TM-533
1600.000
December 1974

RESULTS OF MAGNET PROTOTYPE EVALUATION FOR THE FERMILAB ENERGY DOUBLER PROJECT

B.P.Strauss, D.F.Sutter, E.Ioriatti and W.Habrylewicz,
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

SUMMARY

The Fermilab Energy Doubler project will require some 744 dipoles 6 meters long and 240 quadrupoles of varying lengths from 1.5 meters to 2 meters. Since earliest conception the Energy Doubler has been envisaged as an adjunct accelerator located in the same tunnel as the present Main Ring and capable of reaching a final proton energy of ~1000 GeV. To do this using a lattice similar to the Main Ring's requires a bending field of 45 kilogauss and, consequently, superconducting magnets.[1] The magnet fabrication and testing program was initiated in September 1972, operated the first test magnets in January 1973, settled on a shell type geometry by June 1973, tested and evaluated a matched set of dipoles by November 1973 and operated the first 6 meter, or "20 ft", prototype dipole by March 1974. The 20 ft dipole did not perform satisfactorily, reaching less than 50% of design current and exhibiting excessive training. Consequently, a redirection of the program channeled further efforts into a 2.5 ft model program to identify and correct the sources of difficulty and to enable resumption of 20 ft prototype construction.

The first phase of the 2.5 ft program has included the construction and testing of 12 magnets and is essentially complete. It has led to the promise of an improved wire and a slightly more conservative magnet design that is now being used in the construction of 2 1/2 and 10 ft models.

Events in an intensive development program do not proceed in logical sequence. While the 2.5 ft model program has been in active progress, two additional 20 ft prototype dipoles of the original design and one 7 ft quadrupole have been completed. One of these, 20 ft dipole #2, has been successfully operated in the forced flow liquid helium pump loop.[2] A 7 ft warm iron quadrupole has also been tested successfully and would be adequate in present form for use in the Doubler project.

EARLY MAGNET TESTING

Much of the direction of the Energy Doubler magnet development program has been determined by the initial boundary conditions imposed.[3,4] Requirements for a small overall cross-section, for having fields that vary linearly with excitation current and for reducing refrigerator costs arising from cooldown and eddy current heating have led us from the outset to explore using warm iron magnets. This is, of course, a controversial decision and does impose stringent mechanical requirements on the thermal-isolating magnet supports.

After a review of the many geometries used for producing dipole and quadrupole fields with superconducting magnets, studies concentrated on a shell versus a pancake geometry. Six dipole magnets and a cold iron quadrupole all of length ≤1 meter were tested in this phase of our program.[3,5] To summarize briefly: the quadrupole performance was excellent. It exhibited no training, achieved a gradient of 11 kG/inch over a 2.5 inch bore and operated at a 5 second cycle time. Wire used was a 1345 filament NbTi conductor having a Cu:SC ratio = 2:1 in a 0.150x0.075 inch solid copper matrix. Three pancake magnets and one shell magnet were compared initially. One of the pancakes and the shell, constructed of wire similar to that used in the quadrupole, achieved 35 kG with iron; but the pancake was very ramp rate sensitive while the shell magnet exhibited no ramp rate sensitivity, even when ramped with a 10 second repetition rate. The other pancakes did not perform as well, and while this geometry might have been pursued, our experience coupled with that accumulated at other laboratories caused the shell geometry to be selected as the Doubler prototype.

The essential question of whether or not two shell magnets could be duplicated with sufficient field "quality" to operate an accelerator was explored by tests carried out in summer and fall of 1973 on a matched pair of magnets, the so-called "Dual Dipoles".[6] Each magnet is 74 cm long and is constructed on a 3.5 cm diameter round bore tube using 2 sizes of superconducting wire: a 0.075x0.150 inch, 1345 filament wire for the inner shell and a 0.056x0.112 inch wire for the outer pair of shells. Fields were measured in a 2.6 cm i.d. warm bore insert using both constant frequency rotating and stepped cos nθ harmonic coils. Worst case deviation from an ideal dipole, computed from

$$\frac{\Delta B}{B_o} = \sum_{n=1}^{\infty} b_{2n} x^{2n}, \text{ where } b_{2n}$$

