PERMANENT GRADIENT MAGNETS FOR THE 8 GeV TRANSFER LINE AT FNAL

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Abstract

The 8 GeV transfer line feeding protons into the new Fermilab Main Injector has been built using strontium ferrite permanent magnets. This article addresses the design and manufacture of the 67 combined function magnets; permanent horizontal and vertical bend dipoles [1] and quadrupoles were also built. The combined function magnets were built with a mean integrated strength at midaperture of 0.56953 T-m (central field nominally 0.15 T), and a gradient of 3.23% per cm relative to the dipole strength (nominal gradient = 0.48 T/m). Thermal compensation of these bricks was effected by use of a nickel-iron alloy. The magnets were thermally cycled from 20°C to 0°C to condition the ferrite against irreversible thermal losses; the compensation was measured with a flipcoil and verified with a rotating harmonics coil. We present details of the magnet assembly process and also summarize the magnetic measurements.

1 GRADIENT MAGNET DESIGN

An overview of the 8 GeV transfer is described elsewhere at this conference [1], and details regarding the general permanent magnet design strategy is discussed in [2]. In this article we focus our attention on the gradient, or combined function, magnets. The basic design of the gradient magnet is a 0.16 T gradient dipole with a vertical gap of 5.08 cm and an 8.89 cm good-field aperture in the bend direction (physical horizontal aperture is 13.97 cm). Overall dimensions are 19.1 cm high by 24.1 cm wide by 4.10 m long. The weight is 910 kg. The magnets are straight, and the sagitta of the beam inside the magnet is 1 cm.

1.1 Side bricks

A significant design decision made in the 8 GeV line magnets was to include side bricks which drive flux into the pole tips from the sides. These provide a more magnetically efficient design than one without side bricks, since the field strength drops ~40% when they are removed. This compact design provides the 0.15 T average bend field needed to follow the 8 GeV line tunnel. The side bricks also provide field shaping at the edges of the aperture.

While the side brick design proved economical and more than adequate for meeting the 8 GeV line field quality requirements, a number of design and production issues have since arisen which argue against the use of side bricks in higher-quality storage ring magnets (e.g., the Recycler Ring [3]).

One difficulty observed with the side brick design was the magnet-to-magnet variation in the field shaping due to small variations in the side brick positions. Another difficulty was that some multipoles (especially the normal 6-pole) exhibited an undesirable temperature dependence. This is caused by the placement of the compensator, which is interspersed with the top and bottom bricks but not the side bricks, with the result that the field shaping from the side bricks has a temperature dependence.

2 MAGNETIC MEASUREMENTS

2.1 Thermal measurements

Thermal measurements were made on every magnet using a flip coil to measure the change in strength between 0ºC and room temperature. Figure 1 shows the distribution in relative strength change with temperature (dB/B)/dT in units of 10^{-4} /ºC. We attempted to adjust the amount of compensator to limit the maximum variation to ±1.0 units/ºC, but some magnets were allowed to go beyond this limit.

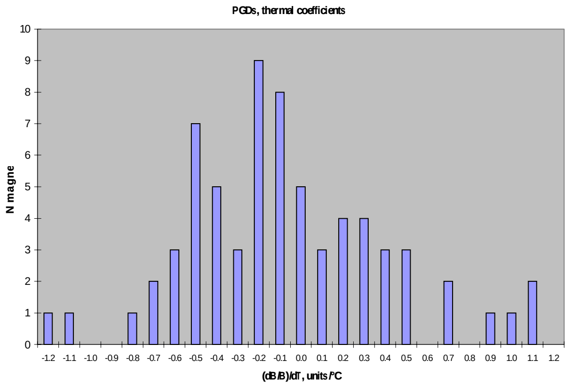

Figure 1. Histogram of thermal coefficients for the gradient magnets.

[†] Work supported by the U.S. Department of Energy under contract number DE-AC02-76CH03000.

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0-7803-4376-X/98/$10.00 © 1998 IEEE

2.2 *Strength measurements*

The magnet strength was measured using two different instruments. We first used a flipcoil to measure the integrated dipole strength; this information was then used to trim the amount of ferrite needed to bring the magnet strength within 0.01% of the target value (0.56953 T-m). The magnet was then measured again, this time using a rotating Morgan coil. This coil not only gave us the strength, but also the low order harmonics up to 14-pole. Figure 2 shows the distribution in magnet strength, and the agreement between the two different probes is satisfactory. Most of the magnets fall within the desired strength tolerance.

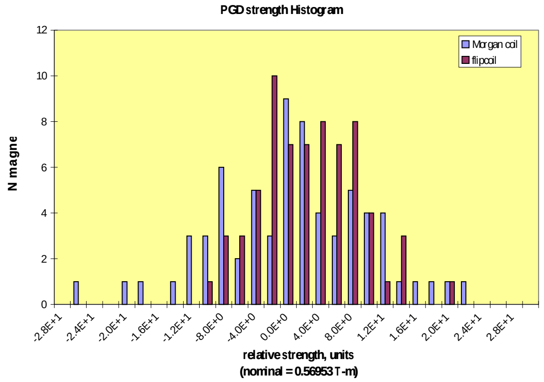

Figure 2. Strength histogram of the gradient magnets.

2.3 *Harmonics measurements*

The field quality specification for 8 GeV beamline dipoles and gradient magnets was set to 10 units (0.10%) of the total measured B_y vs. x along the midplane as measured by a rotating Morgan probe placed at the center of the aperture. Since the observed field defect is dominantly a gradient error arising from non-parallelism of the pole tips, this scales roughly to $\Delta B/B$ = 0.2% over the good field region (4.45 cm vertical x 8.89 cm horizontal). This specification represents a compromise between the minimum field quality required for adequate performance of a transfer line (where ~0.5% would be adequate) and the Recycler permanent magnet field quality [3], which must be in the range of 1-2x10^{-4} over a 2.54 cm aperture.

