

A NOVEL EPOXY-FREE CONSTRUCTION METHOD  
FOR FABRICATING DIPOLE MAGNETS AND TEST RESULTS\*

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Abstract

Three model superconducting dipole magnets, 1m length and having a bore diameter of 76mm, fabricated without epoxy resins or other adhesives, have been built and the first two have been tested in He I and He II. The conductor is the 23-strand Rutherford-type cable used in the Fermilab Doubler/Saver magnets, and is insulated with Mylar and Kapton. The two-layer winding is highly compressed by a system of structural support rings and tapered collets. Little "training" was required. Quench currents greater than 95 percent of "short sample" were obtained in He I with rise-times of 15 to 20 seconds to a central field of 4.6T; 6.0 T in Helium II.

Introduction

Epoxy has been used in accelerator dipole construction to fix the coil's shape after winding so that the coil parts could be transferred from the winding fixtures to the final magnet assembly. Examples are the AC series at RHÉL, Isabelle at BNL, ESCAR at LBL, Doubler at FNAL and the similar U.N.K. magnets at Saclay and Tristan models at KEK. Once the coil is assembled into its outer supporting structure, the epoxy bonding or adhesive function is no longer needed. The epoxy may contribute to reduced magnet stability through helium exclusion and may initiate training through heat generation associated with epoxy cracking under thermal and mechanical loading. Therefore, we set out to build and test dipoles using epoxy-free or dry winding techniques to determine if improved performance can be realized.

We have developed a winding scheme in which the magnet is built up, layer by layer, into its final form so that no epoxy or other adhesive is required. Several benefits in production simplifications are anticipated. The first dipole magnets using the dry winding techniques, have a winding cross-section that is similar to the FNAL doubler magnets except that we use external aluminum structure rings rather than the FNAL stainless steel collar structural system. Our first test magnets performed to short sample levels and show promise for future larger and higher field magnets.

Construction Method

Figure 1 illustrates the construction details of the windings.

1. A collapsible removable mandrel is attached to a two-motion winding table. A cylindrical bore tube, which is slotted to be mechanically compliant in the magnet straight section, rests on the mandrel.

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2. Next, a helical wrap of nylon is wound over the bore tube to serve as electrical insulation, spacer and helium passageway.
3. The inner layer of insulated superconductor is then wound, under tension against a split central island and under temporary hold-down fixtures at the magnet ends. Both top and bottom halves of the magnet are wound before the next step. Two coil layers are wound from one length of superconductor, thus avoiding splices between layers; therefore, the two spools of cable for the respective outer windings are stored on outriggers to the winding machine.
4. The first coil layer is clamped to the bore tube with a series of leaf-chains.
5. The winding is circumferentially compressed from the split central island. The spreaders are then removed and filler blocks inserted.
6. A helical winding of monofilament nylon is wrapped under tension over the winding and the leaf-chains are removed one-by-one as the wrap progresses axially. At this stage, the compressive stress in the windings is about 4000psi.
7. The above procedure is repeated for the outer layer.
8. The center mandrel is collapsed and removed.
9. The completed coil is radially compressed further by hydraulically assembling external cylindrical aluminum structure rings onto tapered collets that rest on the outside nylon wrap of the coil. End plates and longitudinal rods complete the assembly.

Conductor and Insulation

23 strand NbTi Rutherford Cable nearly identical to that used in the FNAL Doubler magnets, is used in the 2-layer 76 mm I.D. D-7 magnet series. Each strand has stabrite or other insulation but the cable, as a whole, is unfilled and rather springy. Kapton and Mylar film insulation is helically wrapped over the cable. 25µm thick Kapton is wrapped around the conductor with a gap (some 20 percent) between turns. Over this, and with the upper film covering the lower gaps, is wrapped the Mylar film, also with a gap between turns. In D-7A, the Mylar film is 25µm thick but was found to be overly fragile from the standpoint of scuff resistance and propensity to electrical shorts. In D-7B, 50µm Mylar film is used.

