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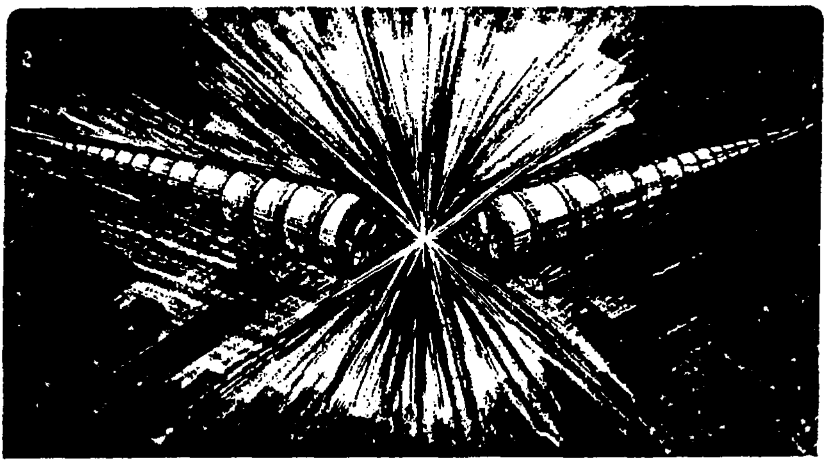

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Abstract

A four layer, 5 cm beam tube aperture, 1-m, long model accelerator dipole has been built and recently tested at the Lawrence Berkeley Laboratory. The conductor for this dipole is graded. The cable used for the inner two layers has about 30 percent more superconductor than that in the outer two layers, so the conductors reach the short sample limit at nearly the same current. This magnet is the third of a series of high field dipoles under development at LBL and has been tested at 1.8 and 4.2 K in liquid helium at one atmosphere pressure. Because of the large forces exerted at high field the magnitude and distribution of prestress in the assembled coil is quite important. The stress in each layer was measured and adjusted quite closely during the assembly process. The magnet achieved 9.08 T at 1.8 K and 7.15 T at 4.4 K. These fields appear to correspond to the critical current limits of the conductors in the region of the splice between layers 3 and 4. Training behavior, ramp rate sensitivity and magnetic field measurements are described.

Introduction

During the past several years a part of the superconducting magnet program at the Lawrence Berkeley Laboratory has been to develop high field accelerator dipole magnets, the ultimate goal being 10 T.[1] The approach followed has been to design coils[2,3] and develop conductors[4,5] that together can produce very high fields. Two distinct paths have been followed, one is the use of NbTi at 1.8 K[6] in coils made of concentric layers of cable conductors;[2] the other uses Nb_3Sn at 4.2 K in flat pancake coils, also made of cables. The Nb_3Sn coil is of the "wind and react" type and is described in a companion paper in this conference.[7]

Magnet Design and Fabrication

The magnet described here is made of NbTi multifilamentary superconductor in the form of a "Rutherford" cable. It, D-9C, is the third of the D-9 series of magnets made of conductors having increasing critical current capabilities. To achieve higher critical fields than previous accelerator dipole magnets such as the FNAL doubler or the proposed HERA[8] accelerator at DESY, the radial thickness of the windings was increased, the amount of turn-to-turn insulation was decreased to two 0.025-mm layers of kapton, the copper to superconductor ratio was reduced to about 1.0, and the conductor manufacturing process was changed to improve the critical current density in the superconductor.

Four layers of Rutherford cable are used in this design which is shown in Fig. 1 and described in Table I. The conductor is graded with a heavier cable used for the inner two layers than the outer two. The characteristic of the conductor used in this magnet are given in Table II. For comparison purposes the characteristics of the conductors used in the two magnets D-9A and D-9B are also included in Table II.

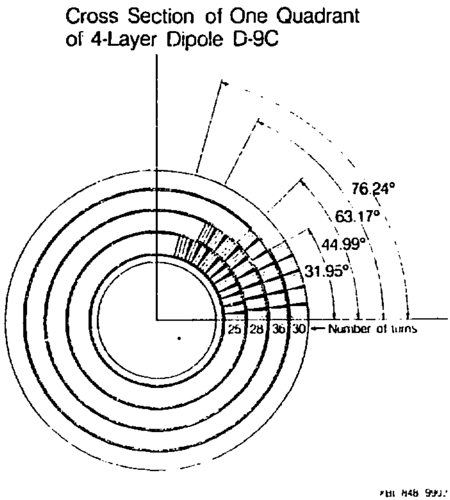

Figure 1. A cross section of the central field region of the 4-layer dipole D-9C.

