LBL-11782

CONF-810314--122

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the 1981 Particle Accelerator
Conference, Washington, D.C., March 11-13, 1981

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

C. Taylor, R. Althaus, S. Caspi, W.S. Gilbert,
W. Hassenzahl, R. Meuser, J. Rechen, and
R. Warren

March 1981

MASTER

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

LBL-11752

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

C. Taylor, R. Althaus, S. Caspi and W. S. Gilbert
W. Hassenzahl, R. Meuser, J. Rechen, and R. Warren
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1981

---

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division of the U. S. Department of Energy under Contract No. W-7405-Eng-48.

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

C. Taylor, R. Althaus, S. Caspi, W.S. Gilbert
W. Hassenzahl, R. Meuser, J. Rechen, and R. Warren

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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 RHEL, 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.
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

---

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

behavoir of dry windings is quite non-linear; the winding fixture has been designed to allow for the initially large strain required to assemble the conductors. At high pre-stress 10,000 to 15,000psi, the compresive modulus is 2-3 x 10^6psi. This final compression is accomplished with the ring-collet system. The coil pre-stress can be significantly reduced by long term creep of the insulation at room temperature.

The D-7 Series of Dipole Magnets

As stated above, these magnets have approximately the same winding cross-section as the FNAL doubler magnets. They are 86.4 cm long overall, with an open 7.6 cm diam. bore. The compression rings that cover the magnet have an O.D. of 17.8 cm, with end plates and longitudinal tie rods outside of them. The coil windings are in two layers of insulated cable described above. The first layer of D-7A had 74 turns; D-7B, 78 turns. The second layer of both totaled 50 turns. Non-coil azimuthal and end space was filled with aluminum spacers in D-7A, NEMA G-10 in D-7B. The completed, nylon-wrapped coil O.D. was 11.9 cm. The central field at a 5000A current level is 4.6 T in D-7A, 4.75 T in D-7B with no iron.

Tests

For testing, these magnets were vertically mounted, without an iron shield, in our pressurized helium-II test facility, which is described elsewhere[1].

Magnet instrumentation included quarter-coil voltage taps, strain gauges on outside structural rings and on a caliper in the bore, and quench-inducing heaters adjacent to the inner coil windings.

Cryostat instrumentation included temperature and pressure sensors and a coil adjacent to the magnet for use in quench detection. External electrical energy extraction was provided.

The primary goal of these tests was to see how elimination of epoxy effects magnet training. A secondary goal was to investigate the training behavior in pressurized He II[3].

In general, the instrumentation and test plans were set up to observe and obtain data on training in He I and He II, ramp-rate sensitivity, heat generation in cyclic operation, magnet deformation, and energy required to quench, using pulsed heaters on coils.

Test Results, Magnet D-7A

1) Training. The initial quenches at 4.4K were caused by electronic problems and an extreme rate sensitivity. Later examination of these runs shows that no real transitions (quenches) occurred at slow ramp rates. In the belief that transitions had occurred, the magnet was next run in helium II to 6500A, which is 30 percent higher than the 4.4K short-sample current. All subsequent slow-ramp quenches at 4.4K were at conductor short-sample current, 5000A at 4.6T central field (B_0), 5.2T field on the conducter in the straight sections, and 5.7T maximum field (B_{max}). Although no real training behavior was observed in this magnet we cannot know whether the magnet would have trained if it had been initially energized with slow charge rate at 4.5K.

2) Rate sensitivity. Sensitivity of the magnet to heat buildup produced by rates of change of field from 10^{-3}T/sec to 5T/sec were obtained both in normal helium at 4.4K and in helium-II at temperatures from 1.8K to 2.0K. An initial extreme sensitivity to field ramps greater than 10^{-3}T/sec, (possibly due to a short) became less severe during the course of these tests. Ramp rates of 0.2T/sec to 5000A at 4.4K and 1T/sec in superfluid helium were achieved during the later stages of the tests.

3) Heat generation. The unique properties of superfluid helium allowed us to use the entire helium-II volume as a sensitive calorimeter. The magnet current was cycled with a triangular wave-form having several amplitudes, rates and base-current offsets. The measured temperature rise of the bath was converted to heat input in watts and joules/cycle, given in more detail in reference (3). These runs were made after the rate sensitivity referred to above had stabilized at reasonably low values.

