3.1A 8 GEV LINE PERMANENT MAGNETS

The 8 GeV line uses four types of permanent magnets: a gradient dipole (combined-function magnet) used in the normal arc cells, a short dipole used for horizontal bends in the arc cells, a vertical bend dipole used to pitch the beam down coming out of the Booster, and a normal quadrupole used in the "reverse bend" cells near the beginning of the line. The 8 GeV line optics are discussed in Chapter 2.4.1.

Table 3.1A-1. Types and numbers of permanent magnets for 8 GeV line.

Type	Description	L_{PHYS} (in.)	L_{MAG} (in.)	Integrated Strength	Number installed	Spares
PDD	Horizontal Bend Dipole	102	97	0.56953 T-m	45	1
PDV	Vertical Bend Dipole	145	140	0.8220 T-m	4	1
PGD	Gradient Dipole	161.5	157.5	0.56953 T-m + 1.851 T-m/m	65	6
PQP	Permanent Quadrupole	24.75	20	1.481 T-m/m	9	1

Only one polarity of each type is required, since the bend direction of dipole permanent magnets is reversed by installing them upside-down. The focusing action of gradient and quadrupole magnets is reversed by rotating them 180 degrees about a vertical axis (i.e. switching the upstream and downstream ends). By convention, the permanent magnets installed right side up bend protons to the right, and the horizontally defocussing configuration corresponds to protons entering the label end of quadrupole and gradient magnets.

Permanent Magnet Design

The designs are so-called "hybrid" permanent magnets in which the field is driven by permanent magnet material and the field shape is determined mainly by steel pole pieces. Strontium ferrite permanent magnet material is used for reasons of stability and cost. A representative assembly drawing (in this case the gradient dipole) is given in Fig. 3.1A-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 sets the magnetic gap. The entire assembly is enclosed in a flux return shell 0.75” thick. The magnets are straight and solid “bar stock” components are used throughout rather than laminations. The pole tip steel is 1008 low carbon steel and the flux return is construction grade (A36) steel. A temperature compensation alloy which cancels the temperature coefficient of the ferrite is interspersed with the permanent magnet material at the top and bottom. In the PDD and PDV dipoles, this compensator alloy is placed directly inside the magnet gap.

The end fields of the magnets are terminated by Flux Clamp/ End Plate assemblies which are magnetically connected to the flux return shell. See Fig. 3.1A-2. These prevent the stray flux from leaking out. An aluminum retainer plate immobilizes the beam tube and protects the magnetic pole tips from magnetic debris and curiosity seekers. The end plates are removable to allow access to the ends of the pole tips for shimming operations. The flux return extends 2” past the ends of the pole tips at each end and the end plates are 0.5” thick, so that the mechanical lengths of the 8 GeV line permanent magnets are 5” longer than their pole tip (magnetic) lengths.