are the measured harmonic coefficients, shows a maximum excursion from central field B_o of about 6×10^{-4} at a radius of 1.52 cm, and a usable field extending out to ~70% of the 2.75 cm inner wire diameter. Transfer functions, measured with an NMR probe, agreed to 0.16% d.c., and a.c. tracking as measured with bucking coils was better than 5 parts in 10^4. A significant quadrupole component of 0.4%/inch was found, about 25% of which was caused by a magnetized seam weld in the warm bore tube. The rest of the error is presumed due to an asymmetry that crept in during fabrication. These magnets are still in operation having been placed in the Fermilab Main Ring extracted beam line to test operation in a high radiation environment.

20 FOOT PROTOTYPES

While the dual dipole magnets were successful in achieving adequate field quality and percent of short sample (90%), the wire used was material available and not capable of reaching 45 kG with current densities required for Doubler geometry. Optimism, the desire to circumvent normal development delays and the high promise of the first wire purchased specifically for use in Doubler magnets led us to attempt immediate construction of full scale prototype 20 ft dipoles with the cross-section shown in Figure 1. The design features Mylar banding between the inner and outer two shells and around the outside, an elongated bore tube 5 cm wide and 3.5 cm high and two sizes of superconductor. Both have 2300 filaments, a 2:1 Cu to NbTi ratio and a twist of one turn per inch. The inner shell was made with 0.075x0.150 inch and the outer two shells with 0.050x0.150 inch wire keystoned to a trapezoidal cross-section for optimum packing. Three of these magnets have now been built and two tested, both in horizontal cryostats without iron. Testing of 20 ft #1 was a valuable evaluation of cryogenics and magnet combined in one system. Excessive heat leak in the magnet suspensions prohibited operation with a CTi 1400 refrigerator using the counter-flow cooling scheme proposed for

*Operated by Universities Research Association, Inc. under contract with the U.S. Atomic Energy Commission.

the Doubler. Operation with pool boiling liquid helium was possible and addition of an external liquid nitrogen shield helped, but other problems such as severe thermal oscillations, which would empty the dewar of all helium, made power testing difficult. As can be seen in Figure 2 a total of 13 magnet quenches were accumulated during two separate tests. The magnet showed extensive training and only reached 1260A; less than 40% of short sample as measured along a no-iron load line.

At this point a considerable redirection of resources into a 2.5 ft model program was initiated to identify the sources of difficulty. But the 20 ft 3-shell magnets were not abandoned since much of their difficulties were due to cryogenic problems and two more units were near completion. Subsequently, 20 ft #2 was installed in the liquid helium pump loop where in June 1974 27 quenches were accumulated, as shown in Figure 2.[2]

In this test, also without enhancement iron, the magnet performed better than 20 ft #1 but still exhibited excessive training and did not reach design current. While magnet performance was an expected disappointment, operation with the forced flow pump loop was very successful. Quenches caused only relatively minor perturbations of pump loop operation, and carbon resistance thermometers placed in the magnet showed that complete thermal recovery from a quench required less than 5 minutes.

As part of the full scale prototype program a 7 ft quadrupole has been tested to 2170A, corresponding to a highest field of 13.8 kG at the wire and a gradient of 10.9 kG/inch with no iron. Since this test took place after the 2 1/2 ft model program was well underway, parametric variation of structure was done by testing with a) no coil impregnation and Mylar banding to hold wires in place, b) with "drip dry" epoxy impregnation and c) with the Mylar banding replaced by stainless steel banding. Best test runs were with the Mylar banding on the unimpregnated coil, the worst with drip dry epoxy and Mylar banding. The results imply that stainless steel banding with no coil impregnation would have produced the best results with this quadrupole design.

2 1/2 FOOT MODEL PROGRAM

The two problems besetting 20 ft #1, excessive training and failure to go to measured short sample, could have been caused by failure to physically constrain the coils, problems with wire properties or inadequate coil cooling. The most logical assumption appeared at the time to be wire motion, but ultimately 12 models were used to investigate all three possibilities, as summarized below:

- Tests to explore structure were done with 2 1/2 ft models #1, 2 and 3 (and 20 ft #2), all constructed with the cross-section shown in Figure 1, and #4, 5 and 7, which are 4-shell magnets as shown in Figure 3.

