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PERMANENT DIPOLE MAGNETS FOR THE 8 GEV TRANSFER LINE AT FNAL

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Abstract

The transfer line that will serve to transport 8 GeV protons from the Booster to the new Fermilab Main Injector has been built using permanent magnets. A total of 46 horizontal bend dipoles and 5 vertical bend dipoles were built for this beamline; 67 gradient magnets [1] were also built. The magnets were built using magnetized strontium ferrite bricks. Thermal compensation of these bricks was effected by use of a nickel-iron alloy. The dipole magnets were built with a mean integrated strength of 0.56954 T-m, and an rms spread of 0.06%. The magnets were thermally cycled from 20°C to 0°C to condition the ferrite against irreversible thermal losses, and the compensation was measured with a flipcoil. The magnet strength was adjusted by varying the number of bricks installed at the magnet ends. Details of the assembly process and a summary of magnetic measurements are presented here.

1 THE 8 GEV TRANSFER LINE

The design of the Fermilab Main Injector (FMI) calls for protons to be extracted from the existing Boster at 8 GeV and transported 756 m for injection into the FMI [1]. This transfer line is comprised of three major sections; the long central section, consisting of a long string of periodic FODO cells, is made entirely of permanent magnet dipoles, quadrupoles, and gradient magnets. The motivation for employing permanent magnets wherever possible in the line was primarily to acquire the manufacturing and operating experience necessary to ensure the success of the future Recycler Ring [2].

1.1 8 GeV beamline permanent magnets

The 8 GeV line uses four types of permanent magnets: a gradient (combined function) dipole [3] used in the normal arc cells, a normal quadrupole [4] used in the reverse bend cells near the beginning of the line, a short dipole used for horizontal bends in the arc cells, and a vertical bend dipole used to pitch the beam down coming out of the Booster. The horizontal and vertical bends are very similar in design, and are the focus of this paper.

Type	L_{mag} (m)	$\int$Bdl (T-m)	$\int$ gdl (T)	N
Horizontal bend	2.464	0.56953	0	45
Vertical bend	3.556	0.8220	0	4
Gradient	4.00	0.56953	1.851	65
Quadrupole	0.508	0	1.481	9

12 Permanent magnet design

We have elected to use "hybrid" permanent magnets in the 8 GeV line; in this type of design, the field is driven by permanent magnet material and the field shape is determined by the geometry of steel pole pieces. For reasons of stability and cost, we use strontium ferrite as the permanent magnet material. A drawing of the double dipole (horizontal bend) magnet end view is shown in Fig. 1; the permanent magnet bricks drive flux into the pole tips from the top and sides.

The pole tips are supported by an aluminum spacer which determines the height of the magnetic gap. The pole assembly plus bricks are contained in a flux return shell that is 1.91 cm thick. We use solid bar stock components for the poles and flux returns rather than laminations. The pole tip steel is 1008 low carbon steel. A NiFe temperature compensation alloy is used for cancellation of the -0.2%/C temperature coefficient of the ferrite, and in the dipole magnets is inserted into the sides of the magnet aperture.

In order to limit stray flux from leaking out, the end fields of the magnet are terminated by flux clamp / end plate assemblies which are magnetically connected to the flux return shell. An aluminum retainer plate immobolizes the beam tube and protects the magentic pole tips from magnetic debris. The end plates are removable to permit access to the ends of the pole pieces for shimming

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operations. The flux return extends 5.08 cm past the ends of the pole pieces at each end; the end plates are 1.27 cm thick; therefore, the mechanical length of these magnets are 12.7 cm longer than the magnetic (pole piece) length.

The magnets are designed to fit around an elliptcial beam pipe with inner dimensions under vacuum of approximately 4.57 cm (vertical) x 9.91 cm (horizontal). A transition to a 10.16 cm round pipe has been provided on all magnets.

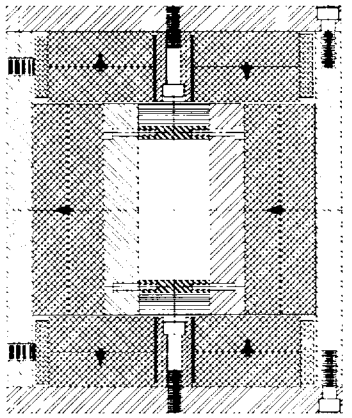

Figure 1. Cross section of the vertical bend dipole.

2 MAGNET ASSEMBLY

2.1 *Magnetization of bricks*

Ferrite bricks are shipped unmagnetized from the foundry and are magnetized shortly before assembly using a 2 T electromagnet. The ferrite is purchased in standard size 1"x4"x6" bricks, with the 1" dimension ground to ±0.005" flatness and the 4"x6" dimensions left at a tolerance of ±0.060". The dipole side bricks are cut in half before magnetization. In the early stage of the production run, the magnetic strengths of the bricks were individually measured; this measurement became superfluous as the production line became more efficient.

2.2 *Mechanical assembly*

The assembly process begins with the machining of the pole tips from solid bar stock. The pole tip spacing is set by bolting them down against aluminum pole tip supports at either edge. Magnetized bricks are then glued with epoxy to the flux return plates. Both the vertical and horizontal bends employ a "double-dipole" design in that two layers of bricks are used behind each pole, providing 5.08 cm total thickness of magnetic material. A double layer of bricks are also glued onto the side flux return plates. The flux return plates are then lowered carefully onto the pole tip assembly using mechanical fixturing to control the magnetic forces [6]. A steel end plate is bolted onto each end of the magnet to terminate the flux lines.