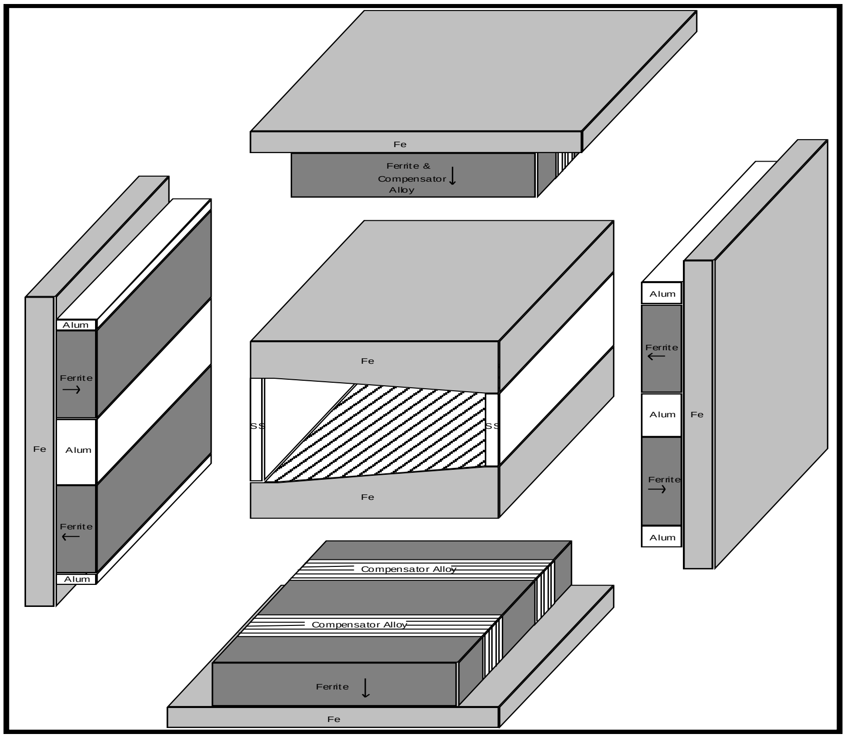

Figure 3.1A-1 - PGD permanent magnet assembly sequence.

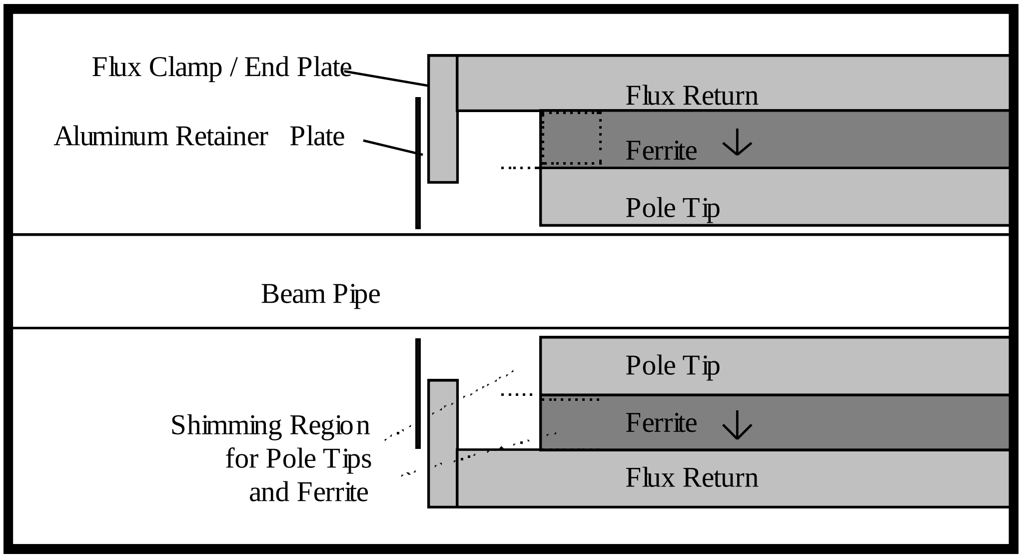

Figure 3.1A-2 - Side view of magnet, showing transition from naked beam pipe to magnet flux return. The beam pipe is held in place by an aluminum retainer plate with slotted holes which allow for ±1cm transverse motion of the beam pipe. Also indicated are the regions at the ends of the pole tips which are available for shimming the field shape (not needed for the 8 GeV transfer line magnets), and the ends of the ferrite bricks which are used to trim the strength of the magnet by adjusting the total amount of magnetic material.

All magnets are designed to fit around an elliptical beam pipe with inner dimensions under vacuum of approximately 1.8” (v) x 3.9” (h). The beam pipe has the ability to move transversely ±1cm inside the gradient magnets and quadrupoles, a feature which allows adjustment of the effective bend strength by ±3%. A transition to a 4” round pipe has been provided on all magnets.

8 GeV Line Magnet Key Performance Specifications

Table 3.1A-2 contains the basic specifications for the 8 GeV line permanent magnets. Many of these are design guidelines rather than absolute performance specifications. These are discussed at exhaustive length in MI Note 150.

Table 3.1A-2. Key Design Parameters for Permanent Magnets in 8 GeV line.

