### Title
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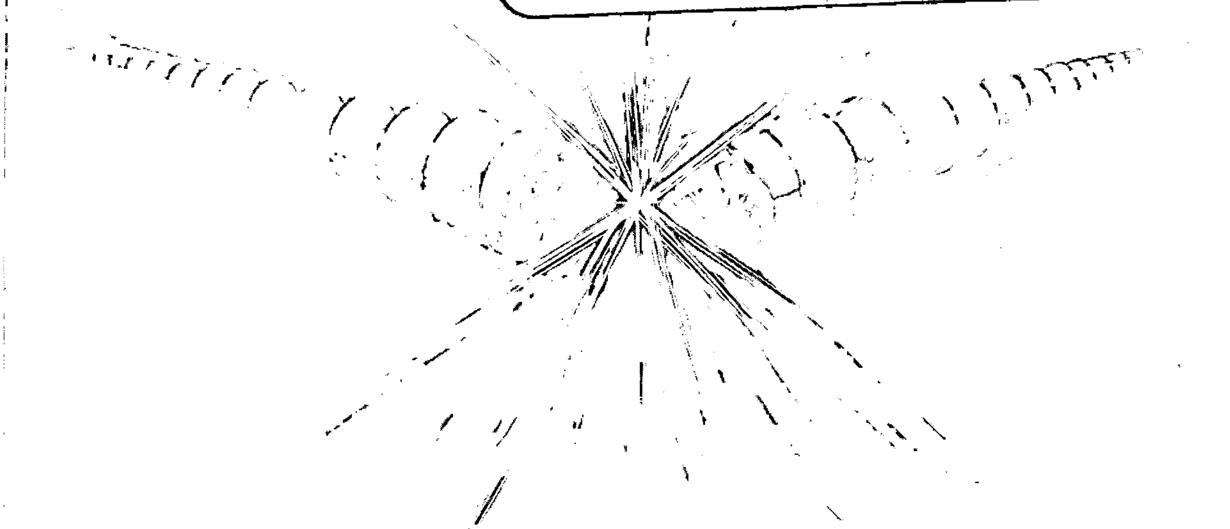



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# LBL PROGRAM ON 1 METER LONG, 50 MM DIAMETER BORE, DIPOLES WITH FIELDS GREATER THAN 8 TESLA*

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## Abstract

Model dipole superconducting magnets with central fields above 8 tesla are being developed for future multi-TeV colliding beam accelerators. The first three models are 1 meter long, have nominal 50 mm diameter cold bores, and utilize Nb-Ti superconductor operating in He II at 1.8 K. None of the three models had an iron flux-return yoke. The maximum central fields achieved are 8.0, 8.6, and 9.1 tesla -- all short-sample performance at 1.8 K for the conductors used. At 4.3 K the maximum central fields are from 1.5 to 2.0 tesla lower. In one design, the superconductor is arranged in four concentric cylindrical layers, sometimes called a four-shell geometry. With higher current density Nb-Ti we expect this design to reach 10 tesla central field and a two layer design to reach 8 tesla. The other design uses 8 flat pancakes with upturned ends. Improved Nb-Ti should also allow this design to reach 10 tesla central field. This geometry is being used for our $Nb_3Sn$ wind-and-react dipole to be operated in He I at 4.3 K.

## Program Summary

Existing high-energy accelerators have reached a size that appears to be a limit of machines using conventional magnets, and the first accelerator using superconducting magnets is now in the process of being commissioned and should soon be operational. Because they allow both size and operating costs to be reduced superconducting magnets appear to be the clear choice for future high-energy synchrotron accelerators, unless some other acceleration technology is developed.

The optimum field and bore of the superconducting magnets destined for future machines are not so certain. The choice of these parameters will be based on tradeoffs among many factors. The lower the field, the larger the accelerator. On the other hand the required quantity of superconductor increases faster than the design field . At very high field, greater than about 11 T, the current carrying capacities of commercially available superconductors becomes too small for consideration. It is certain that there will be an optimum cost at some intermediate field. In addition, at very high energies, synchrotron radiation, which increases as the local field to the fourth power, may be a limiting consideration because of the increased refrigeration load. A likely upper limit imposed by these consideration is 10 T. This field was set as an ultimate design goal for the magnets we are developing.

