IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

TESTS OF A 3 METER CURVED SUPERCONDUCTING BEAM TRANSPORT DIPOLE MAGNET*

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Summary

Initial tests of one of the curved 3 m long superconducting dipole magnets[1] intended to generate 6.0 T and produce a 20.4° bend in the primary proton beam to a new D-target station at the Brookhaven National Laboratory AGS have been completed. Although this magnet, whose window frame design generally follows that of the successful "8°" and "Model T" superconducting dipoles,[2,3] demonstrates many of the desirable characteristics of these earlier magnets such as excellent quench propagation and good ramping properties, it has only reached a disappointingly low magnetic field of 3.5 to 4.0 T. Because of the great interest in superconducting magnet technology, this report will describe the diagnostic tests performed and plans for future modifications.

Introduction

The design of the 3 m long curved superconducting beam transport dipole magnet is based on that of the 8° window frame magnets which have been operating for over 7 years in a primary proton beam line at the AGS. The parameters of the 3 m magnet are given in Table I and a more complete description of the magnet is found in reference 1.

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D BEND SUPERCONDUCTING MAGNET PARAMETERS

I. DIPOLE MAGNETS - 2 EACH	
BEND ANGLE	10.20° PER MAGNET
MAGNET IRON O.D.	19.25" (48.895 cm)
MAGNET IRON LENGTH	120" (3.048 m)
CORE PACKING FACTOR	96%
COLD BORE DIAMETER	2.875" (7.303 cm)
MAGNET GAP HEIGHT	5.850" (14.859 cm)
MAGNET COIL HEIGHT	5.725" (14.542 cm)
MAGNET COIL I.D.	3.250" (8.255 cm)
L_B ASSUMED	121.06" (3.075 m)
B AT 30.9 GeV/c	6.0 T
B AT 28.5 GeV/c	5.5 T
I AT 6.0 T	1654 AMPS
NI AT 6.0 T	883,236 A.T.
STORED ENERGY @ 6.0 T	~ 700 kJ
INDUCTANCE @ 6.0 T	~ 0.5 H

Table I.

Constraints imposed by other components in the D-line beam required that the primary proton beam be of very low divergence, a divergence however which led to a beam size at the superconducting magnet of up to 5 cm when 99.9% of the intensity distribution of the beam was included. To minimize the overall size of the magnets, the magnet was curved through 10.2° to follow exactly the trajectory of the beam thereby avoiding the dimensional increases necessary in straight bending magnets from sagitta considerations.

In addition to this curvature, other differences in design compared to the earlier window frame magnets are: sextupole bias windings are connected electrically in series with the main dipole windings; the two outer layers of the main dipole coil are wound with "graded" conductor, i.e., conductor whose cross-sectional area is about 60% of that of the conductor in the inner layers; the main dipole conductor is larger and approximately 2.4 times stiffer than conductor used in previous magnets.

Test Arrangement

The arrangement of the power supply and the instrumentation connections to the "D" bend dipole magnet in its cryostat are shown in Fig. 1. In