Design Lifetime	30 years
Operating Temperature	20°C (68°F) to 35°C (95°F)
Storage Temperature	5°C (41°F) to 50°C (120°F).
Humidity	0%-100%
Corrosion Resistance	All parts resistant, plated, or painted.
Bakeout Compatibility	Not needed
Temperature Coefficient of Field	±0.01%/°C
Time Stability	ΔB/B < 0.02%/yr. after first month aging

Radiation Resistance	$\Delta B/B < 1\%$ for 1 GigaRad
Shock & Vibration	$\Delta B/B < 0.05\%$ from normal handling
Radiation Activation	Comparable to steel/copper magnets
Vertical Aperture (dipole & grad. mag.)	2.0” between the pole tips (at X=0)
Good-Field Aperture (dipole & grad.)	±1.0” at $\lvert \delta By/B_0 \rvert < 0.1\%$ (100% tested) ±1.75” at $\lvert \delta By/B_0 \rvert < 0.2\%$ typ.(not tested)
Quadrupole Pole Tip Radius	1.650” (XY = 1.350 in^{2,}, same as MI)
Magnet Sagitta	Zero (straight magnets)
Beam Sagitta Inside Dipole	~1cm (dipoles & grads), 1.5cm (vert bends)
Field Uniformity in Z	±5% (systematic) ±5%(random)
Bend Center uncertainty	±3cm in Z (measured and surveyed)
Field Strength Modification	possible in range [+3%,-5%].
Field Shape Modification	+/- 5 units (modify end shims)
Magnetic Field in Flux Return	<1 Tesla
Termination of End Fields	via Flux Clamp / End Plate of Magnets
End Fields	<5 Gauss 2.5 cm past end of magnet
Beam Pipe Fixturing	allows ±1cm horiz. range of motion (grads)
Survey Fiducials	8 “nests” at corners of magnets
Mechanical Rigidity (sag) of dipoles	< 0.010” for 25% , 75% support points

Permanent Magnet Material

Type 8 Strontium Ferrite [1] was chosen as the permanent magnet material because of its low cost and high stability over time, temperature, and radiation. Strontium ferrite is the material of choice in automotive applications and is available at low cost in standard grades and sizes from multiple vendors. It has documented stability in applications such as NMR magnets and is commonly used in ion pumps in accelerator applications. Material from the three major US vendors were evaluated and performed well in the R&D program.

We have studied the time stability (field strength vs. time) of a number of our model “stability test magnets” measured with an NMR probe over an 8-month period. This data is consistent with logarithmic aging at approximately 2×10^{-4}/decade. (“Logarithmic aging” means that one expects equal increments of aging from 1 year to 10 years, from 10 years to 100 years, etc.) This corresponds to 0.06% field change between 10 days and 30 years. Aging at this level, if it occurs, can be easily accommodated by occasional recentering of the gradient magnets over the lifetime of the 8 GeV line.

Magnet Assembly

The assembly sequence is as follows (see Fig. 3.1A-1). The pole tips are machined 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 epoxied to the top flux return plates. Strips of compensator alloy are interspersed between the bricks above and below the pole tips, and aluminum spacer bars are used to separate the "side bricks". The flux return plates are then lowered (carefully!) onto the pole tip assembly using mechanical fixturing to control the magnetic forces. The magnet is measured using a flip-coil at the magnet factory and shimmed by adding magnetic material at the ends of the pole tips. A steel end plate which terminates the flux lines is then bolted onto each end of the magnet.

Details of the assembly procedures are given in the travelers for each type of magnet. Production drawings [2] of the four magnet types are stored in the Technical Division archives.

Magnetization and Strength Trimming

Ferrite bricks are shipped unmagnetized from the foundry and are magnetized immediately prior to assembly using a 2 Tesla dipole. The material is purchased in standard 1"x4"x6" bricks, with the 1" dimension ground to ±0.005" flatness and the 4"x6" dimensions as-fired ±0.060". The dipole side bricks and quadrupole bricks are cut in half before magnetization. The magnetic strengths of the bricks are individually measured and they are assembled into "kits" each of which contain a specified total magnetic strength. The magnet design is such that a magnet fully loaded with bricks of nominal strength is 3~5% stronger than required. Dummy bricks, fractional bricks and spacers are used to control the total strength of the "kits" to correct for brick-to-brick and lot-to-lot variations. A final strength trim is accomplished by adjusting the amount of ferrite at the ends of the magnet, which can take place by removing the cover plates at the ends of the magnets. This trimming operation was performed in the MP9 magnet factory using a dedicated flip coil system to measure the integrated magnetic strength. The acceptance tolerances on the strength measurements were 0.1%, 0.2% and 0.6% for the dipoles, gradient magnets, and quadrupoles respectively. The strength measurements on all magnets were independently verified with a harmonics probe after shipment to Fermilab's Magnet Test Facility (MTF).

