Fermilab

TM-696
1610.000

THE TECHNOLOGY OF PRODUCING RELIABLE SUPERCONDUCTING DIPOLES AT FERMILAB

W.B.Fowler, P.V.Livdahl, A.V.Tollestrup, B.P.Strauss, R.E.Peters, M.Kuchnir, R.H.Flora, P.Limon, C.Rode, H.Hinterberger, G.Biallas, K.Koepke, W.Hanson and R.Brocker

I. INTRODUCTION

During the last few months serveral full size prototype dipole magnets for the Fermilab Energy Doubler have been successfully tested. This has been the result of several concurrent programs in conductor development as well as magnet construction, production and testing. We consider that our present magnets have achieved their design goal. Progress to this point has solved many pitfalls. We will describe our present technology as well as some of the decisions that led to our present design.

II. CONDUCTOR DEVELOPMENT

The configuration of the conductor has grown from a monolithic strip, 0.075 by 0.150 inch, to a 23 strand keystone shaped cable with nominal dimensions of 0.050 by 0.300 inch. The need to use the cable was required to reduce the ac losses as well as to move to another, easier to fabricate, alloy system. The present conductor is specified to perform at 5200A at 5T and in some instances has been delivered at specification.

The Laboratory has engaged in a program to purchase large quantities of semi-finished components used in the manufacture of the finished strands. The motivation for this was to insure a more uniform end product. While achieving this goal we have also found that the quality of the intermediate products has increased as a function of the scale of production. For example, the resistivity ratio of the delivered starting copper billets has risen from the specification of 180:1 to a mean of 260:1. In addition the mechanical quality of the niobium alloy rod has improved.

The recent purchase of over 9 million feet of 0.027 inch diameter composite strands has resulted in a significant reduction in price while maintaining high cryogenic performance. It is hoped to extend this program to include the cabling and insulation of the final conductor.

III. COIL CONSTRUCTION

Most of our recent work has been on the E series of dipoles. The cross section of these two layer 3 inch bore magnets is shown in Fig. 1. This geometry was chosen because it is easy to fabricate and has both a maximum transport current and inductance that match well with existing power supplies.

The dipole coil package is formed as both a top and a bottom coil, each made of two layers forming saddle shaped coils. In double layer winding, the conductor is wound out from the center in a flat spiral on one layer. After a layer-to-layer transition is made at the center of this coil, the second level is wound out from the center in an opposite spiral. The leads end up conveniently on the outer edges of the coil and no internal splice is required; the entire double layer can be made of one length of conductor.

Manuscript received August 17, 1976.

Fermi National Accelerator Laboratory, P.O.Box 500, Batavia, Illinois 60510

Operated by Universities Research Association, Inc. under contract with the United States Energy Researcl and Development Administration

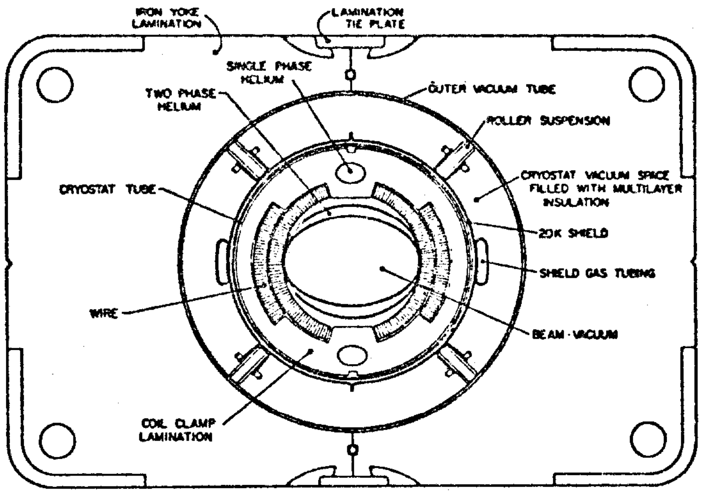

Fig. 1. Cross Section of Energy Doubler E Series Dipole

Thirty-four turns are wrapped into the first layer and 21 in the second. In the top pair the last half turn in the outer shell is omitted to form a lead at the back end of the coil. An additional cable is then placed into the void and becomes a bus-conductor. The magnet thus has a lead pair at each end.

The required conductor placement which gives fields good to one part in 10^4 at one inch from the center at the midplane is shown in Table I.