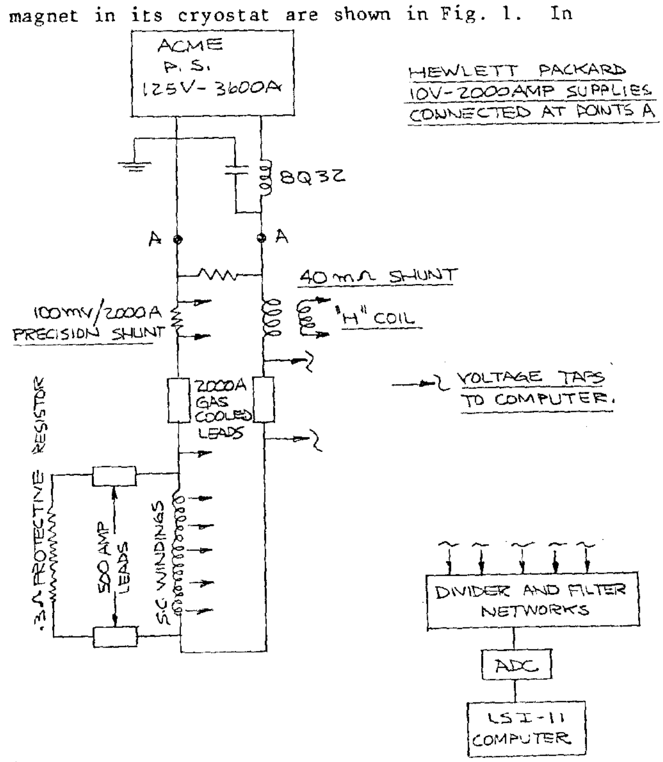

Fig. 1. Schematic showing the arrangement of the power supply and the instrumentation connections for the "D" bend dipole tests.

addition to the 125 V ACME power supply, a 10V Hewlett-Packard power supply was used in cases where it was desirable to have an ungrounded supply. Instrumentation signals from voltage taps, search coils, and temperature sensors on the magnet system were led to a control trailer to indicate on meters and oscilloscopes or for digitizing and recording with a PDP LSI-11 computer. In the later test series, acoustic signals from the magnet helium vessel were monitored by microphones coupled to the mounts on the vacuum tank for the chains supporting the magnet vessel in the vacuum tank.[1] Strain gauges were also mounted on the iron yoke of the magnet.

*Work done under auspices of U.S. D.O.E.

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The helium vessel and vacuum tank utilized in the magnet tests constitute the curved horizontal cryostat to be installed in the primary proton line.[1] The innovative design of the vacuum tank incorporating a removable lid and separately packaged superinsulation blankets has, as intended, permitted both rapid disassembly and reinstallation of the magnet and helium vessel. The cooldown time for the magnet in its cryostat is three days and the measured heat leak to the cryostat approximately 20 w.

Test History

In the initial test period, the magnet was first rapidly cycled to about 730 A (3 T) in an attempt to break the bonds of and shake out quick setting adhesive which had been used in small quantities in a number of places to hold the conductor during the winding of the curved magnet. After approximately 100 fast cycles, the magnet was ramped slowly until a quench occurred at 755 A. This value was less than one-half the 1630 A required for the design operating field of 6 T. During this first period, the magnet was quenched 30 times. The measured quench current is plotted against the quench number in Fig. 2. As can be

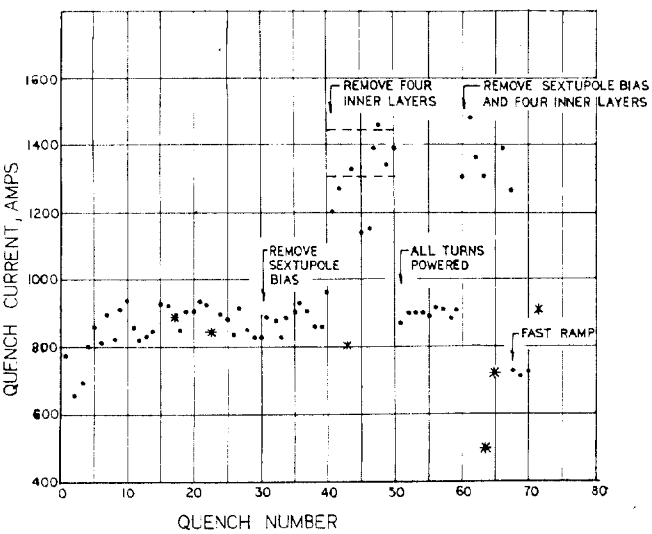

Fig. 2. Quench current versus quench number for the "D" bend dipole magnet.

seen from this figure, after 4 quenches, the quench current settled into a 130 A wide band of currents centered about 885 A and did not improve with time. Although Fig 2 might be interpreted as showing two distinct sub-bands of current up to quench No. 30, this interpretation does not appear to have statistical significance. Quench No. 17 and quench No. 23 are designated by asterisks in Fig. 2 because a low He level was detected in the first case and a rapid ramp rate used in the second. Voltage tap measurements made using storage oscilloscopes during this sequence of quenches showed a pattern which was consistent with all the quenches beginning in the Helmholtz sextupole windings. Since such windings had appeared to be less stable than the main dipole coils in earlier window frame magnets, it was decided to disconnect and bypass these windings and test again.