- Tests to explore wire properties were done with 2 1/2 ft models #5, 6, 6a, 6b and 8, all 4-shell magnets.

- Tests to explore coil cooling concentrated on magnets #9 and 6c.

Tests of Structure

2 1/2 ft magnet #1 consisted of the single, inner shell of the cross-section of Figure 1. The unique feature of this magnet was the first use of stainless steel banding. It operated between 3000 and 4500A with no iron (12 to 18 kG in the bore) and from 3000 to 4200A (19 to 28 kG in the bore) with a cold iron jacket having an 8 cm i.d. and 15 cm length. Data from tests involving unimpregnated and then impregnated coils were somewhat misleading in view of later tests in that it seemed epoxy bonding would cure all problems. The next two magnets, 2 1/2 ft #2 and #3 both had the same type cross-section as 20 ft #1 (Figure 1), but with stainless steel banding around the outer shell as did all subsequent 2 1/2 ft models. G-10 spacers on 5/8" centures and Mylar bands on 2" centers were used to provide cooling channels between the inner shell and the outer shell pair whereas 3/8" Mylar bands on 5/8" centers were used on all 20 ft magnets. Number 2 was tested in three modes: no epoxy, with epoxy and epoxied with close, cold iron (10.2 cm i.d. by 15 cm long). The first 30 quenches without iron are shown in Figure 2. 2 1/2 ft #3 is essentially identical to #2, but the last three quenches were at ~3.5K. These two magnets, while showing less initial training than 20 ft #2 are not significantly different. It was at the end of this sequence of tests that 20 ft #2 was operated in the pump loop, and it became evident that there would be no significant performance degradation in going to the long magnets at these field levels. The small difference in performance seen in Figure 2 can be accounted for by the structural effect of stainless steel banding on the 2 1/2 ft models.

Detailed computer investigations of field distribution through the coils of the 3-shell prototypes showed that there were places where the smaller, 0.050x 0.150 inch, conductor would have to operate at 105% of measured short sample at the design transport current. This, coupled with the attractiveness of lowering current density, led to the 4-shell geometry of Figure 3 which has been followed throughout the rest of the 2 1/2 ft model program.

Magnets #4, 5 and 7 were designed to test a wide range of techniques for preventing structural or wire motion. These ranged from filling the bore tube with solid epoxy to stainless steel banding between the inner and outer shell pair, to aluminum collars heated and then shrunk into place. As can be seen from the quench plot in Figure 4, the structural variations had essentially no effect and all three magnets exhibited almost identical behavior. As these results gradually accumulated, tests were designed to see if gross structural motion or individual wire motion were the principle cause of quenching. Voltage taps placed across each half shell showed that almost all quenches originated in the inner shell pair. Attempts to alter training patterns by powering first the inner and then the outer shell pair separately confirmed inner shell training and showed that outer shells could be trained to $\gtrsim$3000A. These led eventually to the I_1 versus I_2 tests shown in Figure 5, wherein the current I_2, in the outer shell of magnet #5 was set at a fixed value and the inner shell current, I_1, ramped up until a quench occurred. Attempts to fit the data of Figure 5 by a constant wire-force model such as $B_1 I_1 = (K_1 I_1 + K_2 I_2) I_1 = \text{Constant}$, where K_1 and K_2 are appropriate excitation constants, or by treating the structure as a pressure vessel in which the Maxwell stress tensor implies $(K_1 I_1 + K_2 I_2)^2 = \text{Constant}$ have all been unsuccessful thus far. It has been found that the coil quenches with a worst field inside the wire of 27.8 kG over the lower part of the curve and 30.8 kG over the upper part.[7]

Tests of Wire

The above tests coupled with poor resistivity ratios, $\rho(300K)/\rho(4.2K)$ pointed strongly to problems with wire stability. Tests to explore temperature sensitivity using magnet #5 showed only insignificant changes in the quench curve over a range from 5K to sublambda. A special magnet, #8, was constructed with and extra shell pair inside the bore tube specifically to reach 40 kG at low current density. A bore field of 41.8 kG was reached using a cold iron jacket, but only after more than 100 quenches, as shown in Figure 6.