TABLE I
Conductor Placement Data

Coil	Θ Start	Θ Finish	I.D. (in.)	O.D. (in.)	Turns/Coil
Inner	0	73.1°	3.000	3.628	34
Outer	0	37.7°	3.670	4.298	21

We have found that the electrical insulation system is very important to the desired operation of the finished dipoles. The insulation system for the coils has several requirements. The conductors have to be isolated turn-to-turn to withstand voltages of the order of 10V. Extreme parts of the coils must withstand thousands of volts to either ground, companion top or bottom coils, or the bus conductor. For turn-to-turn protection, the conductor is covered in a spiral-wrapped overlapped 0.001 inch thick Mylar tape. Before this wrapping, the cable is ultrasonically cleaned in Freon solvent to remove fabrication-induced metallic slivers. No adhesive is used on the tape because of our experience that any adhesive bonded to the cable causes degraded coil characteristics. Over this Mylar taped cable is wrapped a 0.007 inch lightly epoxy-impregnated 0.25 inch wide glass tape. It is wrapped like a barberpole with 1/16 inch gaps to aid helium permeation. When the coil is formed in its mold there is just enough epoxy to hold the coil together but not enough to drip or seep into the cable itself.

The insulation from inner to outer shells is by intermediate banding. This epoxy-impregnated 1/4 inch wide glass tape, 0.021 inch thick, spaced 3/8 inch apart, is applied in a herringbone pattern down the length of the inner layer or shell. The second shell is then wound on top of this spacer. The gaps form

Presented at the 1976 Applied Superconducting Conference Palo Alto, California

helium convection passages to aid in cooling the outer shell. At the coil ends, the spacer is placed in a chevron pattern to support the coil wraparounds uniformly. Upper-coil to lower-coil insulation is provided by an extra layer of 0.010 inch Kapton at the midplane where they meet. Short-to-ground insulation is provided by a 0.030 inch built-up mat of Dacron-Mylar-Dacron sheet.

With the help of the insulation system the coils are molded to their final dimensions in a fixture after winding, but they will not stay that way without some filler to complete the circular arch. We have designed these fillers or keys into the coil-clamp-collar coil supports to be discussed below. At the half-circular ends of the coils, the coil-clamp collars cannot perform this function. Machined G-10 keys with matched coefficient of thermal expansion fill the gap. They also house the guide and support slot for the layer-to-layer transition.

IV. HISTORY AND PURPOSE OF THE TEST PROGRAM

In July 1975, an extensive test program of two-shell magnets was started at Fermilab. During this program we have tested seven 1 foot D series magnets, three 10 foot D series magnets, nineteen 1 foot E series magnets, two 5 foot E series magnets, four 10 foot E series magnets and four 22 foot E series magnets.

The D series magnets had an inner 2.5 inch bore and were made with 17 strand superconducting wire with individual strands 25 mils in diameter. The success of this program led to the start of the E series magnets, which had a 3 inch bore diameter and were constructed of 23 strand wire with a diameter of 27 mils.

The object of this extensive magnet-test program was to find out how the structure of the magnet affects its performance. The structure of the magnet was varied in many ways, such as changing the method of insulating the wire, changing the mechanical support of the wire, and changing the cooling. Performance was measured by running test curves on the magnet after it had been constructed.

In addition to the above we studied the extraction of energy from a magnet when it quenched. A 22 foot magnet at full field stores approximately 0.5 MJ, which must be extracted in a time sufficiently short that the wire does not heat excessively. At the same time, the insulation of the magnet must be sufficient to withstand the voltages that are developed during a quench.

This test program has been exceedingly fruitful. It has taught us a considerable amount about the support structure, about how magnets quench, and most important it has led to the successful development of the 22 foot magnet. It was not at all obvious at the start of this program that what was learned from a 1 foot magnet could be successfully applied to the construction of 22 foot magnets. This result must be viewed as one of the major achievements of this program.

Training

The evidence seems to indicate that magnets train because the support structure is allowing the wires to slightly move and shift at the high-field point. The frictional forces accompanying this motion pump enough heat into the superconducting wire to make it go normal. If we assume that this analysis is correct, then we can understand the major features that we observe. First, magnets do remember 95% of their training, even over periods of months provided the basic support structure has not been disturbed. If the banding around a magnet is changed, for instance, then the magnet seems to train as though it were a newly constructed coil. On the other hand, if the magnet is temperature-cycled or left sitting around the Laboratory at room temperature for long periods of time, it seems to remember its previous training history.