2.3 *Strength trimming*

The magnet is designed so that a fully-loaded magnet having bricks of nominal strength will be 3-5% stronger than required. Dummy bricks, fractional bricks, and spacers are used to control the total strength and to correct for brick-to-brick and lot-to-lot variations. A final strength trim was performed at the magnet factory using a flip coil system to measure the integrated strength. Trimming is accomplished by removing or adding bricks or partial bricks to the magnet ends as required. The trimming tolerance, as measured with the flip coil, was 0.1% for the dipole magnets. The strength measurements were independently verified using a rotating harmonics coil at the Fermilab Magnet Test Facility.

3 DIPOLE MAGNET DESIGN

The horizontal and vertical bend dipoles are identical in cross section but differ in length and integrated strength. A cross section of the magnet is shown in Fig. 1. The horizontal dipoles (PDD) provide a 20 mrad bend and a nominal bend field of 0.23 T. This higher strength is achieved by stacking the ferrite bricks two deep behind the poles and at the sides of the magnet. The vertical bends (PVB) are longer versions of the PDDs, which are mounted on their sides to provide the bends in the vertical drop region of the 8 GeV line.

The dipoles use a flat pole tip fabricated from a single piece of Blanchard-ground bar stock. No edge shims are needed on the pole face to provide adequate field quality because of the field shaping provided by the side bricks. This represented a significant cost savings over a custom ground pole profile.

A significant design choice for the dipoles was the placement of the compensator material at the edges of the magnet gap region. This is in contrast to the interspersed method used with the gradient magnets. The advantages of the gap comepnsator are 1) the design is more magnetically efficient, since none of the ferrite space behind the pole tip is wasted, 2) less total compensator is used since it only spans the 1" half-gap of the magnet, and 3) the compensator strips run longitudinally and can easily be replaced after magnet assembly. The disadvantage of the gap compensator is a slight sensitivity of the field shape to both compensator placement and temperature. Both effects are accepatble for the gap compensator is a slight sensitivity of the field shape to both compensator placement and temperature. Both effects are accepatble for the 8 GeV line but

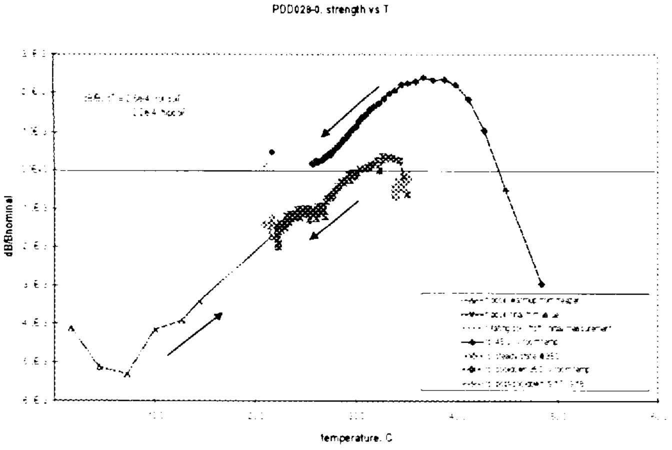

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Figure 2. Thermal cycling of dipole magnet between 0 and 50 C, showing the variation of field strength with temperature.

4 THERMAL CYCLING AND COMPENSATION

4.1 Freezing to condition against irreversible losses

Strontium ferrite can be demagnetized by exposure to low temperatures, due to the positive value of dH_c/dT. This is a one-time loss which depends only on the lowest temperature to which the magnet has been exposed. Typical demagnetizations are 0.1% at 0^oC and 0.2% at -20^oC. There is a lot-to-lot variation of ±10% in H_c. For these reasons we froze each magnet to 0^oC in a custom built refrigerator in the magnet factory prior to final trimming. The refrigerator was large enough to freeze up to 18 magnets overnight. Magnets were measured for strength at room temperature prior to freezing, and were measured again immediately after being removed from the freezer. They were remeasured one last time after they had warmed up to room temperature. The strength losses from freezing were typically 0.1% as expected, and no anomalous strength losses were noted. We warmed a sample of magnets using heating blankets up to 40^oC, and as expected, observed no irreversible losses on the magnets.

4.2 Temperature compensation

The intrinsic thermal coefficient of strontium ferrite, $-0.2\%/^oC$, is reduced to nearly zero by inserting a compensating NiFe alloy (~30% Ni) in the vicinity of the ferrite. This alloy is characterized by a low Curie temperature (~50-70^oC), and therefore the permeability is a strong function of temperature. The alloy shunts flux away from the magnet aperture in a temperature dependent manner, and by adjusting the proportion of ferrite to compensator, one can null out the overall thermal dependence of the field strength. The degree of temperature compensation is linearly related to the amount of compensator material in the magnet. By adjusting the number of compensator strips, we were able to reduce the temperature coefficient to $<0.01\%/^oC$.

The thermal coefficient of all the magnets was measured at the magnet factory by comparing the strength at 0^oC and after warmup to room temperature. We also measured this coefficient on ~20% of the magnets by heating and measuring the change in strength with a rotating coil.

The observed variation in the temperature dependence of the permeability of the NiFe alloy as received from the vendor was ±10%. This made it necessary to iterate the temperature compensation in production. In the dipoles, the compensator strips run longitudinally in the magnet gap, and it was straightforward to adjust the number of strips after initial assembly. This procedure converged in most cases immediately, requiring only an additional cooldown cycle to verify the compensation

4.3 Transient thermal effects

A rapid thermal transient (e.g., condensation from exposure of a frozen magnet to a warm, humid environment) is observed to produce a large strength transient in the magnet (see Fig. 2). This is most probably due to a temporary mismatch between ferrite and compensator temperatures. The thermal transients that produce these effects are much larger than one expects in the 8 GeV tunnel, and is not likely to be an operational difficulty.

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