IEEE Transactions on Nuclear Science, Vol. NS-24, No.3, June 1977

SUPERCONDUCTING COIL MANUFACTURING METHOD FOR LOW CURRENT DC BEAM LINE MAGNETS*

John A. Satti
Fermi National Accelerator Laboratory
Batavia, Illinois

Summary

A method of manufacturing superconducting multipole coils for 40 to 50 kG DC beam line magnets with low current is described. We built small coils and tested them successfully to short sample characteristics. The coils did not train after the first cooldown. The coils are porous and well cooled to cope with mechanical instability and energy deposited in the coil from the beam particles.

The coils are wound with insulated strand cable. The cable is shaped rectangularly for winding simplicity and good tolerances. After the coil is wound, the insulated strands are electrically connected in series. This reduces the operating current and, most important, improves the coil quench propagation due to heat conduction of one strand adjacent to the other. A well distributed quench allows the magnet energy to distribute more uniformly to the copper in the superconductor wire, giving self-protected coils.

We are now fabricating a one-meter long, 43 kG, 6-inch bore tube superconducting dipole. The porous coil design and coil winding methods are discussed.

Introduction

Superconducting magnets with 40 to 50 kG field will soon be required in various beam lines of Fermilab experimental areas. Dipoles and quadrupoles with 6-inch bore tube apertures will be DC operated at various field strengths. To simplify and reduce the cryogenic cooling requirements, low current operation was proposed. Each magnet would have a small lead box, and approximately 250 amps will be carried to the magnets with conventional copper conductors.

Beam transport magnets will be used downstream of targets, and the coils will be subjected to some beam particle energy dissipation. Adding the mechanical instability problem,[1] it is a must that the coil be well cooled by having every superconductor wire in contact with liquid helium. When a magnet is caused to quench from beam particle spray, the quench has to propagate to a good portion of the coil in order to spread the magnetic field stored energy to avoid destruction of the coil. The insulated strand cable with the strands electrically connected in series was proposed.

Insulated Cable and Coil Structure

A rectangular multiconductor cable is wound with insulated superconducting wires. The wires are .040 inches in diameter with twisted multifilaments of niobium - titanium alloy and copper stabilizer. A ratio of 3 to 1 of copper to superconductor is used. The wire is coated with heavy built NYFORM insulation per NEMA Specification MW 17-C. The short sample current rating of the superconductor wire is a minimum of 340 amps at 50 kG field strength.

After the cable is wound with the insulated strands, the rectangular cable is barber-pole wrapped with B-stage glass tape, leaving .125-inch space between wraps. The glass tape is .250-inch wide and .007-inch thick. After the coil is wound, the epoxy impregnated glass tape is cured in a fixture which accurately shapes the outside surface of the coil.

**This work performed under the auspices of the U. S. Energy Research and Development Administration.*

The spiral wrapped cable, after winding, produces a connecting pattern of diagonal channels. The coil is porous where every superconducting strand is in contact with liquid helium. When curing the B-stage glass tape, the coil is, in effect, potted with cooling channels included.

Figure 1 shows a 15-strand cable which is now being used to wind a shell type coil for dipole magnets. In addition to the .032-inch aluminum spacer between coil shells, we have .014-inch wide channels between each cable conductor.

By using an insulated strand cable, a low current coil (many turns) is possible to fabricate with the economy of a higher current coil (fewer turns) with the same current density. A cable can be positioned more accurately than a wire when exact winding is required to minimize field perturbations. Connecting the strands electrically in series after the coil is wound gives a low current coil with the fabrication tolerances of a larger conductor wound coil.

Using the 15-strand cable shown in Figure 1, we were able to wind a porous coil that not only has excellent cooling but also has good quench propagation. Each strand is physically in contact with the other so when one of the superconducting wires becomes normal, heat conduction causes the whole cable to quench. The quench is propagated to 15 different locations in the coil. The wire connections allow the quench to jump from the top half to the bottom half of the coil and, therefore, distribute the quench faster throughout the coil. The magnet stored energy is distributed uniformly without damaging the conductors. This gives a self-protected coil. A well distributed quench also minimizes the induced voltage between strands.