The magnets as constructed at present are generally fully trained in approximately 10 to 15 quenches. It is planned that each magnet would be tested before it is installed in the tunnel. During this test, vacuum measurements would be made, the coil would be trained, it would be verified that it is magnetically accurate and survey marks would be placed on the cryostat to indicate where the coil is located inside. The few quenches that it takes to train a magnet are considered a minor part of this overall test routine. Figure 2 shows the comparison in training of a 1 foot and 10 foot long magnet and Fig. 3 shows the comparison between a 10 and 20 foot long magnet. This has led us to the conclusion that the training is magnet length independent and occurs in the ends.

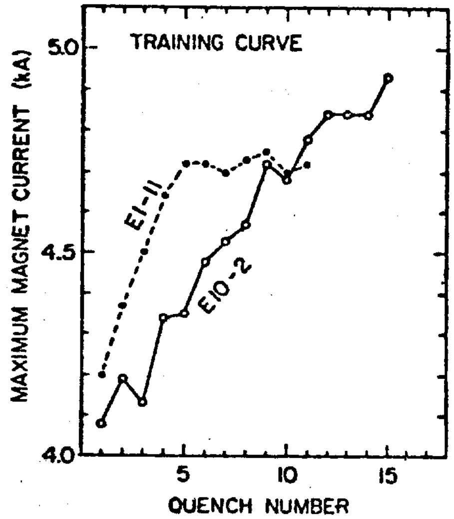

Fig. 2. Training curves of 1-ft and 10-ft magnets.

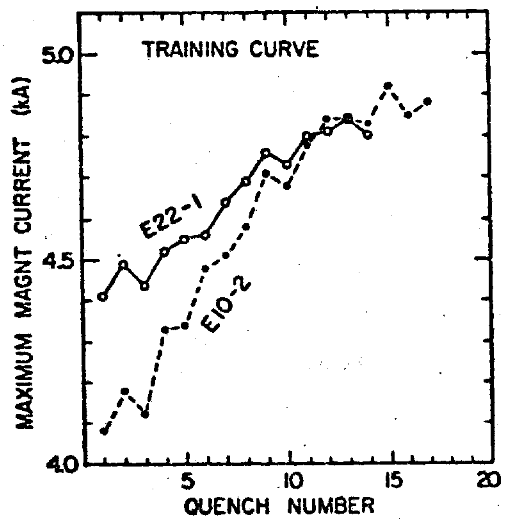

Fig. 3. Training curves for 10-ft and 22-ft magnets.

Ramp-Rate Sensitivity

When a superconducting wire is placed in a time-varying field, there are ac losses that generate heat inside of the conductor. Here we are mainly interested in their effect on the maximum field that can be obtained in a magnet. Suppose the current is increased very slowly. Then the peak field at which the magnet quenches can be close to the short sample limit. On

The other hand Fig. 4 shows a plot of B-quench versus B for magnets E1-15B and E1-17. It is seen that as B increases, the magnet quenches at smaller and smaller values of field. By increasing the pitch of the helically wrapped fiberglass insulation, magnets have been constructed which exhibit virtually no ramp rate dependence up to 40 kG/sec. (A rate 8 times higher than planned for the Doubler.) In fact, it is clear that it will probably be the rf power and refrigeration and not the superconducting magnets that limit the maximum B of the Energy Doubler.

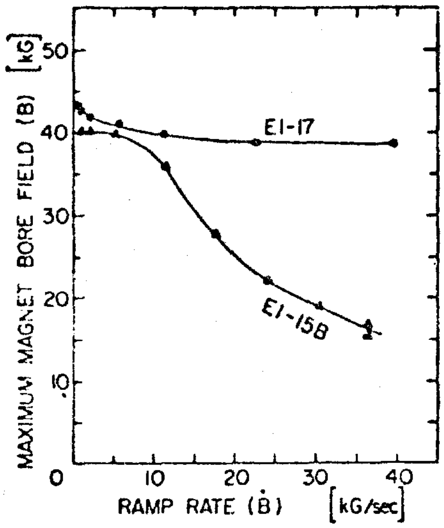

Fig. 4. Dependence of peak field on ramp rate for 1-ft magnets.

Temperature Dependence

The critical current of the superconducting wire is a function of temperature, decreasing as T increases. We have investigated this in detail on several magnets. It has been found that the peak field decreases by about 15% per K, which represents a linear decrease down to the critical temperature near 10K.

Wire Comparison

Magnets E1-17, E1-18, E1-19, and E1-20 were constructed to be identical except for the wire, which was made by four different manufacturers. Figures 5 through 7 show the results obtained with these four magnets for training, ramp-rate sensitivity at two temperatures, and temperature dependence of B-quench. Notice that the shape of the ramp-rate sensitivity curve remains unchanged as T is varied.