Use of a cabled superconductor had been planned from the beginning as part of the development program, but the first such magnet, #6, also represented a significant departure in construction philosophy. The 7 strand cable was insulated only with a 75% coverage "barber pole" wrap of B stage epoxy impregnated glass tape which allowed liquid helium to percolate throughout the structure.

Magnet #6 consisted of an inner shell pair alone and was tested with known shorts. Even so, the magnet operated at 3000A with minimal training until the shorts caused it to burn out. Construction of magnet #6a, a complete 4-shell (see Figure 3), quickly followed and on the first quench went to one of the highest currents achieved in a 4-shell geometry, exhibiting almost no training on subsequent quenches (see Figure 4). This magnet also had known shorts and burned out, the arc jumping from one of the inner coils to a stainless steel intermediate band between the inner and outer shell pair. To prevent a recurrance of this the next magnet, #6b, was built with Mylar banding between the inner and outer shell pair. The Mylar evidently does not adequately constrain the inner wires, and the magnet exhibits training as Figure 4 shows. An attempt to run an I_1 versus I_2 curve on #6b resulted in another burnout. The magnet was replaced; the test tried again; and once more it burned out. The sensitivity to quenches of the 7 strand cable has been a continuing problem and is perhaps due to a central void into which the solder fill was not able to flow, resulting in poorer thermal capacity and less than the specified overall 2:1 Cu to SC ratio. No burnouts have occurred in magnets wound with solid conductor and none in cable wound magnets with current <2500A.

Tests of Cooling

The success of magnets #6 through 6b is in part due to the wire, but these magnets also have superior wire cooling. At 4.2K the heat capacities of copper and NbTi are on the order of 10^{-4} J/g-K. Thus, helium with a specific heat of 4.5 J/g-K has ~10^4 times more heat capacity. To determine how much impact the cooling had on performance, magnets #9 and 6c were built. For #9 the solid NbTi/copper wire was stripped of its Formvar insulation and wound into an inner shell pair using the same barber pole insulation technique employed for #6. In 25 quenches this magnet showed improved performance compared to previous magnets wound with solid wire, but not as good as #6, even with its shorting problems. Nor was the performance as good as magnet #6b's where, before beginning regular tests, a single excitation of the similar inner shells went to 3000A without quenching. Magnet #6c checks the cooling problem from the other direction by asking how badly performance can be degraded by impregnation. The magnet was tested with close iron and as can be seen in Figure 4 the shape of the curve shows excessive training similar to #4, 5 and 7.

CONCLUSIONS

With respect to structure: stainless steel banding provides sufficient mechanical constraint under the loading encountered so far, but it must be used in both intermediate and outer shell banding. Impregnation with epoxy or other plastics is effective in improving performance, but apparently only when they do not interfere with cooling.

With respect to cooling: helium permeation throughout the magnet structure is very desirable, if not necessary. The use of impregnating agents to provide greater coil strength should not be done at the expense of cooling the wire.

With respect to wire: short sample data is necessary to the designer, but it is not sufficient information. Other tests must be developed. Engineering standards and standard testing procedures are needed to allow minimum stability criteria to be set by the buyer which manufacturers can have some hope of meeting. High field stability criteria, particularly as applied to wire operating in a complex magnet structure, are only beginning to be understood. Hopefully, some of the progress may come from this program.[8]

The next magnet, now under construction, follows a more conservative approach. It will be 4-shell configuration on a round bore and will use graded superconducting cable: 0.075x0.150 inch for the inner shell pair and 0.050x0.150 inch for the outer two shells. B stage impregnated glass tape in the 75% coverage barber pole wrap will be used for insulation. The design operating current of 2350 A will produce a central bore field of 45 kG with warm iron of 8" i.d.

ACKNOWLEDGEMENTS

This program has of course intimately involved many other members of the Fermilab staff. It has been a true team effort with all the bumps and hazards but more of pleasures and rewards than expected. Specifically, the guidance of Paul Reardon, Bill Fowler and Darrell Drickey have been a welcome pleasure. To all who participated: Thank you.