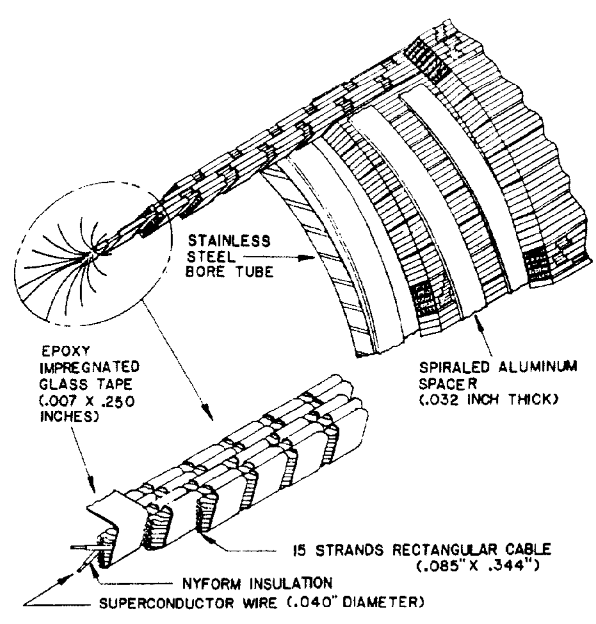

Figure 1: Porous Coil Design

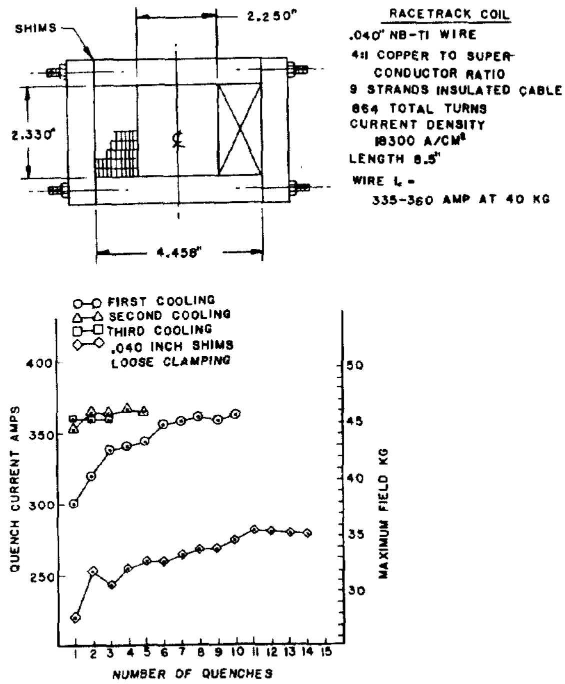

Figure 2: Test Racetrack Coil No. 1

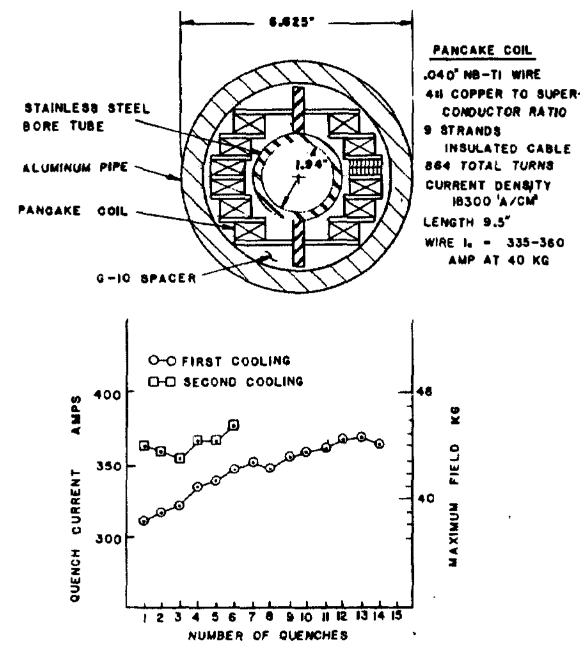

Figure 3: Test Pancake Coil No. 2

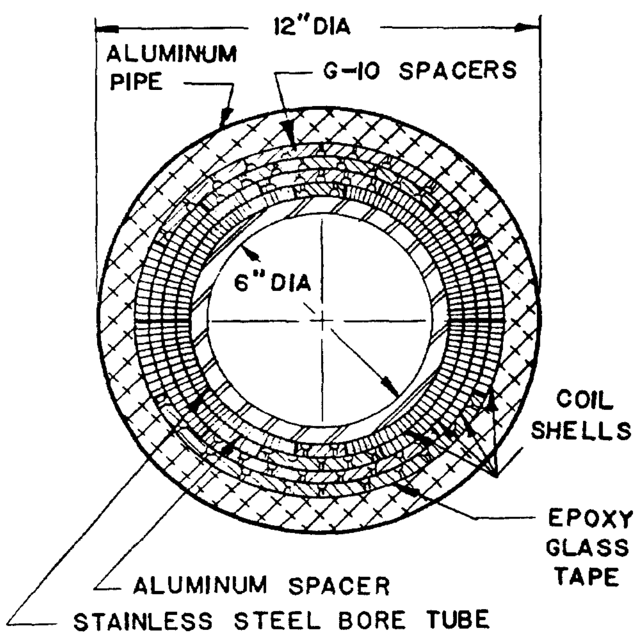

Figure 4: Dipole Coil Cross Section

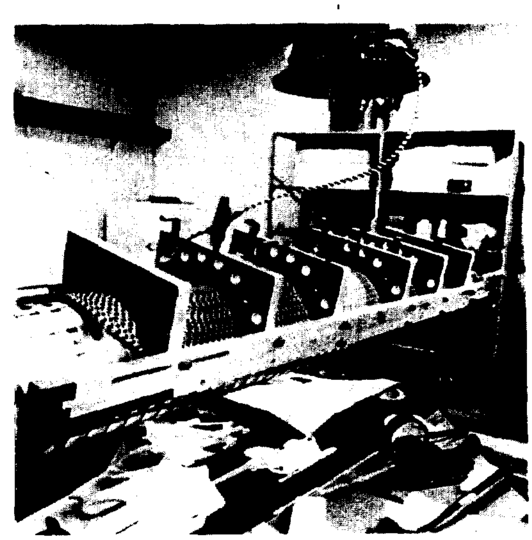

Figure 5: Coil Winding for One Meter Prototype Magnet

Figure 6: Coil Practice Winding

Results of Small Coil Tests

Two small coils[2] were built with different clamping methods. The porous coils are more spongy than epoxy potted coils. We wanted to learn what level of mechanical instability would degrade the coil performance. The object was to apply enough clamping to be able to power the coils to the superconductor short sample characteristics. Existing wire with short samples of 335 to 360 amps at 40 kG was used to make an insulated 9 strand cable.

Figure 2 shows the first coil built with a flat racetrack design. The coil was wound around a stainless steel bore. Aluminum clamping was used to clamp the outside of the coil to resist the magnetic forces. The first quench occurred at 86% of the wire short sample. In the third quench we reached the low value of the short sample, 335 amps at 40 kG. The coil was warmed to room temperature and cooled to liquid helium temperature three times. The coil did not train after the first time. We then unclamped the coil and inserted .040-inch shims to loosen up the clamping. The result was that the coil retrained as expected, and was able to reach 78% of short sample when powered. We, therefore, learned that with adequate clamping, the porous coil can be made to operate at short sample limit.

Our next step was to build a second small coil which would more resemble the full size dipole. The flat pancake coil shown in Figure 3 was built. Pancakes were wound around a stainless steel bore tube. The pancakes were shaped like a racetrack. After the epoxy impregnated tape of the cable was cured around the bore tube, G-10 blocks filled in the void spaces to form a cylinder. Holding the G-10 spacers together with cured epoxy glass tape, the cylindrical coil body was turn-round on a lathe to a .012-inch interference fit with the inside diameter of an aluminum pipe. The aluminum pipe was heated and slid over the coil assembly. As the coil was cooled to cryogenic temperature, the aluminum pipe contracted more than the stainless steel bore tube, thus, clamping the coil symmetrically. The results were that we were able to power the coil to its short sample values after four quenches. Again, as in the first coil, no retraining occurred after the first cooldown.