4) Pulsed heater on the D-7A coil. Small heating strips-adjacent to the inner turns of the coil were used to induce quenches. The uncorrected observations were that for heater pulses shorter than 250ms the energy required to quench the coil at 4000A is about 120mJ at 4.4K and 250mJ at 1.8K. The full test results are given in Refernce 3.

5) Deformation. Strain gauges were mounted on the periphery of one of the central compression rings; the rings deformed as expected.

6) Thermal and mechanical cycling. As part of the first series of tests, the magnet was warmed to room temperature and re-cooled in the cryostat. The first transition at 4.4K was at 4990A and the first at 1.9K reached 6500A, showing that one thermal cycle had not affected the magnet's properties. Then the magnet was warmed up, the compression rings were removed, the magnet was inspected and measured, and the rings were reinstalled. A further short test sequence at 4.4K confirmed the retention of full field capability without training, but with the return of the original poor rate sensitivity, presumably a short.

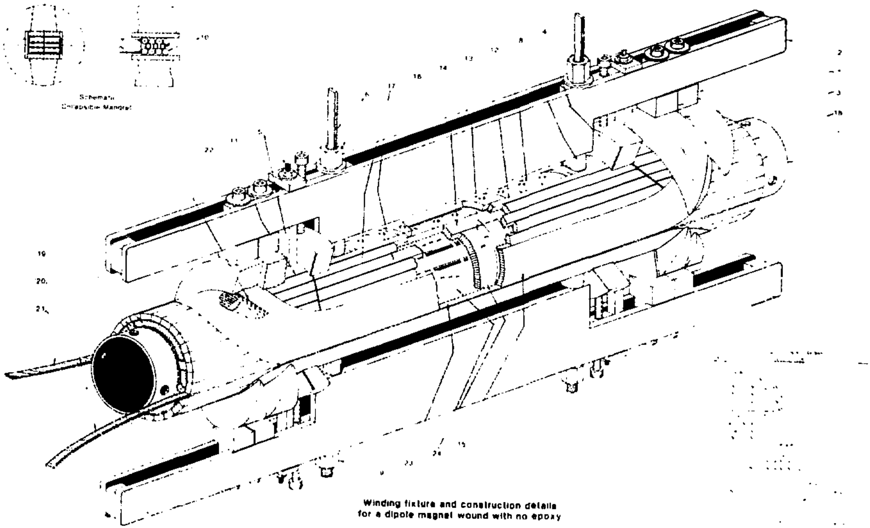
Tests of Magnet D-7B

1) Training. This magnet trained. The first quench was at 3650A, proceeding to 4650A after 23 quenches, where it levelled off. (The Fermilab "Zebra" cable used in this magnet is expected to have a short-sample current limit in this vicinity). The magnet was then run in helium II at several temperatures, reaching 5465A. Returned to 4.4K, current limits were at 4700A. After warm-up and re-cooling, two more quenches at 4.4K were at the 4700A level, showing retention of full training.

2) Rate sensitivity. The magnet was run up to full field at rates as high as 0.3T/sec with no reduction of maximum field attained. A cyclic heat generation experiment was not performed, nor were the pulsed heaters used to induce quenches.

3) Deformation during excitation. This magnet was monitored for deformation of the compression rings during magnet excitation by strain gauges on two rings and by strain gauge instrumented calipers monitoring the polar and side axes of two other rings. A calculation of the expected deformation using a realistic distribution of Lorentz forces fits the data well after the first 5 quenches.

Figure 1:



Winding fixture and construction details for a dipole magnet wound with no epoxy

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.

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

1. R. P. Warren et. al., "A Pressurized Helium-II Cooled Magnet Test Facility", Proc. 8th Int. Cryo. Engr. Conf., Genoa, Italy, IPC Sci. and Tech. Press, Guildford, England, (1980). Also as Lawrence Berkeley Laboratory Rept. LBL-10923.

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

3. R. A. Althaus, et. al., "Performance of Dipole Magnets in Helium-II", 1981 Particle Accelerator Conference. Also as LBL-11754.