The design bore of an accelerator is determined by cost, field quality, alignment accuracy, and the ease with which the beam can be steered. Recent experience at Fermilab indicates that a 75 mm inner winding diameter is satisfactory for synchrotron operation. To reduce cost we have used 58.5 mm for our recent magnet development program and see no fundamental limitation down to about 40 mm. Special consideration must be given to the ends of small magnets due to difficulty in bending conductors around the small radius at the pole.

The development of magnets that operate in the 8 to 10 T range is an extension of the development of lower-field magnets. The local body forces are a product of current density and field. At higher fields the current density in the superconductor decreases and with no other changes this product would remain roughly constant. At high fields, however, increasing the current density in the winding is very effective in terms of the quantity of superconductor required. This is accomplished by developing superconductors with increased critical current capability and by reducing the copper-to-superconductor ratio. The resulting pressure at the midplane of the winding, even for 50 mm bore coils, can approach 138 MPa (20,000 psi), which is about a factor of two greater than the pressure in the Fermilab doubler coils.

We use two commercial superconductors: an alloy of niobium and titanium (Nb-Ti), and a compound of niobium and tin ($Nb_3Sn$), for accelerator dipoles. The approximate field limits for these materials are shown in Table I.

Table I

Maximum Design Field for Superconducting Accelerator Dipoles

| Material | Temperature | Maximum Field |
|---|---|---|
| Nb-Ti | 4.3 K | 8 T |
| Nb-Ti | 1.8 K | 10 T |
| $Nb_3Sn$ | 4.3 K | 10 T |

Operation of magnets at 1.8 K in liquid helium at atmospheric pressure is a fairly recent development. It has been straightforward, considerably simpler, and more reliable than many expected. The experience of laboratories that work with magnets in this temperature range is that the anticipated problem of superleaks has not materialized. This propitious result is because good seals (in particular, heliarc welds) for liquid helium are also superfluid tight. The Nb-Ti dipoles tested generally reach about 30% higher fields at 1.8 K than at 4.3 K.

During the past year we have built and tested three Nb-Ti dipoles. Two are of the layer design,[2,3] as shown in Fig. 1, and one is of the block design,[4] as shown in Fig. 2. Details of magnet design and test results are summarized in Table II and detailed in the sections that follow. At present an additional Nb-Ti dipole of the layer design and a Nb Sn magnet of the block design are being constructed. The status of their fabrication and the planned tests are also described.

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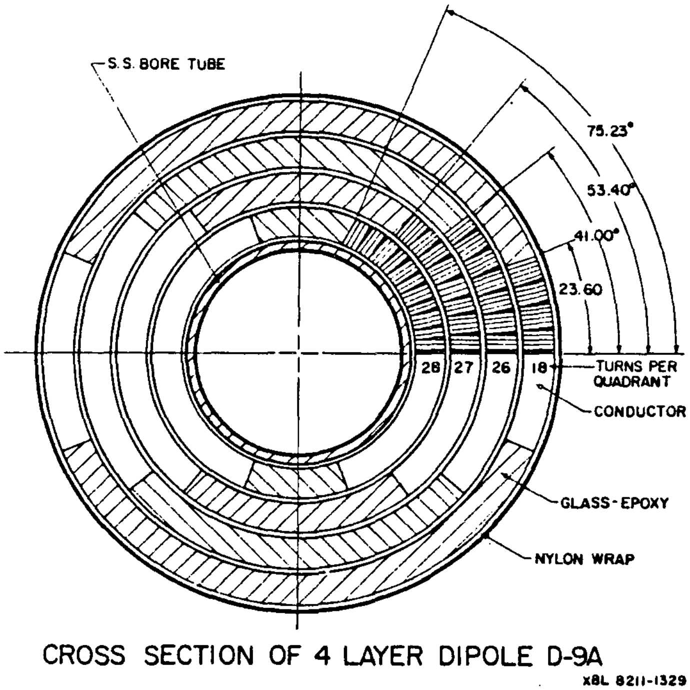


Fig. 1. Cross section of D-9A, a typical 4 layer of 4 shell dipole.