Mechanical Testing Program

Since stress in the winding is not measured directly, but is implied from known stress-strain relationships, we must test all materials used in the magnets. The most difficult material to characterize adequately is the coil winding structure itself. We measure stress-strain relationships, thermal expansion, and creep vs. time, stress, and temperature on multi-conductor bundles in compression at temperatures from ambient to either 77K or 4.2K. The compressive

## Magnet Descriptions

### \*\*A. D-4 (number ESD-10)

I.D. = 16.5 cm  
 Small (4.90 mm X 0.85 mm) RHEL Cable-Staybrite insulation  
 4 current blocks  
 Mylar + B-stage glass insulation  
 4 layers  
 Aluminum ring and collet compression  
 Pre-stress 100 to 200 atmospheres, less than half the Lorentz forces

### \*\*B. D-5

I.D. = 16.5 cm  
 Small RHEL Cable - staybrite insulation --  
 4 current blocks  
 Epoxy in cable - Kapton + Mylar + Epoxy  
 4 layers  
 Aluminum ring and collet compression  
 Cold pre-stress below 100 atmospheres

### \*\*\*C. D-7A

I.D. = 7.6 cm  
 Large (7.55 mm x 1.25 mm) RHEL Cable - Staybrite insulation  
 2 layer design  
 Fermi Doubler Conductor Pattern  
 Kapton 25  $\mu$ m thick  
 Mylar 25  $\mu$ m thick NO epoxy  
 Aluminum ring and collet compression  
 Cold pre-stress about 5,000 psi, greater than Lorentz force

### \*\*\*D. D-7B

Similar to D-7A above but "zebra" cable is used with half the strands insulated with Staybrite and the other half with copper oxide. The thickness of Mylar is 50 microns. The cold pre-stress is somewhat lower than that of D-7A.

\*\* These magnets are described in more detail in ref 6 LBL-10756.

\*\*\* These magnets are described in more detail in ref 7 LBL-11752 (this conference).

## Test Results

### A. ESD-10

Originally this magnet was operated in regular helium in its horizontal cryostat with a warm iron yoke. The training was slow and regular, some 90 quenches to 95 percent of short sample, and is typical behavior for this class of magnet with low pre-stress. The magnet, without the iron, was re-tested in the vertical helium II facility. First the magnet was powered in helium II at 1.8K to 92 percent of the 4.2K short sample limit. Next the temperature was raised to 4.2K and the magnet quenched at the current previously reached in the superfluid runup. Two more quenches at 4.2K confirmed the training curve to be expected in regular helium. We estimate that 50 more quenches would have been required to reach short sample current at 4.2K. Then six more runups or quenches took place in helium II. The current was run to 105 percent of the 4.2K short sample. The system was again warmed to 4.2K, the magnet quenched at 100 percent of short sample.

### B. D-5

This magnet exhibited considerable training together with loss of memory on warming to room temperature. It trained faster in helium II than in helium I but did not reach short sample performance in either cooling mode.

Hysteretic loss was measured in the helium II by observing the temperature monitors while the current was being cycled between two current levels. Calorimetry is convenient in a helium II bath because temperature gradients are negligible even with large heat inputs. The rate of field change varied from 0.02 to 0.20 tesla per second. The extrapolated cycle loss, at zero field change rate, is 120 joules per cycle between 0 and 3.3 tesla, and 22 joules per cycle between 2.9 and 3.9 tesla - about what one expects for magnetic hysteresis alone.

### C. D-7A

The initial testing of this magnet was complicated by a short that caused an extreme charge-rate dependence. A charging time longer than 2000 seconds was required to reach critical current. The first such slow ramp was run in helium II and the short sample limit, at 1.9K, of 6400 amperes was achieved. The associated high voltage from our extraction circuit may have cleared the apparent short. Short sample performance was then achieved in both helium II (6500 A at 1.8K) and helium I (5000 A) at ramp rates up to 1 tesla per second. After a room temperature warm up and cooldown, the magnet still performed at short sample.

Hysteretic loss in helium II was determined as discussed above (in D-5 section). In addition to the expected superconductor hysteretic loss, we had anomalous losses, possibly associated with the magnet short.