TABLE I
Characteristics of the Accelerator Dipole Magnet D-9C Windings

Layer	No. Turns	No. Wedges	ID (mm)	OD (mm)	Midplane (mm)	Pole Angle
1	25	10	58.4	77.4	1.14	76.24
2	28	8	78.1	97.1	0.70	63.17
3	36	6	98.5	115.2	0.13	44.99
4	30	4	115.8	136.7	0.38	31.95

The critical current characteristics of the conductor and the load line for the magnet are shown in Fig. 2. Because there are two distinct conductors in the magnet, the load lines for the peak field point in the straight sections of layers one and three are shown, and the critical current characteristics are given at 1.8 and 4.2 K for both cables.

Fabrication of the coils for D-9C began in June 1983. However, because of other program commitments, the coil was not completely assembled and tested until July 1984. Figure 1 accurately shows the placement of the rectangular conductor and the G-11 wedges. These wedges are used to compensate for the difference in radius from the inside to the outside

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TABLE II

Characteristics of the Conductors for Accelerator Dipole Magnets D-9A, D-9B, and D-9C

	D-9A	D-9B		D-9C	
Layers	1-2-3-4	1-2	3-4	1-2	3-4
No. strands	23	21	23	23	27
Strand diam. (mm)	0.67	0.75	0.67	0.81	0.56
Cu:SC ratio	1.5	1.06	1.3	1.08	1.08
No. filaments	2100	620	500	620	620
Filament size (μm)	9.4	21.3	20.1	22.5	16.2
Overall dimensions (mm^2)	1.19x8.02	1.37x8.05	1.02x8.08	1.42x9.40	0.96x8.26

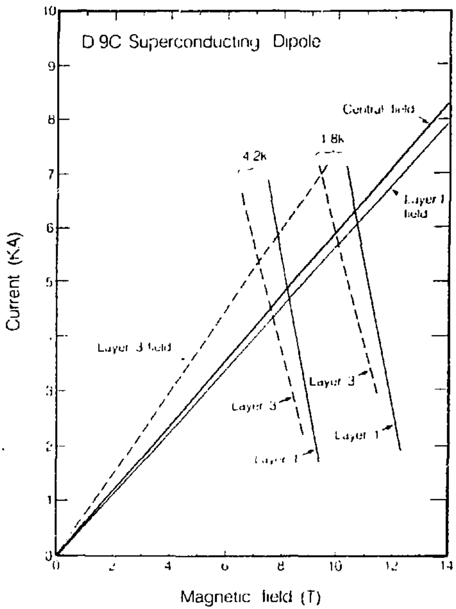

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Figure 2. Load lines and critical current characteristics of layers one and three of dipole magnet D-9C. The dashed lines are for layer 3 and the solid lines are for layer one.

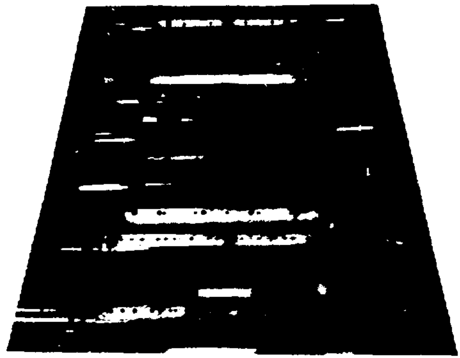

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Figure 3. Several of the completed coils for dipole D-9C ready for final assembly.

of each layer. As is frequently the case with the first coil made of a new conductor its exact dimensions in the as-wound condition, under load cannot be predicted accurately. The midplane shims between the two halves of each layer were adjusted during final assembly to accommodate this manufacturing variation.

One technique that is believed to reduce the training in a dipole magnet is to prestress the winding to a level sufficient to insure that it remains in compression at the maximum field and current. The precompression level established by field and force calculations must be reached at the design dimension.

To achieve the desired prestress in each layer at the design dimensions a known compressive load was applied to the coil with an external hydraulic clamp after each layer was mounted. The outside diameter of the coil and the stress in the coil layers already assembled were measured under this load. The midplane shim of the outermost layer was adjusted to give the correct pressure in all the layers already assembled. After the shim was selected the clamp was removed and the coil wrapped with one or more layers of Kevlar braid under tension so the inside diameter of the subsequent layer would be at the design value. The Kevlar braid was about 0.3 mm thick anbd 3 mm wide. The first layer, as applied, covered about 70% of the coil surface; the 30% void was left for helium ventilation. The second and subsequent layers of Kevlar were wrapped precisely on the first to preserve the helium channels. A set of the coils for this magnet are shown ready for final assembly in Fig. 3.

After completion the coil was insulated with mylar sheets on the outside diameter and a set of rings and collets were applied to bring the final, as assembled, prestress to the design level. The stress in the coil layers, which was measured with strain gauges in the islands, is shown in Fig. 4. This figure shows the variation in stress from the initial prestress state after ringing through the final testing of the coil in liquid helium.

