that was originally planned forced us to use a different cable, generously supplied to us by Dr. Richard Lundy of Fermi Lab.

Layers 1 and 2. A 21 strand cable was supplied by Oxford Airco, Inc. This rectangular cable, after final sizing, is 1.3 mm x 7.8 mm (0.052" x 0.318") and consists of 21 strands having a diameter of 0.030". The copper to superconductor ratio is 1.0. The diameter of the 620 NbTi filaments is 21 μm. Each strand was insulated with Stabrite before cabling.

The individual strands and the final cable were performance (short sample) tested by Oxford Airco at 4.2K and the data are shown on Fig. 3.

Layers 3 and 4. A 23 strand cable, called the low β quad cable, was supplied to us by FNAL. Externally this is a standard size FNAL cable with 23-0.68 mm diameter strands and with the standard keystone angle built in. However the copper:S.C. ratio is reduced to 1.3 and the number of filaments is reduced to approximately 500, yielding a filament size of 20 μm. Each strand is insulated with Stabrite before cabling. The composite strands are supplied by IGC and the cabling performed by New England Electric Wire Corp. The cable was measured for critical current capability at 10 Tesla and 1.85K by A.D. McInturff of FNAL and his data are somewhat less than that shown in Fig. 3.

Previous measurements made by Dr. Yuki Iwasa[3] of the Francis Bitter Magnet Lab at MIT have shown that, for the NbTi we are using, the critical current curves for 4.2K and 1.8K are nearly parallel to each other and almost exactly 3 Tesla apart. The expected critical current curves at 1.8K are shown in Fig. 3.

Test Results for Coil D-9B

Results in several different areas are presented. First the quench or training history of the coil is

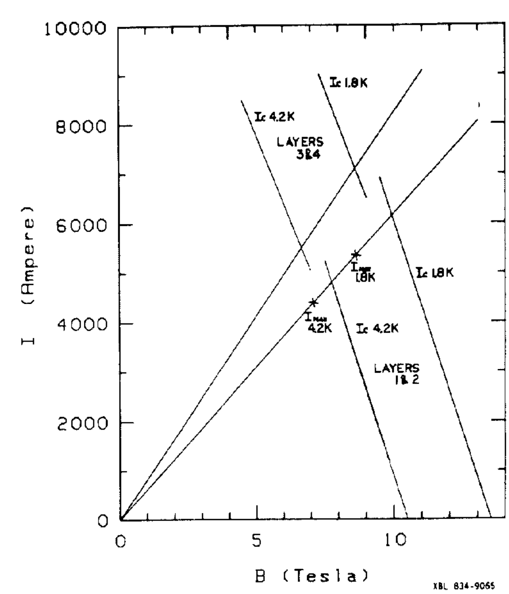

Fig. 3. Load lines for layers 1 and 3 and critical current values for the conductor in layers 1 and 2, and 3 and 4.

described, followed by a comparison of the calculated and observed central field. Then the losses measured by a calorimetric method in He II are given and compared to other coils. Finally the performance of the coil at short sample with the quench protection system disabled is described.

The observed load line in the coil, as determined by a hall probe and magneto resistance probes calibrated at LBL, agrees with the calculated value to about 1%. The load lines for layers 1 and 3 are also shown in Fig. 3. Both halves of layer 1 were seen to quench during the training process and oftentimes both became normal during a quench. We suspect the critical current of the conductor as wound in the magnet, is the observed 5320A in He II and 4420A in He I. Thus the conductor critical current is somewhat less than the value predicted by the manufacturers measurements.

The quenches observed in D-9B are shown in Fig. 4. The first quench was in He I at 3250A, is about 70% the maximum current, 4420A, which was observed in He I after operation at 1.8K in He II. After 33 quenches the coil reached 4270A before some ramp rate studies were performed. One training quench was observed in He II at 4800A at 2.0K. Subsequently several quenches were observed at the material short sample current which varies a few hundred amperes between 1.75K and the lambda point.