The quench currents during this second test period which include quench Nos. 31-40 in Fig. 2, failed to increase by any statistically significant amounts and tests at ramp rates up to 5 A/sec indicated no ramp rate dependence. Most of the quenches in this sequence were recorded by the computer system and showed a consistent pattern of quench initiation in the innermost layer of the main dipole coil. Discernible noises were also heard when the magnet was being powered by using a stethoscope at the room temperature ends of the chains supporting the magnet in the cryostat.

To affect a measurable change in quench current, the first four inner layers of the main dipole coil were next disconnected leaving 65% of the original number of turns in the magnet circuit. The input lead to the new innermost layer was also replaced since there appeared to be a slight possibility that lead heating was initiating the quenches.

During the next test period which included quench Nos. 41-50 in Fig. 2, the quench currents moved to a new band approximately 50% higher than before. The increased currents and reduced number of turns corresponded to a magnetic field intensity which was approximately the same as in the previous tests. The quenches observed in this period were initiated in different coil layers. Acoustic signals were strong both on current rise and fall. Some quenches occurred 10 to 20 minutes after the dipole coil current had reached a set value.

The pattern of quenches seen in these tests including the large variations and long time delays seemed to indicate that elastic motion was taking place when the magnet was charged. This elastic motion could then be followed by much smaller inelastic motions which, either through time and space coincidences or fluctuations in amplitude, finally generated enough energy to exceed the quench threshold. Acoustic signals also seemed to support this scenario. A mechanism suggested to describe such behavior required the straightening of the entire magnet yoke and coil structure under magnetic pressure followed by a stick-slip movement of individual superconducting wires in the coil windings. Optical sights were placed in the cold bore tube of the magnet assembly and at one end of the helium cryostat to check for this straightening effect. No movement was observed to within the limits of measurement (< 0.08 mm).

Following this test, the magnet was removed from the helium vessel and its effective Young's modulus measured to be 5×10^6 psi by observing the deflection of the yoke when a force was applied at its center perpendicular to the magnet axis using an hydraulic jack. The magnet coil assembly was then removed from the iron yoke and inspected. It was discovered that a number of the bolts through the side plates of the assembly which retain the coil windings were loose. The bolts were retorqued pulling the side plates in a total of 0.38 mm and produced a metal-to-metal fit with the top and bottom plates, a fit which had been designed for but not achieved in the previous assembly of the coil. The end brackets of the coil assembly were also modified to give improved support of the coil winding ends. The coil assembly was carefully shimmed and reinserted in the iron yoke. Strain gauges were mounted on the inside radius of the curved magnet yoke.

The quench currents reached in the next test period with all coil turns powered are shown in Fig. 2 from quench No. 51 to 59. No improvement in magnet performance was achieved, the various quench currents falling within the band observed in the first test period. However, the quench currents showed considerably less variation than previously. The sextupole windings and the first four inner layers of the main dipole coil were once more disconnected from the magnet circuit and again, the quench currents under these conditions from quench No. 60 to 66 fell essentially within the same band as quenches 41 to 50. Ramping the magnet at 6 A/sec produced quenches (Nos. 68, 69, and 70) at approximately one-half the quench currents reached at a ramp rate of 0.25 A/sec. The quenches indicated by *'s in Fig. 2 are attributed either to low helium level or power supply malfunction. The noise levels from the magnet as the current was ramped up and down were substantially lower than during previous tests but were clearly audible each time as the limiting quench current value was approached. The noise is described as similar to gravel being poured into a bucket. No noise was detected from the magnet prior to a quench in cases where the magnet quenched after the current had been set at a constant value. The strain gauges mounted on the magnet gave no indication (< 0.002 mm) strain and no significant electrical activity was observed just prior to the start of a quench with voltage taps across coil layers. Similar acoustic tests, performed subsequently on the straight "8°" superconducting window frame magnet, detected no such noise from that magnet.

