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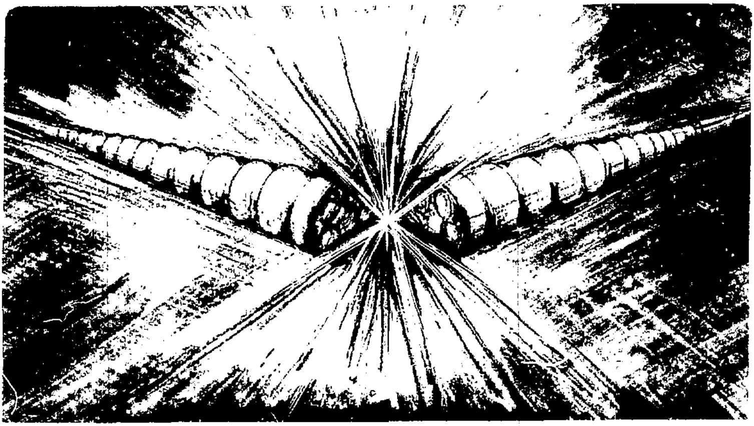

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DESIGN OF EPOXY-FREE SUPERCONDUCTING DIPOLE MAGNETS AND PERFORMANCE IN BOTH HELIUM I AND PRESSURIZED HELIUM II*

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Abstract. Three model superconducting dipole magnets 1m long, without iron, having a bore diameter of 76 mm have been built without epoxy resins or other adhesives and 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 compressedby a system of structural support rings and tapered collets. Little "training" was required to reach quench currents greater than 95 percent of "short sample" in Helium I. The maximum quench current in He II is increased 20 to 30 percent, compared with He I operation at 4.4 K. Test results are given on cyclic losses, heater-induced quenches, and charge-rate effects.

INTRODUCTION

Epoxy has been used in many accelerator dipoles. One purpose is to fix the shape after winding so that coil parts could be transferred from the winding fixtures to the final magnet assembly; another purpose is to support the winding against magnetic loads. 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 Serpukhov, and Tristan models at KEK. Once the coil is assembled into its outer supporting structure, the epoxy bonding or adhesive function is usually 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 mechacical loading. Therefore, we set out to build and test dipoles using an epoxy-free technique to determine if improved performance can be realized.

CONSTRUCTION METHOD

The construction method is described below and is illustrated in Fig. 1.

1. The cable is wound on a cylindrical mandrel that can later be collapsed and removed. A permanent bore tube fitting over the mandrel is used to support the ends of the coil while in the straight section the bore tube is slotted to be mechanically compliant.
2. Next, a helical wrap of monofilament Nylon is wound over the bore tube. It serves as an electrical insulation 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, forming half of the coil, are wound from one length of superconductor to avoid splices between layers. 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 completed first layer is then compressed, by spreading the split central "island" while restraining the windings with the temporary leaf-chain clamps as shown in Fig. 2.
6. A helical winding of monofilament Nylon is wrapped under tension over the winding while the temporary clamps are removed one-by-one as the wrapping 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 cylindrical aluminum rings pressed onto tapered collets that rest on this aluminum slats outside the nylon wrap of the coil. End plates and longitudinal rods complete the assembly.

CONDUCTOR AND INSULATION

A 23-strand Nb-Ti Rutherford Cable, nearly identical to that used in the FNAL Doubler magnets, is used in the two-layer, 76 mm I.D., D-7 magnet series. Each strand has Stabrite or oxide insulation, but the cable, as a whole, is unfilled. Kapton and Mylar film insulation are helically wrapped over the cable. The $25\mu m$ thick Kapton is wrapped around the conductor with a gap (some 20 percent) between turns. The Mylar wrap covers the gaps in the Kapton, but has a similar space between turns. In D-7A, the Mylar film is $25\mu m$ thick. It was found to be overly fragile from the standpoint of scuff resistance and propensity to electrical shorts. In D-7B, and D-7C $50\mu m$ Mylar film is used.