Support Structure

The original support structure, which consisted of internal titanium or procelain rings and external spiral banding, has been abandoned for a new structure consisting of an external stainless steel collar support system.

The original system had to be abandoned for two reasons. First, the two layers of spiral banding were not in torsional equilibrium within each layer and, as the magnet trained, it also twisted as these two layers of banding equalized their tension. Secondly, the rings were not strong enough to keep the magnet from deforming. Nevertheless, a series of these spiral-banded magnets taught us a considerable amount about the role of the support structure and how it affects training. Figure 8 shows a remarkable curve that was obtained on E1-7, a banded dipole. In this test strain gauges were placed on the internal support rings for the

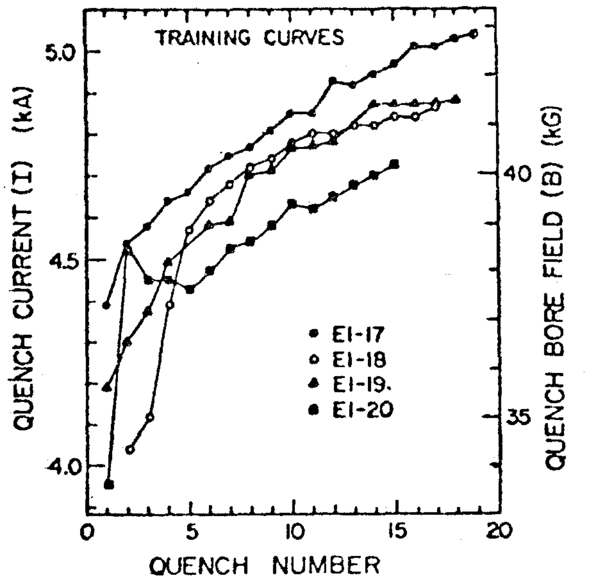

Fig. 5. Training of four identically constructed magnets.

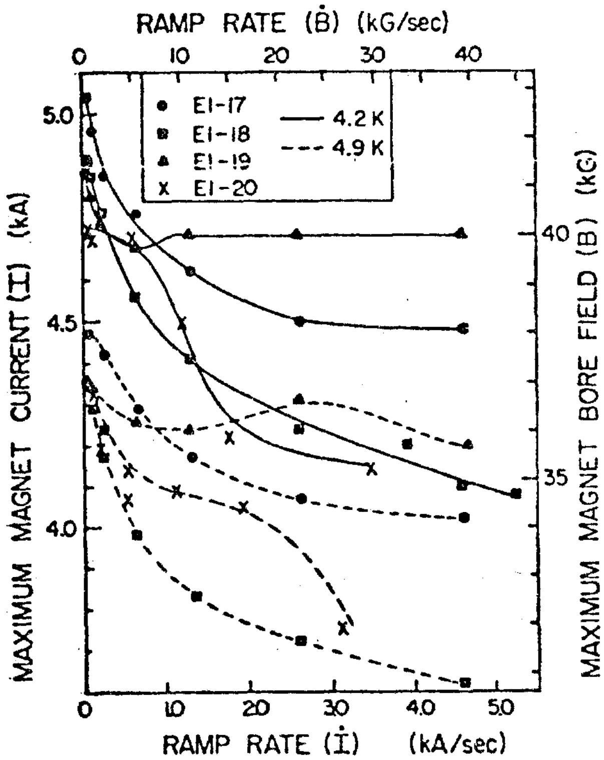

Fig. 6. Ramp-rate sensitivity of four identically constructed magnets.

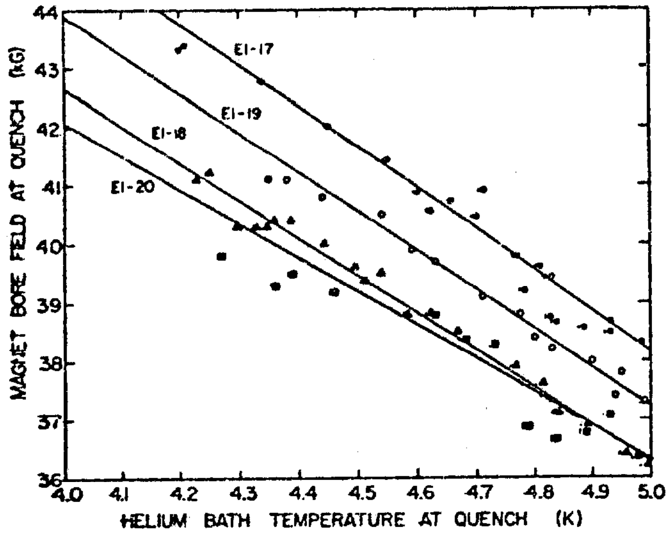

Fig. 7. Maximum field at quench for four identically constructed magnets.