REFERENCES

1. P.J.Reardon and B.P.Strauss, Editors; "Some Preliminary Concepts About the Proposed Energy Doubler Device", Fermilab Technical Memo TM-421-0428, May 1973.

2. P.C.VanderArend, S.T.Stoy and D.Richied, "Cooling of a System of S.C. Magnets by Means of Pumped Subcooled Liquid Helium", Paper U-1, Applied Superconductivity Conference, September 1974.

3. Fermilab Staff, Energy Doubler Design Study, A Progress Report, Fermilab Physics Note FN-263, October 1974.

4. D.A.Edwards, W.B.Fowler, P.J.Reardon, D.E.Richied, B.P.Strauss and D.F.Sutter, "Progress Report on the NAL Energy Doubler Design Study", IXth International Conference on High Energy Accelerators, May 1974.

5. P.J.Reardon, B.P.Strauss, D.F.Sutter, R.McCracken, D.Richied and M.A.Otavka, "Preliminary Modeling and Testing of Ramped Superconducting Dipoles for the NAL Doubler", 1973 Particle Accelerator Conference, IEEE Transactions on Nuclear Science, Vol. NS-20, No. 3, June 1973.

6. B.P.Strauss and D.F.Sutter, "Evaluation of Matched Superconducting Dipoles", Fermilab Technical Memo TM-456-0428, December 1973.

7. T.L.Collins, Private communication.

8. T.L.Collins, "A Magnetic Stability Limit for Multifilament Superconducting Wire", Paper D-7, Applied Superconductivity Conference, September 1974.

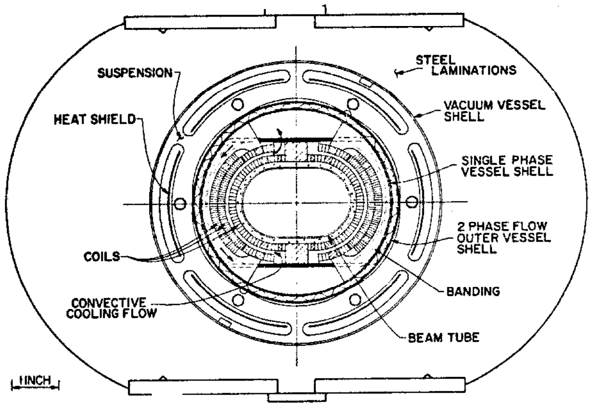

Figure 1. Cross-section typical of 20 ft dipoles #1, 2 and 3 and 2 1/2 ft dipoles #2 and 3.

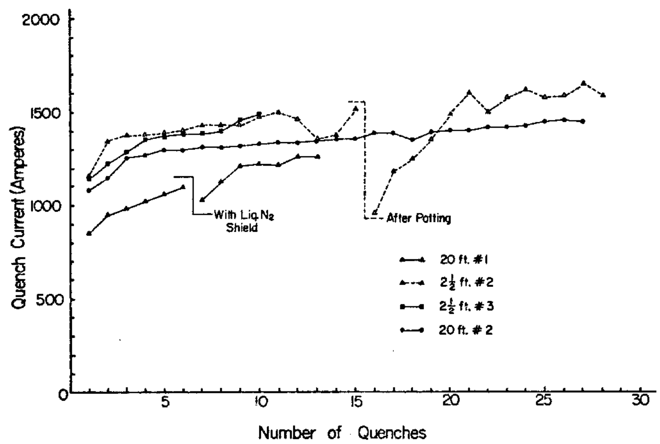

Figure 2. Training curves for 3 shell Doubler Prototype dipoles: 20 ft #1, 2 and 3 and 2 1/2 ft #2 and 3. See Figure 1 for cross-section.