The stress-strain behavior, thermal expansion, and creep of the insulated cable under compression has been measured in a 5000-lb compression testing machine; Fig. 3 shows a typical result for the epoxy-free conductor used in D-7C. More complete results are given in Ref. 1. Note the large, highly non-linear deformation as the cable is first squeezed. The winding fixture has been designed to allow for the large initial compressive deformation required to assemble the conductors. During this process, local yielding of the conductor and insulation occurs at the many regions of high stress. As shown, a low-temperature heat treatment (100C for 4 hrs) while under compression results in about 2 percent creep; after this treatment, the conductor stack is much "stiffer", with an effective compressive Young's modulus of about 3×10^6psi at room temperature and about 6×10^6psi at 77 K; subsequent creep at room temperature is negligible. This accelerated creep procedure was used in assembly of D-7C by heating the completed magnet while it was compressed by the ring-collet system.

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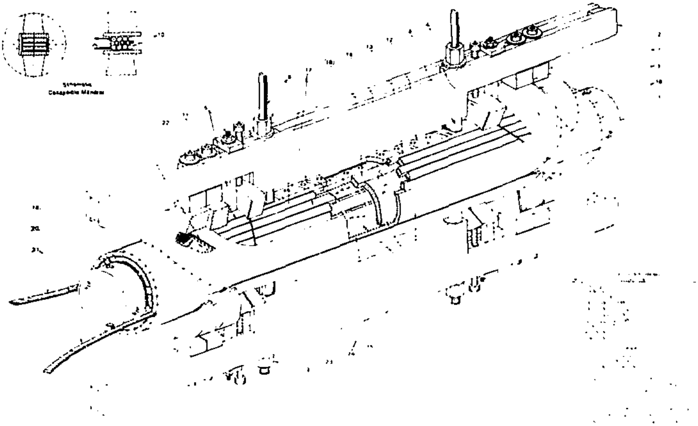


Fig. 1. Winding fixture and construction details for a dipole magnet wound with no epoxy.

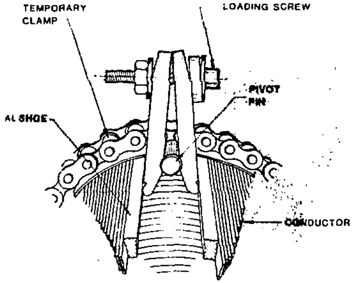


Fig. 2. Tool for compression of windings

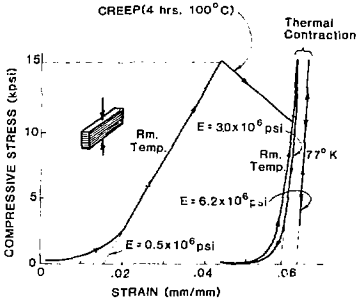


Fig. 3. Effect of accelerated creep on stiffness of insulated cable.

MAGNET DESCRIPTION

Conductor: 23 strand flattened cable; 0.7 mm strand dia., 7.9 mm wide, 1.4 mm mean thickness, trapezoidal shape with 1.7 deg "wedge" angle. D-7A and D-7C have strands coated with "Stabrite"; D-7B has alternate strands coated with copper oxide (FNAL - 'Zebra' configuration).

Turns: First layer: D-7A, 74 turns; D-7B and D-7C 78 turns. Second layer: 50 turns.

Bore dia.: 76 mm.; Outside dia. of windings (including Nylon wrap): 119 mm.; Outside dia. of Al clamp ring: 178mm; Length: 864 mm overall.

Pre-compression: D-7A and D-7B, ~8 kpsi; D-7C, ~20 kpsi. The desired coil pre-stress was not achieved in either magnet D-7A or D-7B because of creep in the windings and un-equal division of the pre-stress between layer 1 and layer 2. However, D-7C is highly pre-stressed..

TEST FACILITY

A facility for testing superconducting accelerator magnets in a pressurized bath of helium II has been constructed and operated [2, 3]. The volume of helium II surrounding the superconducting magnet was 130 liters. Minimum temperature reached was 1.7 K at which point the pumping system was throttled to maintain steady temperature.

A two-reservoir system, similar in principle to that of Claudet [4] and Bon Mardion [5,6], is used. The lower vessel, which contains the magnet and is completely filled with liquid, is pressurized to slightly over one atmosphere by contact with an upper saturated helium bath. This 28-liter upper bath also intercepts the major conduction heat loads from the vessel supports, current leads, and instrumentation leads, and supplies coolant to reduce the lower vessel temperature below T_λ. This coolant for the lower vessel is withdrawn as a liquid at 4.4 K from the upper vessel, cooled in a counterflow heat exchanger, expanded across a JT valve to a low pressure and temperature, vaporized in a coil immersed in the lower reservoir, and warmed in the counterflow heat exchanger before exhausting to the vacuum system.