Table 1

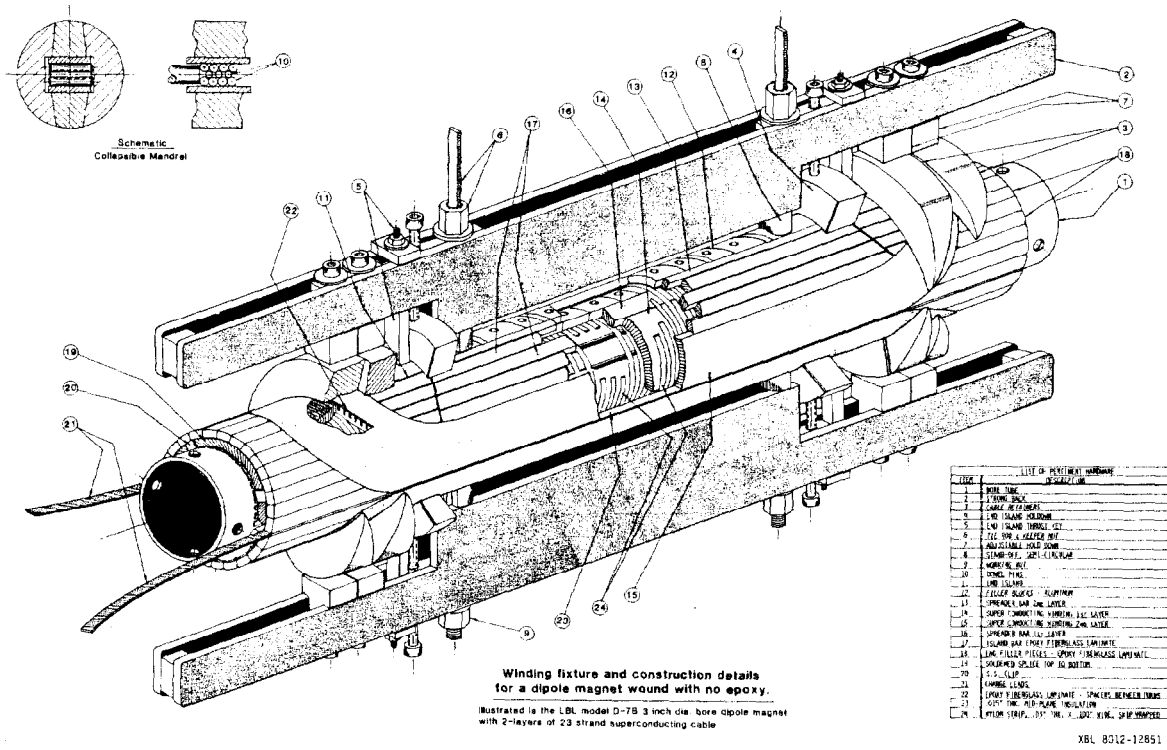
Current Range, A	Current Rate A/s	Temp Range, K	Heat Rate, W	Heat Rate, J/cyc
0-1000	240	1.85-1.90	6.98	58.6
0-1000	120	" "	1.94	32.3
4000-5000	180	" "	2.35	26.0
4000-5000	120	" "	0.99	16.5
500-600	290	1.95-2.00	7.69	6.4
2500-2600	290	" "	7.25	6.0
4950-5050	290	" "	6.77	5.64
2000-3000	240	" "	3.20	26.7

Electrical heaters were built into the magnet between the center island and the first conductor turn of the inner layer. The heaters could be powered either in a continuous or pulsed mode. For heat pulses longer than about 250 milliseconds quench current depended on the power delivered to the heater, whereas for shorter times, it depended on total energy. Table II contains the heater quench data, at various magnet currents, in helium I and helium II. It is clear that several times as much energy is required to initiate a quench in helium II as in helium I. The quantitative interpretation of this data is uncertain because not all the heater energy is delivered to the superconductor.

### D. D-7B

D-7B has 50 percent thicker insulation than D-7A. Charge rates up to 0.3T/s produced little effect on quench current. Some training in helium I was observed, to the short sample current of 4700A amperes. In helium II, the 2K short sample limit of 5465 amperes was achieved on the first quench.

Figure 1:



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Conclusions

Stable magnet behavior and reasonable training can be realized using this type of cable without epoxy. Thorough knowledge of the thermal and mechanical properties of all of the materials of construction is required to arrive at the desired conductor placement and coil pre-stress, coupled with close control of dimensions during manufacture. Methods and materials are being evolved with these goals in mind.

References

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2. W. Gilbert, et. al., EXS 40, 11th International Conference on High Energy Accelerators, p. 858, (1980). Also as LBL-10756.
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Test Results, General

From our present knowledge of the properties of the magnet materials we know that the desired coil pre-stress of about 10,000psi was not achieved in either magnet D-7A or D-7B. Most of the quenches in this magnet were in the inner coil. Under-estimates of room-temperature creep and un-equal division of the pre-stress between layer 1 and layer 2 contributed to the inadequate pre-stress in both magnets.

Future Plans

These magnets, requiring simple tooling, are relatively easy to build and test, so are well suited to the study of materials and the effect of pre-stress on training. The same construction technique can be used for larger bore and higher fields. We are now building magnets with a 13.3 cm bore diameter and a length of 1.22 meters. The coil will have three layers and should develop at least 5.5T.