The lot #, serial #, measured strength, and installed position of each ferrite brick was recorded in the travelers for all magnets in the 8 GeV production run. This was done to facilitate tracking of any strength or drift anomalies which might have been occurred in production due to nonuniformities or quality control problems in the ferrite. As of yet no such anomalies have been uncovered, and it is currently felt that this level of documentation is unnecessary for further (e.g. Recycler) production of these magnets.

Thermal Cycling (freezing) the magnets

The strontium ferrite material can be demagnetized by exposure to low temperatures, due to the shifting of the demagnetizing "knee" in the B-H curve to lower H values with decreasing temperature. This is a one-time loss which depends only on the lowest temperature to which the magnet has been exposed. Typical demagnetizations are in the range of 0.1% at 0°C and 10% at -20°C. The degree to which a magnet is demagnetized by a given temperature depends on the "load line" of the magnetic design, i.e. the position on the B-H curve that each region of ferrite is operating on. It also depends on the position of the knee (the coercivity H_C) of the magnetic material which exhibits significant (±10%) lot-to-lot variation from the manufacturer. For these reasons we decided to "freeze" each magnet to 0°C in a custom built refrigerator in the magnet factory prior to final trimming. The refrigerator could process up to 18 magnets overnight. Magnets were measured prior to freezing, at the end of freezing immediately after they were removed from the refrigerator, and after they had returned to room temperature. The strength losses from freezing in production were in the range of 0.1% as expected and no anomalous strength losses were noted. Positive temperature excursions (up to 40°C) were observed to have no irreversible effects on the magnets.

Temperature Compensation

The intrinsic temperature coefficient of the Ferrite material (-0.2%/°C) is canceled[3] by interspersing a “compensator alloy”[4] between the ferrite bricks above and below the pole tips. The compensator is an iron-nickel alloy with a low Curie temperature and therefore a permeability which depends strongly on temperature. This shunts away flux in a temperature dependent manner which can be arranged to null out the temperature dependence of the ferrite. The degree of temperature compensation is linearly related to the amount of compensator material in the magnet. Thus the degree of compensation can be “fine tuned” to the required accuracy by adjusting the amount of compensator at the ends of the magnet in a manner similar to the strength trimming with the ferrite. For example, a 20-fold reduction of the temperature coefficient (from 0.2%/°C to 0.01%/°C) requires that the amount of compensator in the magnet be adjusted correctly to 1 part in 20. This was our acceptance specification in production.

The temperature coefficient of all magnets was measured at the MP9 magnet factory during the warm-up period following the “freezing” of each magnet. In addition, the temperature coefficient of ~20% of the magnets was verified at MTF using a rotating coil and a positive temperature excursion produced by heating blankets and an insulating wrap.

The observed variation in the temperature coefficient of the compensator alloy received from the vendor in production was in the range of ±10%. This made it necessary to iterate the temperature compensation in production in one of two ways. For the case of the straight dipoles, the compensator strips run longitudinally in the gap of the magnets and it proved possible to remove and replace these strips with the magnets fully assembled. Since the typical number of compensator strips required was ~13 on either side of the gap, it was straightforward to adjust the amount of compensator to within ±5% of nominal by adding or removing integer numbers of strips of compensator. This procedure was found to converge immediately, requiring in most cases only a single additional cooldown cycle to verify the compensation of the trimmed magnets.

The compensator situation in the gradient magnets was more complicated. In this design the compensator runs transversely between the bricks behind the pole tips and cannot be replaced after assembly of the magnets. The partial disassembly of the magnet necessary to retrim the compensation takes approximately two hours and was incompatible with the desired 2 magnets/day production rate. Thus we decided to pre-mix the compensator strips from a number of production lots into the kits for individual magnets. This made the compensator alloy a uniform and predictable product across a large number of magnets. After some false starts (apparently due to difficulties with the reproducibility of the magnet measurement apparatus) this procedure was successful at reducing the fraction of magnets which had to be reworked to less than 10% of the total production.

Nonlinearities of Temperature Compensation

The ultimate limit to the temperature range of the compensation technique is set by the nonlinearities of the opposing temperature coefficients. The ferrite material appears to be highly linear over the relevant temperature range; however, the compensator material tends to become weaker as it approaches its effective Curie temperature of ~55°C. Fig. 3.1A-3 indicates the degree of compensation that we are able to achieve on a test magnet using ferrite and compensator materials from the production (low bidder) vendors.