Magnet instrumentation includes quarter-coil voltage taps, strain gauges on 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 [7, 8].

Test Results, Magnet D-7A

The initial testing of this magnet was complicated by a short that caused an extreme rate dependence. A charging ramp longer than 2000s was required to reach short-sample current. The first such slow ramp was run in helium II, and the short sample limit of 6400 A at 1.9 K was achieved. The associated high voltage from the extraction circuit may have cleared the apparent short because short sample performance was then achieved in both helium II (6500 A at 1.8 K) and helium I (5000 A at 4.4 K) at ramp rates up to 1 tesla per second. After a warm-up to room- temperature and a second cool-down, the magnet still performed at short sample. Then the magnet was warmed up and the compression rings were removed; the magnet was inspected and measured and the rings were reinstalled. A test at 4.4 K confirmed that full-field capability was retained, without training, but the original poor rate sensitivity, returned, presumably due to a short.

Hysteretic loss was measured in the helium II by observing the temperature monitors while the current was being cycled between two current levels. Typical losses are 60J/cycle/kA at 300 A/s between 2.5 kA and 2.6 kA; 26J/cycle/kA at 180A/s between 4 kA and 5 kA. Calorimetry is convenient in a helium II bath because temperature gradients are negligible even with large heat inputs. In addition to the expected superconductor hysteretic loss, anomalous losses were observed, possibly associated with the magnet short.

Electrical heaters were built into the magnet between the center island and the first conductor turn of the inner layer. For heat pulses longer than about 250 ms, quench current depended on the power delivered to the heater, whereas for shorter times, it depended on total energy. Table I 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.

Tests Results D-7B

Magnet D-7B trained as shown in Fig. 4. The first quench was at 3650 A, proceeding to 4650 A where it levelled off. The magnet was then run in helium II at several temperatures, reaching 5465 A. Subsequently at 4.4 K, quench current was 4700 A. After warm-up and re-cooling, two more quenches at 4.4 K were at the 4700 A level, showing retention of full training.

The magnet was run up to full field at rates as high as ~1T/sec with no reduction of maximum field attained as shown in Fig. 5. A cyclic heat generation experiment was not performed, nor were the pulsed heaters used to induce quenches.

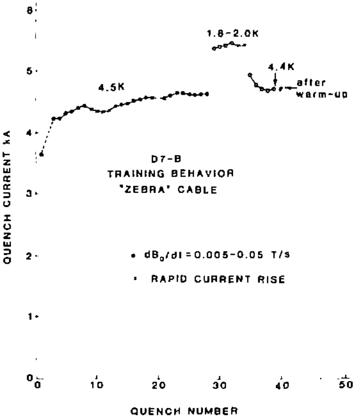


Fig. 4. Training behavior of D-7B with 'Zebra' cable.

TABLE I

I	Helium I <250 ms	Helium I 1sec	Helium I Cont.	Helium II <250 ms	Helium II 1sec	Helium II Cont.
2000A	220 mj	1200 mj				
3000A	180 mj	750 mj				
4000A	120 mj	390 mj	0.45W	220 mj	1000 mj	1.3W
4500A	90 mj	270 mj				

Pulsed and Continuous Heat Input Required
to Quench a superconducting Dipole D-7A.

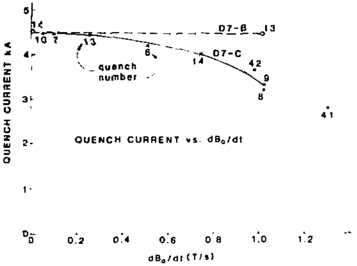


Fig. 5. Quench Current vs. Charge Rate

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 strains observed after the first five quenches.

Test Results D-7C

This magnet is identical to D-7B except: a)'Stabrite' cable is used instead of 'Zebra' cable, and b)there is approximately 20 kpsi (cold) compressive prestress instead of ~8 kpsi. Fig. 6 shows the training behavior, which is similar to D-7B; however, a higher current of 5800 A (short-sample) was reached in He II after one training quench at 5500 A.

