Measurements of Loma Linda Proton Therapy Gantry Dipoles

Henry D. Glass, Peter O. Mazur, James W. Sim
*Fermi National Accelerator Laboratory**
P.O. Box 500, Batavia, IL 60510

Abstract

We describe the procedures used by the Fermilab Magnet Test Facility (MTF) to perform tests of dipoles to be installed in the beam lines of the Loma Linda University Medical Center Proton Therapy Facility. The dipoles were manufactured in two styles, one style having a 45° bending angle and the other a 135° bending angle. The tests included magnetic field measurements using a Hall probe and the measurement of coil temperatures, voltages, and water flow rates. The probe was mounted on a movable cart which could be wheeled along the magnet beam pipe; we mounted extensions onto each end of the beam pipe to allow for the probe to measure the magnet end fields. The probe was also mounted at varying transverse positions on the cart to allow for field shape measurements, from which body quadrupole and sextupole coefficients were determined. A longitudinal sampling of the field down the entire length of the magnet allowed us to measure the total integrated field of each magnet. Hall probe measurements were controlled by a C program running on a Unix workstation.

I. Introduction

This report describes the procedures used by the Fermilab Magnet Test Facility to perform tests of the Loma Linda gantry dipole magnets, and also to present the measurement results. The dipoles consisted of two classes, a 45° class (of which there are two styles called Type 1 and Type 2), and a 135° class. The tests included magnetic field measurements with a single Hall probe and some auxiliary measurements of coil temperatures, voltages, and water flow rates.

*Operated by Universities Research Association under contract with the United States Department of Energy

0-7803-1203-1/93$03.00 © 1993 IEEE

II. Measurement Apparatus

Each magnet was mounted on MTF Test Stand C and powered by two PEI power supplies connected in parallel. Magnet current was measured by a Holec transductor and read out by a digital voltmeter. The Low Conductivity Water (LCW) system provided cooling at a nominal 26.5 liters/minute flow rate. Thermocouples attached to the supply and return monitored coil temperatures. The Hall Probe was read out by a Digital Teslameter (Group-3 Corp. Model DTM-141), which featured a digital display and a GPIB interface for computer readout.

The probe was mounted on a wheeled cart which was positioned longitudinally by rolling inside the magnet's beam tube. Stainless steel extension tubes, having the same cross section as the beam tube (5.08 cm x 2.54 cm), were attached to each end of the magnet to allow the cart-mounted probe to measure the magnet's end fields. The far end of the extension tube on each end extended 54.0 cm beyond the plane of the first lamination.

A cloth tape measure was attached to the cart and ran along the inner radius of the beam tube and out the lead end of the magnet. The longitudinal (z) position was measured by reading the tape measure at the end of the extension tube. Transverse (x) position was defined to be zero at the center of the beam tube, and to increase toward the convex side of the magnet. Different probe x-positions were obtained by using screws to mount the probe at the desired position on the cart. Mounting holes were drilled allowing x-positions of 0., ±6.35 mm, and ±12.7 mm.

Figure 1 displays a conceptual topview of a Loma Linda magnet as it was mounted on the test stand. The figure shows the coordinate system used.

III. Measurement Procedures

Magnetic field measurements were controlled using the *ptscan* (version 1.22) program, which was developed at MTF for controlling Hall and NMR measurements of Main Injector magnets. This program, which runs on a Unix workstation, operates by reading a set of commands contained in a file called a 'checklist.' The checklist contains all of the commands needed to perform the measurement

PAC 1993

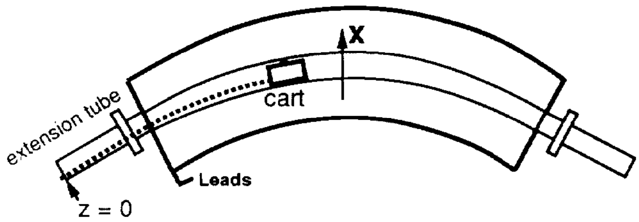

Figure 1: Top view of a typical Loma Linda gantry dipole. The z origin is at the end of the Lead End extension tube.