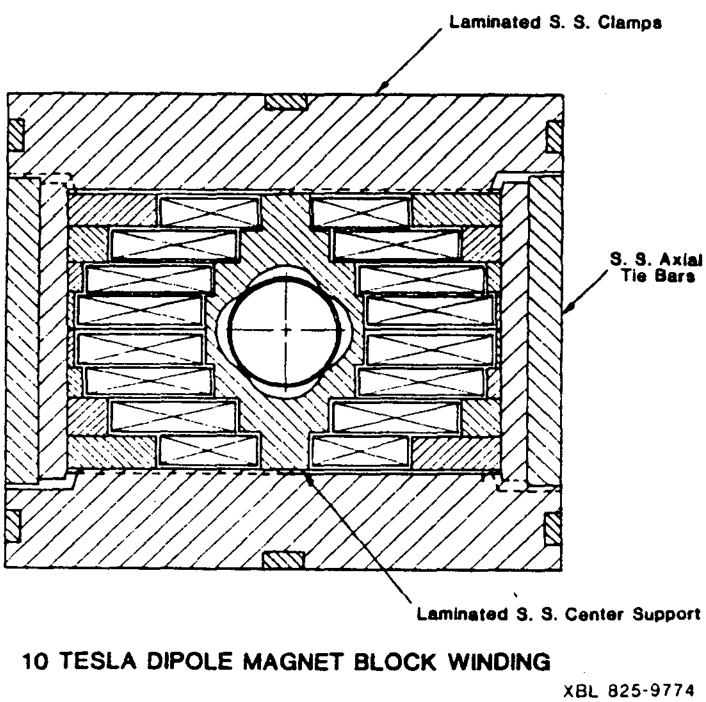


Fig. 2. Cross section of a block design coil having 8 flat pancakes.

Table II

Summary of Small-Bore, Nb-Ti Accelerator Dipoles Designed and Tested at LBL

| Magnet Name | Design | Field (tesla) 4.3K | 1.8K | Cu:Sc Ratio | Training |
|---|---|---|---|---|---|
| D-9A | 4 layer | 5.9 | 8.0 | 1.5 | No |
| D-9B | 4 layer | 7.1 | 8.6 | 1.0-1.3 | Yes |
| D-10B | 8 pancakes | 7.0 | 9.1 | 0.9 | Yes |

Layer Magnets

The 4-layer magnets described here are a logical extension of work on 2 and 3-layer magnets already developed at LBL. A transverse cross section of coil D-9A is shown in Fig. 1. Some characteristics of the D-9A and D-9B windings are presented in Table III. The winding angles for the four layers were selected to minimize field aberrations.

Table III

Design Angles and Number of Turns in Each Layer of Coils D-9A and D-9B

| | Angles (°) D-9A | D-9B | No. of Turns D-9A | 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 |

The coil winding can support an inward radial load in the straight section and when clamped under the maximum stress remains separated from the stainless steel bore-tube by about 0.5 mm. A layer of 1-mm-thick nylon monofilament is wound over each layer to (1) provide a pre-compression before the subsequent layers are applied, (2) aid the external rings in supplying the final preload, and (3) provide a path for helium to flow circumferentially around the coil. The ends of the coil, which are not self supporting, contact the bore-tube and are under both a radial load and some circumferential load due to the nylon banding and external rings.

The ends of the coil layers are staggered, with the outer coils shorter, to reduce the maximum field at the innermost turn of the first layer. The high-field region is in the straight section of layer one. Neglecting end effects, the maximum field rise in the straight section of layer 1 is about 3 on the first turn.