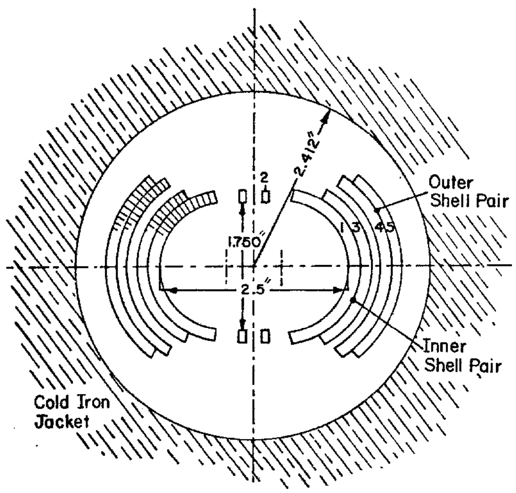

Figure 3. Cross-section typical of 4 shell 2 1/2 ft dipoles #4, 5 and 7 with solid conductor and #6, 6a, 6b and 6c with 7 strand cable.

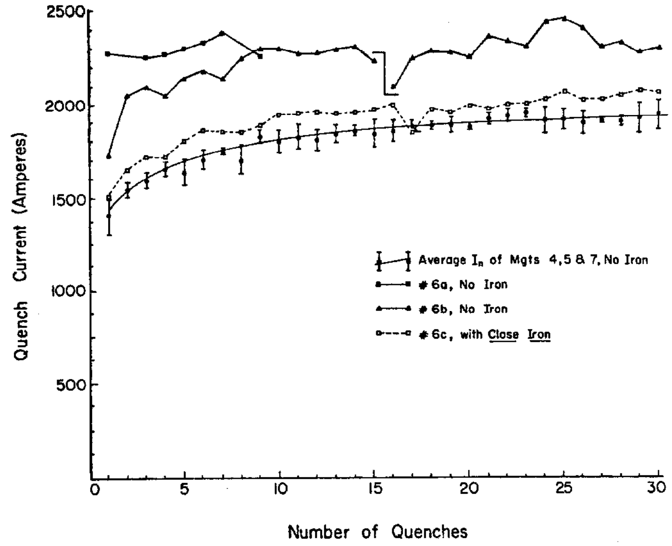

Figure 4. Training curves for 4 shell 2 1/2 ft dipoles #4, 5 and 7 (solid wire) and #6, 6a, 6b and 6c (7 strand cable). Magnet #6c has close iron in partial saturation.

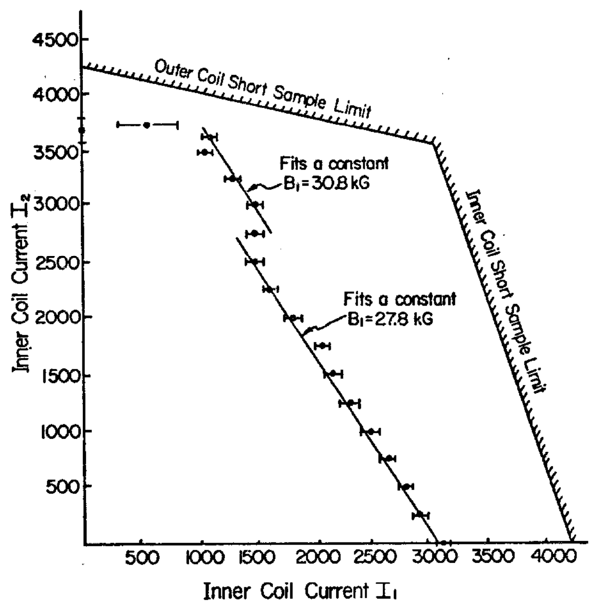

Figure 5. Outer coil current versus inner coil current for 2 1/2 ft #5. B_1 is the highest field value at any conductor in the inner shell. All quenches started in inner coils. Five quenches were taken per point.

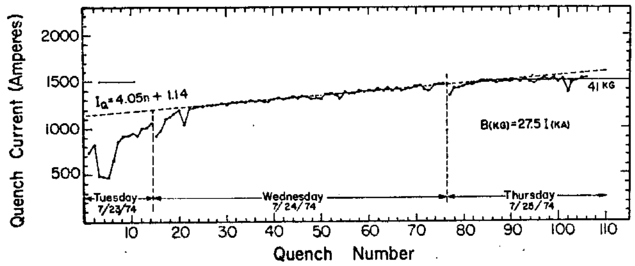

Figure 6. Training curve for 2 1/2 ft #8, a 6 shell magnet made with solid conductor. Test made with close iron.