sequence. The *ptscan* program, as it executed the checklists, instructed the measurement technician to manually position the probe. Magnet current was set under computer control, and was digitally displayed on the workstation screen. The probe position was entered manually by the measurer, while magnet current and probe reading were obtained by reading GPIB instruments. All data were then recorded to a data file. All current ramps were executed sufficiently slowly (100 A/s typically) to avoid overshoot. In each of the checklists indicated below, we first measured the probe offset by placing the probe inside a mu metal shield. This offset was automatically subtracted from the data by the readout device. Prior to taking field measurements, one or more hysteresis ramps were executed.

A. *Checklists*

1. Central Field Measurement: Position probe in magnet center; loop from I=0 to I=3100 A in 100 A steps; then loop from I=3100 A to 0 in −100 A steps.

2. Body Field Measurement: Loop from I=0 to I=2500 in 500 A steps; then from 2600 to 3100 in 100 A steps. Measure at 3 different longitudinal positions.

3. End Field Measurements: measure longitudinal profile of each end at 12.7 mm intervals. Do at 2000 A and 3100 A.

4. Off-Axis Measurements: At three different longitudinal positions in body, measure field at $x = \pm 12.7$ mm, ± 6.35 mm, and 0. Do at 2000 A and 3100 A.

5. Longitudinal Scan: Measure longitudinal variation of field inside body of magnet in 2.54 cm steps (for 45° magnets) or 5.08 cm steps (for 135° magnets). Do at 2000 A and 3100 A.

6. Water Temperature, Coil Voltage, Flow Rate: record these quantities as a function of current from 0 to 3000 A in 500 A steps.

IV. Measurement Results

The data for each magnet are reported in [1]. The data report includes a tabular listing of the measurements from each checklist, a set of graphs, and a list of calculated results (field integral and harmonics). The tabular listings of magnetic measurements include: x and z positions, transductor voltage; magnet current, B field reading from Hall probe, and time from beginning of measurement sequence. Listings of nonmagnetic measurements included the coil voltage, water supply and return temperatures (thermocouple readout), the LCW flow rate, and the water supply and return pressures.

A. *Field Integral Calculation*

The quantity $\int Bdl$ was calculated by combining the data for the end fields and the longitudinal scan. This calculation was performed by the following method:

1. A radius of curvature correction was made to the z-position measurement. As listed in the data tables, z is the tape measure reading along the inside radius of the beam tube. To find z along the center of the beam tube, we calculated

$$z_{center} = z_{tape} \cdot \frac{R}{R - w/2}$$

   where R is the beam tube radius of curvature (134.6 cm) and w is the beam tube width (5.08 cm).

2. We wanted to measure the field at constant current, but the power supply was observed to fluctuate and drift over the course of the measurement, and also the mean measured current was different from the nominal current. For each data point, we calculated the field at the nominal current i_0 from the measured field at current i by applying the correction

$$B(i_0) = B(i) - (i - i_0)\left(\frac{dB}{di}\right).$$

   The field derivative dB/di was calculated from the Central Field measurements and was assumed to be constant in z.

3. The corrected B fields were calculated from two measurement sets: in the 'pass 1' set, the probe sampled the field as it was moved towards increasing z, and in the 'pass 2' set the probe moves toward decreasing z. We calculated the average field at each z and standard deviation from these two sets.

4. We then integrated the field over the z-range which included the entire magnet and extended 33 cm beyond each end. This was far enough out so the end field had fallen below 1% of the body field. Integration was performed using the trapezoidal rule. The statistical error in the integral was calculated from the

standard deviations in $B(z)$. A systematic scale error of 0.2% for the 45° magnets was estimated from the observation that the cloth tape measure reading depended on the tension applied by the measurer. For the 135° magnets, we switched to a fiberglass tape measure, which had an advantage of being much less vulnerable to stretching, and for these magnets we did not list a scale error.

We note that while the Hall probe, whose active area was about 2.5 mm x 2.5 mm, significantly undersampled the z variation of the field, we believe the error due to undersampling is small.