The 2.46 mm thick, 52.5 mm inside diam. bore tube is an integral part of the coil and is vacuum tight. Pins are welded into holes in this tube to provide an index for mounting the pre-assembled coil halves and to support the coil against the circumferential force of the nylon during winding.

The conductor used in D-9A is similar to the FNAL Rutherford cable but the copper-to-superconductor ratio in the conductor is 1.5. The cable is very lightly compacted by a "turk's head" while in the winding line under tension. This operation produces a rectangular conductor with a final size that is uniform throughout the coil and brings the internal structure of the conductor into final registry to remove distortions that might have been introduced during handling. For example, in the year or so between manufacture and coil winding the conductor may be respooled several times and passed over several pulleys during the cleaning and inspection process. This final compaction and sizing is quite important because of the strong dependence of the coil pre-stress on the conductor dimensions.

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 radial dimensions of the layers) the same but the thickness of the outer two layers' cable some 30 less than that of the inner two layers' cable. Thus the current density in the outer layers is increased by this 30%. Delays in fabricating the thinner cable that was originally planned forced us to use a substitute, which was generously supplied to us by Dr. Richard Lundy of FNAL. This conductor gave an increase in current density in the outer two layers of 18%.

The conductor for layers 1 and 2 was 21 strand cable 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 0.75 mm(0.030"). The copper-to-superconductor ratio is 1.0. The diameter of the 620 Nb-Ti filaments is 21 μm. Each strand was coated with Stabrite solder before cabling. The conductor for layers 3 and 4 was 23 strand cable, called the "low β quad" cable. Externally this is a standard size FNAL cable with 23 strands of 0.68 mm diameter and with the standard keystone angle built in. The copper-to-superconductor ratio is 1.3, and the number of filaments is approximately 500, yielding a filament size of 20 μm. Each strand is coated with Stabrite solder before cabling.

## Test Results for Coils D-9A and D-9B

The D-9A dipole performed better than any other first coil in a series that we have constructed. At 4.3K the first quench was at 80% of short sample currents, and the second was at 100%. The performance in He II at 1.8 K was similar, with the first two quenches at 90 and 100% of short sample, 7.2 and 8.0 T, respectively. During the second test of this coil we hope to learn if relaxation of prestress in the nonmetallic portions windings will affect performance.

The first quench observed in D-9B was in He I at 3250A, about 70% of 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 short-sample current, which varies a few hundred amperes between 1.75K and the lambda point.

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 pre-stress 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. This was a result of using conductor in the outer two layers that we had not characterized adequately. In addition, the low copper-to-superconductor ratio of the inner two layers may have decreased coil stability.

At the time of this meeting (August 1983) the D-9A is being tested again, and the field quality, which was not determined in the first test, is being measured. The calculated field harmonics for D-9A and D-9B and the preliminary results on D-9A are given in Table IV.

## Block Design Magnet

The block, or flat pancake, coil geometry is shown in Fig. 2. The coil sections are wound from heavy rectangular cable in flat pancake or racetrack pairs. The particular geometry was chosen to enable heavy $Nb_3Sn$ cable to be wound into a small-aperture dipole.

Table IV

Field Quality of Dipoles D-9A and D-9B. Harmonics are given relative to the dipole field at 20 mm radius. The calculated harmonics are for the dipoles, as assembled. Field quality would be expected to improve for later magnets in a series with a specific design and a well defined conductor.

| | D-9A | | D-9B |
|---|---|---|---|
| Harmonic | Calculated | Measured | Calculated |
| $B_2/B_1$ | - | 0.00065 | - |
| $B_3/B_1$ | 0.0031 | 0.0039 | 0.0076 |
| $B_4/B_1$ | - | 0.00043 | - |
| $B_5/B_1$ | 0.0042 | 0.0017 | 0.0015 |
| $B_6/B_1$ | - | 0.00038 | - |
| $B_7/B_1$ | 0.0005 | 0.0012 | 0.0005 |

While waiting for the experimental $Nb_3Sn$ cable to be fabricated, we built D-10B, using Nb-Ti cable, to test the new geometry for fabrication practicality and also to test the magnet for training and other pertinent behavior.