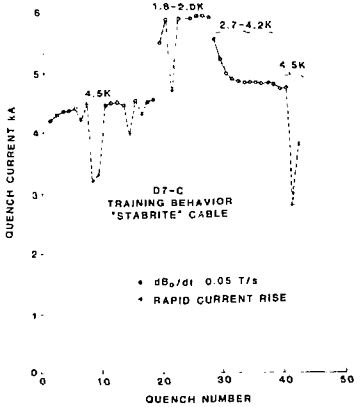


Fig. 6. Training behavior of D-7C with "Stabrite" cable.

The quench current is not affected by a charge rate of 0.1T/s but decreases significantly as charge rate is increased to 1T/s as shown in Fig. 5. Hysteretic losses were measured in helium II; at 200A/s, we measure between 36J/cycle/kA and 46 J/cycle/kA for cycling between 0 and 5 kA, 2.5 and 5 kA, and .05 and 2.5 kA; at 400A/s, the losses range between 70 and 90 J/cycle/kA.

Both 'Stabrite' magnets D-7A and D-7C have similar loss vs. charge rate behavior, even though the cable in D-7C is under much higher compressive stress, which is expected to decrease the interstrand resistance and thereby increase losses. We do not yet have comparable loss measurements for a magnet wound with 'Zebra' cable, but we expect losses to be much reduced.

CONCLUSIONS

This construction method requires simple tooling and model magnets are relatively easy to build. Therefore, this type of magnet is well suited for evaluating the behavior of different construction materials and different pre-stress.

Stable magnet behavior and reasonable training can be realized using this type of film-insulated cable, having relatively low porosity for He and no epoxy.

FUTURE PLANS

We are now building a magnet with a 133 cm bore diameter and a length of 1.22 meters, which will have three layers and should develop at least 5.5T.

REFERENCES

1) R. Meuser, S. Caspi, and W. S. Gilbert, "Measured Mechanical Properties of Superconducting Coil Material and Their Influence on Magnet Performance", VII International Conference on Magnet Technology, LBL-12438.

2) R. P. Warren et. al., "A Pressurized Helium II-Cooled Magnet Test Facility", Proc. 8th Int. Cryo. Engr. Conf. Genoa, June 1980, IPC Sci. and Tech. Press, Guildford, England, LBL-10923.

3) Caspi, S., "Gravitational Convection of Subcooled He II at Atm. Pressure", Proc. 8th Int. Cryo. Engr. Conf., Genoa, June, 1980, IPC Sci. and Tech. Press, Guildford, England, LBL-10928.

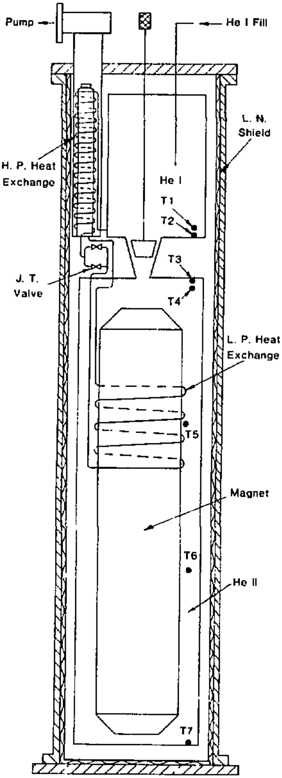
4) Claudet, G. Lacaze, A., Roubeau, P. Verdier, J. 1974. Proc. 5th Int. Cryogenic Engineering Conf. Kyoto, IPC Sci. and Tech. Press, Guildford, England, p. 265

5) Bon Mardion, G., Claudet, G., Vallier, J. C., Proc 6th Int. Cryogenic Engineering Conf. Grenoble, IPC Sci. and Tech. Press, Guildford, England, p. 159, (1976).

6) Bon Mardion, G., Claudet, G. Seyfert, P., Verdier, J., Adv. Cryo Engineering, Plenum Press, New York, NY, U.S.A., vol. 23, p. 358, (1978).

7) W. Gilbert et. al., "Testing of Accelerator Dipoles in Pressurized Superfluid Helium", CXS 40 11th International Conf. on High Energy Accelerators, p. 858 (1980), LBL-10756.

8) R. A. Althaus, et. al., "Perf. of Dipole Magnets in Helium-II, 1981 Part. Accel. Conf., LBL-11754.



XBL 805-9703

Helium II cryostat