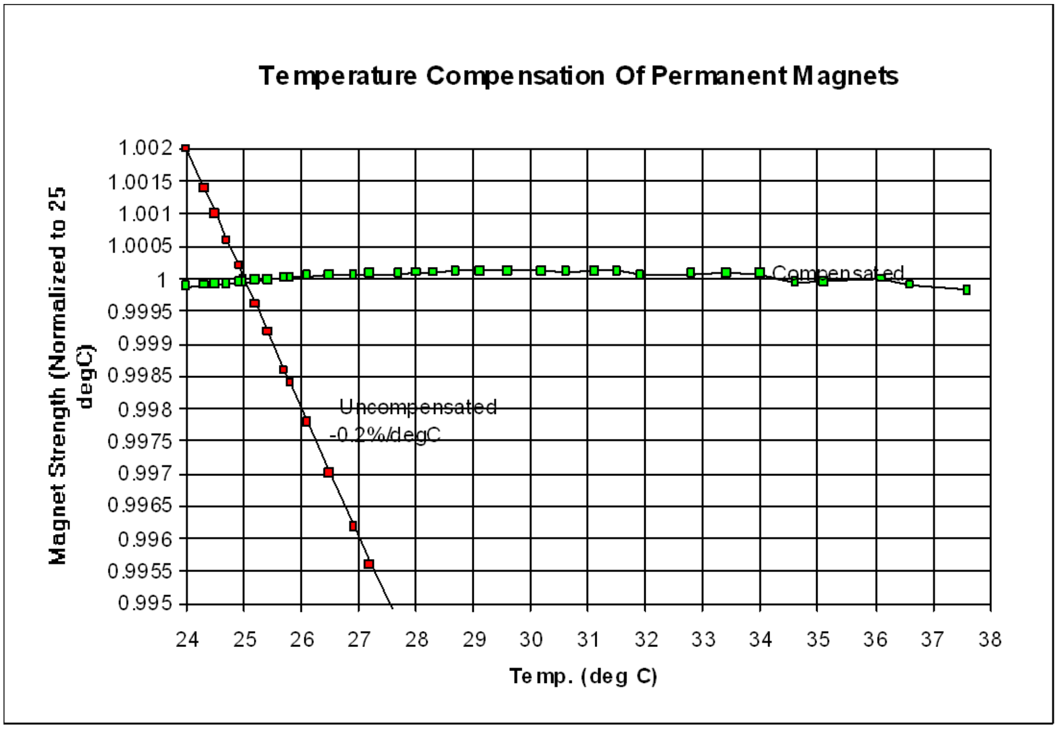

Figure 3.1A-3 - Field Strength vs. Temperature for a Stability Test Magnet using preproduction samples from the selected vendors for Compensator Alloy and Ferrite.

Magnet Sorting and Thermal Coefficients

In production, the amount of compensator was not fine-tuned to this accuracy and a maximum temperature coefficient of ±0.01% /°C was tolerated. Following production, the measured thermal coefficients of individual magnets were used in the assignment of magnets to positions along the line. This procedure simultaneously optimized the closed-orbit distortion of the line at three different operating temperatures, and effectively used the betatron phase advance between magnets to cancel opposing temperature coefficients of the magnets. After sorting, the calculated horizontal closed-orbit distortion due to temperature changes of 10°C was less than 0.5mm RMS.

Transient Thermal Effects

A rapid thermal transient (such as can be produced by several hundred watts of heating tape, or condensation from exposure of a frozen magnet to a warm, humid environment) is observed to produce a large strength transient in the magnets[5]. This is believed to be due to a temporary temperature mismatch between the ferrite and compensator when the magnet is out of thermal equilibrium. The effect is most pronounced in the straight dipoles where the compensator is located in the magnet gap and the ferrite is located by the flux return, and can be as large as ~50 units. The thermal transients which produce these effects are substantially larger than one expects in the 8 GeV line tunnel, and it remains to be seen whether this is an operational difficulty.