The superconducting cable used for this coil is wrapped with (25 μm) 1 mil-thick overlapped Kapton, which is coated with B-stage epoxy except for the inner four turns of each pancake. The pancakes are wound in pairs and assembled into half magnets that are baked at 120°C to cure the B-stage epoxy. The two halves are then assembled in the final clamping structure, and the magnet is pre-stressed using shims and external bolts.

A Rutherford rectangular cable of 27 strands of .0318" (0.81 mm) diameter is used. For highest current density, a low copper-to-superconductor ratio of 1 was specified, and possible problems with conductor stability were anticipated. The actual Cu:S.C. ratio turned out to be even lower, 0.86. The strand contains 409 Nb-Ti filaments, each approximately 29 μm in diameter. Each strand was coated with Stabrite.

The cable dimensions, without insulation, are 0.056" x 0.446" (1.42 mm x 11.33 mm). The manufacturer (the superconducting strands were fabricated by Magnetic Corporation of America and the cabling was done by New England Electric Wire Corporation) had considerable trouble in supplying this cable due to wire breakage during cabling. Various repairs of sections of cable had to be done at LBL. Therefore we have no information on how uniform the cable might be throughout the magnet.

## Test Results for D-10B

The first quench at 4.3K was about 80 percent of its short-sample, or some 5.5 tesla central field. The training was moderately slow, some twenty five (25) quenches to short sample. It is not clear whether this slow training is due to a superconductor stability problem, which might result from a low copper-to-superconductor ratio, to structural and pre-stress problems, or to some particular defect in one pancake pair from conductor or manufacturing defects. Most quenches occured in the pancake pair 3 and 4 bottom. The maximum central field reached at 4.3K is 7.0T, and we believe it to be short-sample performance because the same current is reached before and after operation at higher currents in He II. Also the character of the quenches, which is quite reproducible, is that of conductor operating at short sample. Some training also occurred in He II, in which a peak field of 9.1 tesla was reached.

## Current Work

We are in the process of constructing two additional dipoles having nominal 50 mm cold bores. One is a four-layer design called D-9C and is similar to the two magnets, D-9A and D-9B. The differences are mainly in the conductor, which is graded. The conductor strands in the two cables used in D-9C are from the same billet and have a 1.0 copper-to-superconductor ratio. The cable for layers 1 and 2 has 21 strands of 0.79 mm (0.0318") and that for layers 3 and 4 has 27 strands of 0.67 mm (0.023") conductor. The current density in the outer two layers is 60% higher than in the inner two layers. Special fabrication fixtures for winding this coil are complete, and half of one layer has been wound.

The D-10A coil is a wind-and-react $Nb_3Sn$ coil made of 8 pancake layers. It is similar in cross section to D-10B, which was described above and shown in cross section in Fig. 2. The conductor is wrapped with a glass insulation that can withstand the abrasion of winding and the ~ 700°C reaction temperature.

The conductor for D-10A is a 11 strand $Nb_3Sn$, Rutherford cable supplied by the Intermagnetic General Company. Each strand is 1.7 mm (0.068") diameter and has 2 to 3 μm diameter filaments. The copper-to-superconductor ratio is 1.0.

The first half of D-10A has been fabricated and is shown in Fig. 3. Both D-9C and D-10A should be completed and tested, including magnetic field measurements, in 1983.

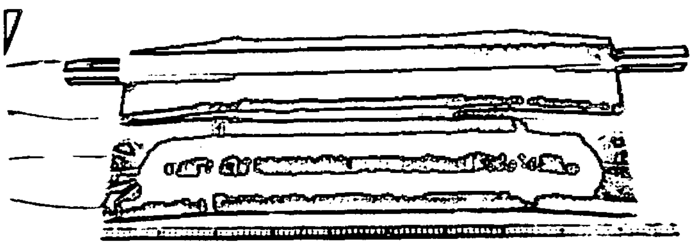

Fig. 3. The first half of the $Nb_3Sn$ dipole, D-10B, and the shaped bore tube.


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