B. *Harmonics Calculation*

We estimated the normal quadrupole and sextupole (b_1 and b_2) from the off-axis measurements by fitting the measured field shape to a polynomial. This calculation was performed in the following way:

1. A current correction to the B fields was made using the Central Field dB/di measurement as described in the previous section.
2. At each z position, the off-axis fields were normalized to the fields at $x = 0$ by calculating

$$B_n(x) = \frac{B(x) - B(0)}{B(0)}.$$

3. The normalized fields $B_n(x)$ were averaged over all z's and standard deviations calculated. This was an attempt to approximate an integrated field shape; since only three z positions within the body were measured, this approximation is rather coarse, but the field shape did not vary substantially within the body.
4. The harmonic coefficients were estimated by doing a least squares fit to a polynomial

$$B_n(x) = b_1 x + b_2 x^2.$$

   Only the off-axis points ($x \neq 0.$) were used in the fit; the $x = 0$ data point was accounted for by constraining the fit to pass through zero.

The results are reported in ***units***, where 1 unit is defined as 10^4 times the relative strength of the multipole to that of the dipole at 2.54 cm radius from the center of the beam tube.

V. Observations

In the 45° magnets, the center of each magnet in z was characterized by a dip in the field. Figure 2 shows a typical case. This corresponds to the point where the two halves of the magnet lamination packs are joined together. The joining is not as tight as would be desired, and a small gap may be observed.

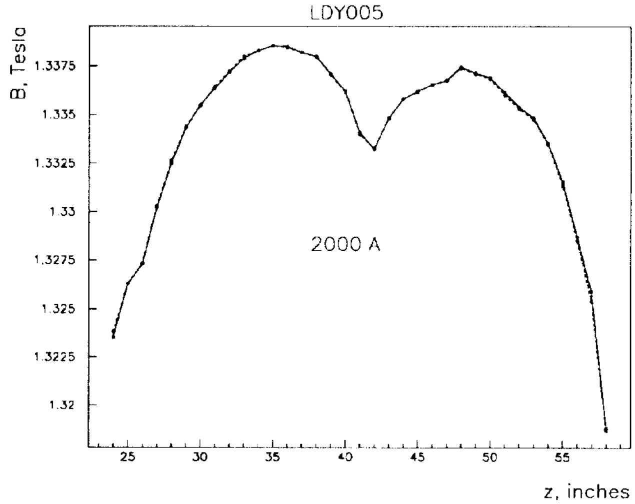

Figure 2: Longitudinal scan of a typical 45° magnet at 2000 A. The two longitudinal segments are joined at z = 42.

The longitudinal behavior of the 135° magnets is much more complex. The magnets are built from 6 joined sections, plus endpacks, and a 6-fold structure is observable in the body z-scans. At 2000 A, the amplitude of the modulation in field is about 6 mT out of a 1.332 T mean, or about 0.5% fluctuation. At 3100 A, the magnets are heavily saturated, with a typical sextupole of −22 units.

current, A	$\int Bdl$, T-m	b_1, units	b_2, units
2000	1.42272	-3.4 ± 0.8	5.9 ± 1.7
3100	1.94910	-1.7 ± 1.8	-23.9 ± 3.8

Table 1: Field integral, b_1, and b_2 for a typical 45° magnet. The field integral error was $\sim 5 \times 10^{-4}$ T-m.

VI. Acknowledgements

The authors would like to thank the following individuals at MTF for their contributions to this effort: S. Agrawal, A. Bianchi, J. Garvey, P. Hall, D. Hartness, C. Reid, E. Schmidt, H. Stahl, M. Thompson, and D. Validis. The authors also appreciate useful conversations with G. Coutrakon, J. Johanning and M. Notarus of Loma Linda University Medical Center.

References

[1] H.D. Glass, P.O. Mazur, and J.W. Sim, "Loma Linda Gantry Dipole Measurements," Fermilab Magnet Test Facility Report, MTF-92-014.