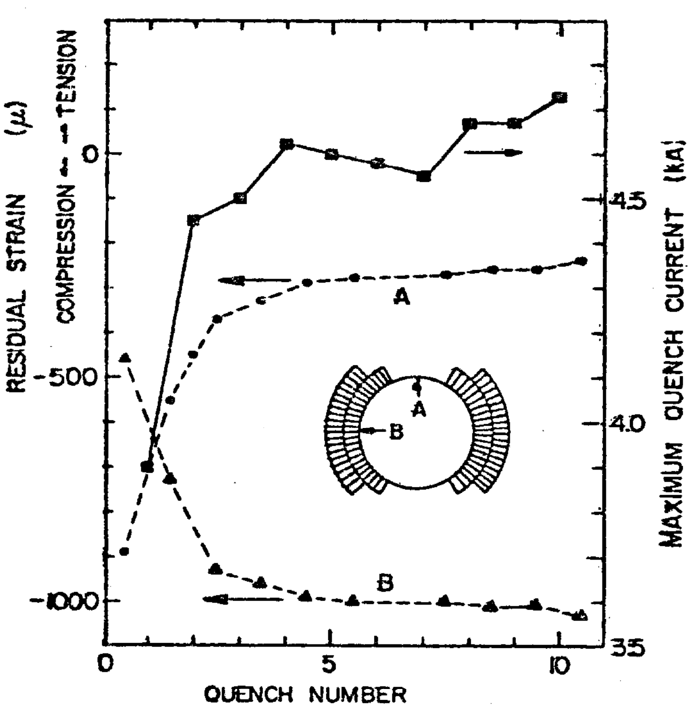

Fig. 8. Strain and quench training in a banded magnet.

magnet. The curve shows the strain gauge readings at two points on the ring separated by 90° and the regular training curve of I-quench versus number of quenches. It is seen that as the magnet trains, its shape is permanently altered. The distortions observed are as much as 25 mils on the radius and are much too large if we are to maintain the accuracy of our conductor placement.

These data led us to the design of the external stainless-steel support collars. These collars are stiff enough so that the displacement as measured by strain gauges is only 4 mils on the radius. Magnetic measurements on some real magnets in their cryostat are being made to see if this displacement is enough to generate a sextupole moment that is too large to be tolerable. It is thought that this will not be the case and preliminary measurements on E5-1 do not indicate a significant sextupole moment that is a non-linear function of current. The calculation of the sextupole moment is difficult because all the exact displacements involved are not known.

Conductor-Placement Accuracy

One more problem investigated during the 1 foot model program has been the accuracy of the conductor placement. The 1 foot magnets are too short to lend themselves to accurate magnetic measurements, which is the ultimate way to investigate the question of whether or not the conductors are placed with sufficient accuracy. On the other hand, we have cut a number of the magnets in half after they have been tested and measured optically the position of the individual conductors. A program has been written that allows the field to be calculated from these measurements. This has taught us how to position the conductors with high accuracy in a magnet. The ultimate test of this will be when we make magnetic measurements on a 22 foot magnet in a cryostat. Parallel to this program, we are constructing a series of 5 foot magnets with the most accurate techniques that we have. These 5 foot magnets will be placed in a small reusable cryostat and measured magnetically. A 5 foot magnet is long enough so that the end configuration can be studied independently of the two-dimensional field in the center of the magnet. This program is just now starting with E5-1. From the measurements made so far there is no indication that a magnet with sufficient accuracy should be unduly difficult to construct.

V. CONCLUSIONS

We have constructed prototype dipoles that are acceptable with respect to mechanical structure, cooling and operation. Several tests are now underway to measure the exact magnetic field.

ACKNOWLEDGEMENTS

This program has, of course, intimately involved many other members of the Fermilab staff. It has been a true team effort with all of the tribulations but more of the rewards than expected. Specifically we would like to cite the participation of the crew at our Magnet Facility and Technical Services Groups. Our magnet testing crew worked long hours running these devices. Ernie Ioriatti and Wally Habrylewicz led the efforts of this group of people and deserve special recognition. The guidance of Robert R. Wilson, Laboratory Director and Energy Doubler Group Leader, has been a welcome pleasure.