Table 1 shows the systematic and random harmonics for the ensemble of gradient magnets. Figure 3 shows the typical field shape along the midplane (reconstructed from harmonics b3 – b7); also shown are the best and worst cases among all the magnets. Even the magnet with the worst field shape is within the 8 GeV tolerance. A histogram of the normal gradient (b_2) is shown in Fig. 4.

PGD harmonics	*mean*	*std deviation*
b2	8.23E-02	4.32E-04
b3	2.39E-04	1.60E-04
b4	-3.89E-04	1.65E-04
b5	-1.24E-04	1.51E-04
b6	3.62E-04	1.44E-04
b7	-5.10E-05	1.60E-04
a2	6.73E-05	2.55E-04
a3	3.78E-05	1.59E-04
a4	-3.04E-05	9.31E-05
a5	-1.70E-05	8.55E-05
a6	-5.90E-06	7.13E-05
a7	-2.59E-08	6.33E-05

Table 1. harmonic coefficients through 14-pole for the 68 PGD magnets.

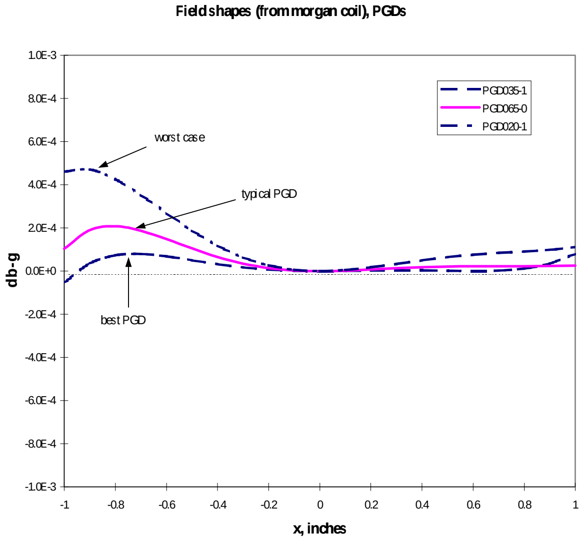

Figure 3. Field shapes of typical and extreme cases in the gradient magnets.

Our basic manufacturing strategy was to specify machining tolerances of typically 75 µm for the steel pole tips, which is sufficient to obtain roughly 0.1% field defect over the aperture. The dominant source of field error arose from assembly tolerances in the parallelism of the pole tips, producing a gradient error of roughly 1x10^{-4} for a mismatch of 25 µm between the two pole tip side supports.

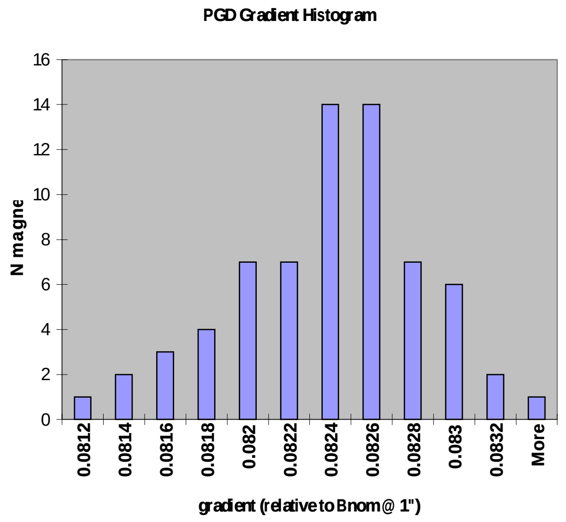

Figure 4. Histogram of normal quadrupole (gradient) for the PGD magnets.

2.4 Longitudinal bend centers

Some care had to be taken during magnet assembly to insure that the longitudinal bend center of the magnet was near the physical center. In the early stages of production, as experienced with the double dipoles [2], bricks were laid down on the pole tip beginning at one end, and proceeding down the length to the other end. This sometimes resulted in a longitudinal gradient (dB/dz nonzero). To avoid this phenomenon, we modified the assembly procedure for the gradients so that we first laid bricks down in the center of the pole tip, and then proceeded outward towards both ends. This resulted in a more uniform distribution of B(z). We mapped the longitudinal profile of each magnet with a Hall probe, and used these data to determine a bend center relative to the physical center. The distribution is shown in Figure 5. The requirement was to keep the bend center within 1 cm of the physical center, and the figure shows that this was achieved for nearly all of the magnets.

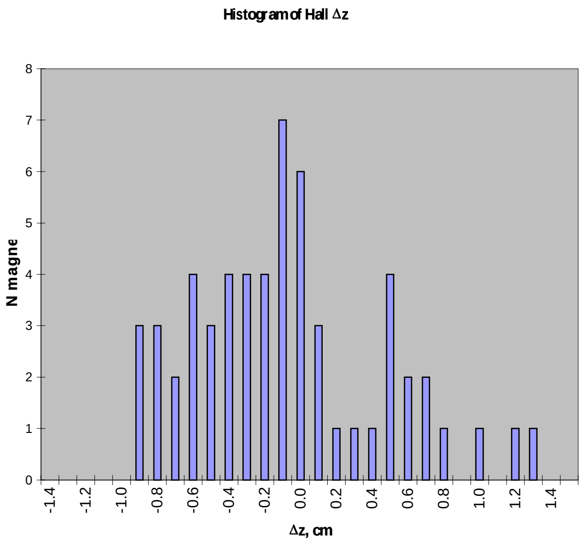

Figure 5. Distribution of longitudinal bend center for the gradient magnets.

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