Because of the emphasis placed on understanding the reasons for the low quench currents, a major effort to measure the field quality was not made. Qualitatively, no evidence of long time constants associated with shorted turns was seen. The magnet could be ramped to full field in a few minutes. There was evidence of eddy currents in the poles which were only partially laminated.

Possible Causes for Quenches at Currents Below the Design Value

One possible mechanism for the observed pattern of quenches, as suggested above, might be a gross elastic motion in the magnet structure followed by a number of small random inelastic movements. These small movements through fluctuations in time or space correlations eventually exceed the energy threshold required to initiate a quench (estimated to be approximately 10 mJ/gm of conductor for this well cooled magnet).

The acoustic signals appear to fit the hypothesis that the entire magnet structure is being straightened. An analogy with fluid pressure inside a Bourdon tube shows that the magnetic pressure of the coils might produce a straightening moment. With a series of optical sights in the magnet bore tube, an upper limit of < 0.38 mm can be set on changes in the sagitta of the magnet yoke. Measurements of the effective Young's modulus of the yoke (5×10^6 psi) and upper limits on the moment indicated expected changes of approximately 0.20 mm in the sagitta. Measurements with strain gauges on the magnet yoke set an upper limit on changes in the sagitta of 40 times less.

In other magnets of the window frame type, the yoke formed a "metal-to-metal" fit around the conductor windings, i.e., the space between the iron side plates of the central coil assembly was precisely the sum of the thicknesses of the mandrel, the conductors and high purity aluminum sheets. Initially, in this magnet, the side plates could only be drawn to within 0.38 mm of this dimension because of the presence of discrete amounts of the quick-setting adhesive used during coil assembly, raising the possibility that the conductor was not sufficiently constrained by the yoke. As noted above, the central coil assembly was carefully refitted but this refitting did not result in an improved magnet performance.

The failure of the quick-setting adhesive used during the coil assembly under electromagnetic pressures at low temperature is considered an unlikely possibility as a cause for the erratic quench currents observed. Such failure would probably lead to a more consistent "training" behavior.

Although the clamping arrangement for the side support of the saddle-shaped ends of main dipole coil is very similar to that used in earlier magnets, the curved structure of this magnet and the increased stiffness of the conductor used resulted in a bowing out of the conductor beyond the ends of the side plates. Some modifications of the end clamps were made prior to the last tests but the possibility of conductor motion in the saddle-shaped ends requires further investigation.

Electrical shorts also appear to be unlikely initiators of the magnet quenches because of the lack of any significant ramp rate dependence and the absence of any indication from either direct electrical or magnetic field measurements. Finally, it is possible that a construction error unique to this magnet resulted in an insufficiently supported conductor. However, the fact that the quenches were initiated in different layers of the magnet windings cast some doubt on such an error being a cause of the magnet quenches.

Future Plans

Since the performance of this curved magnet contrasted markedly with the consistent success of previous straight window frame magnets in reaching or exceeding their design specifications, it may be that the below design value performance is related to the curved structure. An effort is therefore being undertaken to design and build a straight magnet approximately one-half (1.5 m) as long. Testing of this magnet is expected to begin in April, 1981. Future plans for the curved magnet include impregnating the coil ends in epoxy or wax to minimize motion in the coils ends, and, if no improvement in performance results, impregnating the entire magnet windings to reduce conductor motion every where.

Acknowledgments

It is a pleasure to acknowledge the dedicated efforts of the technicians and designers associated with this project. Considerable assistance was received from a number of groups in the Experimental Planning and Support Division of the Accelerator Department. Among these are the Helium Systems, the Cryogenic Target, and the Experimental Areas Groups. Finally, we would like to express our deep appreciation to Derek Lowenstein and Lyle Smith for their continued support and encouragement.

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