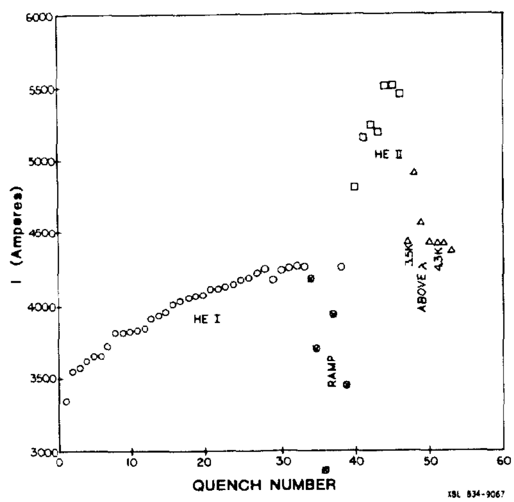

Fig. 4. Training history of D-9B

The slow training of D-9B in He I, in contrast to the lack of training in D-9A is attributed to the different levels of prestress in the two coils. (During charging the compressive load in the inner layer of D-9B was observed to decrease to zero at about 3500A.) In addition, the low copper to superconductor ratio of the inner two layers may decrease coil stability.

The losses in D-9B were measured calorimetrically in He II. These losses are given in Fig. 5 along with the values for D-9A and D-10B.[2] The difference in the curves can be attributed to the different filament sizes, and the different quantities of conductor in the coils.

The Colliding Beam Accelerator magnets[3] are "self protecting" in the sense that when a quench occurs in one of these coils essentially all of the stored magnetic energy is deposited in the coil and the maximum local temperature does not exceed a safe value. A large fraction of the coil must go normal if it is to withstand such an energy dump. Achieving a large normal region can be accomplished by a combination of a high quench propagation velocity and having the quench jump from layer to layer.

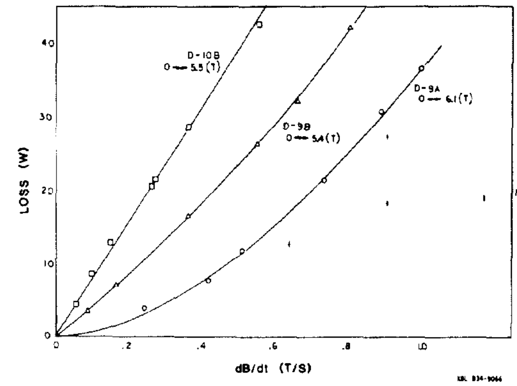

Fig. 5. Losses in coils D-9A, D-9B and D-10B. The differences can be ascribed to different filament sizes and different quantities of conductor in the coil.

To study the quench propagation velocity and to determine if normal regions occurred in the outside layers, we introduced a delay in "firing" the protection circuit. At critical current in He I a quench starting in layer 1 induced normal regions in the second layer in 50 ms and in the third and fourth layers in < 100 ms. This data has not been analyzed completely but suggests coils of this type could be made self protecting.

Acknowledgements

The authors wish to acknowledge the devoted effort of Roy Hannaford, Fred Perry, Al Borden and Larry Parsons in fabrication and assembly of this coil, and in particular Jim O'Neill who not only led the shop team but aided in planning and scheduling the work. The programs for coil design were made available by Robert Meuser.

References

1. W.V. Hassenzahl, C. Peters, W. Gilbert, C. Taylor and R. Meuser, "A Four Layer, Two Inch Bore, Superconducting Dipole Magnet," to be published in the Proceedings of the 1982 Applied Superconductivity Conference.

2. S. Caspi, W. Gilbert, R. Meuser, C. Peters, J. Rechen, C. Taylor, "A Layer-Wound, Ten Tesla Superconducting Dipole Magnet," Proceedings of the 1983 Particle Accelerator Conference, Santa Fe, New Mexico.

3. A.J. Stevens, J.G. Cottingham, A. Ghosh, K. Robins, and W.B. Sampson, "Quench Protection Studies of CBA Magnets," Proceedings of the 1983 Particle Accelerator Conference, Santa Fe, New Mexico.