All the strands were connected electrically in series. The order of connection was done so that all of the strands in the top half of the coil were connected before going to the bottom half. Thus, we were able to measure quench propagation across the conductor joints. We observed quench propagation times of approximately 20 msec from insulated strand to strand and 100 - 200 msec from cable to cable.[3] A maximum voltage of 200 volts was measured between strands. We found out that our solder joints backed up with copper strips were cryogenically super stable, and the quench was hard to propagate through. However, the portion of the coil that quenched was sufficient to deposit the stored energy and protect the coil. We learned that in future coils, the interconnection between strands from the top to bottom half of the coil is required to satisfactorily spread the quench throughout the whole coil. The solder joints definitely do not need additional copper stabilizer and may be joined by a simple cold weld.

Dipole Magnet Fabrication

A cos θ distribution dipole coil is now being fabricated. The coil has a 6-inch bore tube and it is made up of 4 shells. Figure 4 shows a cross section of the coil body. A 15 strand insulated cable is used to wind the shells on the magnet bore tube. Each shell is independently cured on the bore tube with a machined mold. This gives an accurate foundation for winding of the next shell. An aluminum tape spiral wrapped between each shell forms a channel which liquid helium can flow through for convection cooling. The last coil shell is wrapped with impregnated glass tape. After the tape is cured, the coil assembly is machined round on a lathe to an interference fit with the clamping aluminum pipe. The pipe is heated to 300°F to expand and it is fitted over the coil. A moderate clamping results at room temperature. As the coil is cooled to cryogenic temperature, the aluminum contracts more than the stainless steel bore tube, further clamping the coil compositive structure. The aluminum pipe was sized to work within the yield stresses and to exert a force on the coil to exceed the magnetic forces from the coil winding.

The coil has been designed to operate with a central field of 43.3 kG[4] with a current of 3719 amps in the 15 strand cable. Connecting the insulated strands electrically in series reduces the operating current to 248 amps which is approximately 72% of the short sample critical current. This increases the size of the minimum energy needed to quench the magnet.

Figure 5 shows the winding of the first coil shell for the one meter prototype magnet. A previous practice winding shell is shown in Figure 6. After curing, the coil shell was removed from the bore tube for inspection.

The design, fabrication, and performance of the dipole magnet is the effort of many people which I hope will be published after the coil has been tested.

Acknowledgments

I wish to acknowledge the contributions of J. Colvin, J. Guerra, T. Prosapio, E. Ramirez, L. Robinson, and S. Tonkin for winding and preparing the coils. F. Browning, T. Dillman, L. Kula, A. Skraboly, and E. Tilles contributed in the design of fixtures and components fabrication. The author is indebted to P. Garbincius and P. Mazur for continuing support. I wish to thank H. Edwards, R. Kolar, and J. McCarthy for their help and use of the cryogenic testing facility. Thanks to R. F. Meserve of New England Electric Wire Corporation for the fabrication of the insulated cable.

References

1. M. N. Wilson, Stabilization of Superconductors for Use In Magnets, IEEE Transaction on Magnetics, Vol. Mag-13, No. 1, January 1977.

2. J. Satti, Fermilab, Proton Department, Eng. Notes, Low Current Superconducting Coil Test No. 1, 76-0401, September 15, 1976, and Coil Test No. 2, 76-0402, December 13, 1976.

3. P. Garbincius, et al, Measurement of Quench Performance of A Low Current Superconducting Pancake Dipole, Fermilab TM to be published.

4. S. Snowdon, Design of Superconducting High Energy Beam Line Dipole-Magnetostatics, 1977 Particle Accelerator Conference, Chicago, Illinois