The measured stress in each of the four layers is about 10,000 psi in the assembled magnet. The design goal was greater than 12,000 psi in layers 1,2, and 3 and about 8,000 psi in layer 4. This goal could not be achieved because layer 3 was slightly oversize

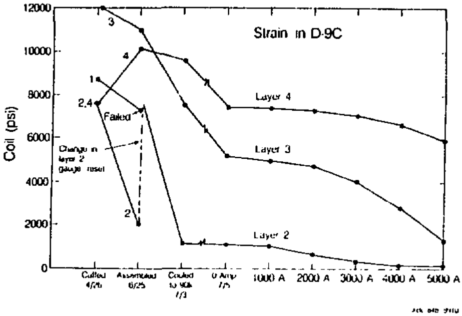

Figure 4. Strain history of three of the four layers of dipole magnetg D-9C. The as constructed stress of the coil was about 25% less than the design stress value.

even though the smallest possible midplane shim was used. The effective "hardness" of this layer denied adequate compression on the inner two layers.

The strain gauge in layer 1 failed shortly after assembly, and there was an apparent zero shift in gauge 2. The change in gauge 2 could be the result of one of the two active elements separating from the aluminum substrate. The exact cause cannot be determined until the coil is disassembled.

Tests of D-9C

The coil was first tested in helium at 4.2 K and trained to 3854 A, 6.24 T in 8 quenches. It was then cooled to 1.8 K and trained to a maximum field of 9.08 T, 5316 A in 14 quenches. This training sequence was rather extended in time as magnetic field measurements and ramp-rate sensitivity tests were being carried out at the same time. The quench history is given in Fig. 5. After training at 1.8 K the coil reached 4261 A, 7.15 T, at 4.4 K.

The quenches observed were mainly in the two outside layers and appeared to be in the region of the splice between them. Subsequent inspection of the splice region showed the conductor from both layers 3 and 4 had partially uncabled close to the splice and was poorly constrained in this area. This is also a region of fairly high field. The high field region is just outside the turnaround at the ends of layers 1 and 2. The field there may be considerably greater than that in the straight section. This placement of the layer to layer joints is quite different from that used in the two previous magnets which both reached critical current in the straight sections.

Magnetic Measurements

The field quality of D-9C is given in Table III. The rather large sextupole in the integrated field is due to the end design of the coil. The third and fourth layers are made shorter than the other two layers to reduce the field rise on the ends of the two inner layers. The use of three dimensional field calculations using computer programs that are now under development should allow coil ends of this type to be fabricated with small sextupole components.

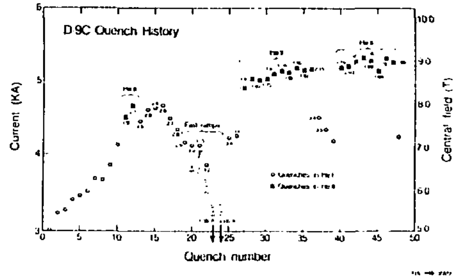

Figure 5. Quench history of dipole magnet D-9C.

TABLE III
Harmonic Content of the Magnetic Field in the Superconducting Dipole D-9C. Fields Are Given in % of the Dipole Field at a 2 cm Radius.

Harmonic	Central Field	Integral Field
B_2/B_1	0.03	0.09
B_3/B_1	0.17	1.60
B_5/B_1	0.03	0.03
B_7/B_1	0.02	0.02
B_9/B_1	0.03	0.03

The sextupole component in the central field is produced mainly by the midplane shims in layers one and two, which were made larger than the original design to accommodate a small conductor thickness variation, as discussed above.

Ramp Rate Measurements

The ramp rate sensitivity of the coil was determined by fast ramps at 4.4 K, and is given in Table IV. This decrease in quench current for high ramp rate is typical of that seen for dipole magnets made of this type of cabled conductor.

TABLE IV
Ramp Rate Sensitivity of Magnet D-9C

Ramp Rate T/s	Quench Current A
0.1	4261
0.25	4224
0.4	3867
0.7	2335
1.0	1190

Conclusions

The previous magnets in this series, D-9A and D-9B, had joints between layers in low field regions several centimeters from the windings. Both these magnets reached critical current and the training, which was less than observed in D-9C, was in the straight sections of the coils at the highest field region. Modifying the layer-to-layer joints in this magnet might be sufficient to allow the coil to reach 10 T. Since precompression was lost in layer 2 during cooldown, it is possible that the inner two layers can be made larger by increasing the midplane shims so both layers one and two will have a larger prestress after cooldown. Of course larger shims at the midplane will have a deleterious effect on the magnetic field quality.

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