Gradient Magnet (PGD) Design

The basic design of the PGD gradient magnet is shown in Fig. 3.1A-1. It is a 1.59 kG gradient (combined-function) dipole with a 2” gap and a 3.5” good-field aperture (5.5” physical aperture) in the bend direction. Overall dimensions are 7.5” high by 9.5” wide by 161.5” long. The weight is 2000 lb. The magnets are straight and the sagitta of the beam inside a magnet is 1 cm. A cross section of the magnet is shown in Fig. 3.1A-4, and a field map in Fig. 3.1A-5.

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 a design without side bricks, since the field strength drops by ~40% when they are removed. This allows a compact design to provide the 1.5kG average bend field needed to follow the 8 GeV line tunnel. The side bricks also provide useful field shaping at the edges of the aperture, which reduces the amount of end shimming necessary at the edges of the pole tips.

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 arose which argue against the use of side bricks in higher-quality storage ring magnets e.g. for the Recycler. First, the amount of edge field shaping from the side bricks appeared to be underestimated in the POISSON model of the magnet. The first prototypes of each of the side brick designs showed an excess of field strength at the edges of the aperture. In order to obtain the optimal field shaping at the edges, the side bricks had to be moved upwards by inserting 3/16” shims on either side of the midplane spacers. This reduced the strength of the magnet by a small amount (<2%) which was well within the range of the strength trimming.

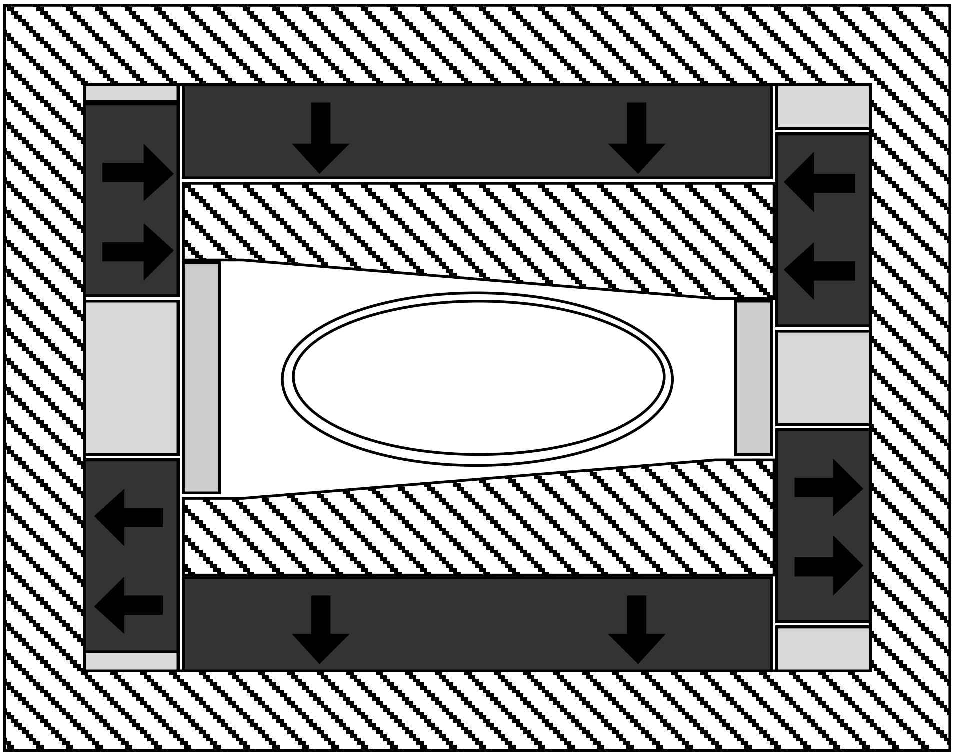

Figure 3.1A-4 - 8 GeV Line Gradient Dipole Permanent Magnet (PGD)

The second difficulty observed with of the side brick design was the magnet-to-magnet variation in the field shaping from the side bricks. These fluctuations were at the level of a few x10-4 total field defect at 1" as described in the section on measurements. Presumably this was due to variations in the relative strength and installed position of the side and top bricks.

The final difficulty with the side brick design is that the observed multipoles exhibited some temperature dependence (a fraction of a unit per degree C) [6]. This is due to the compensator being interspersed with the top bricks but not the side bricks, with the result that the field shaping from the side bricks is temperature dependent.

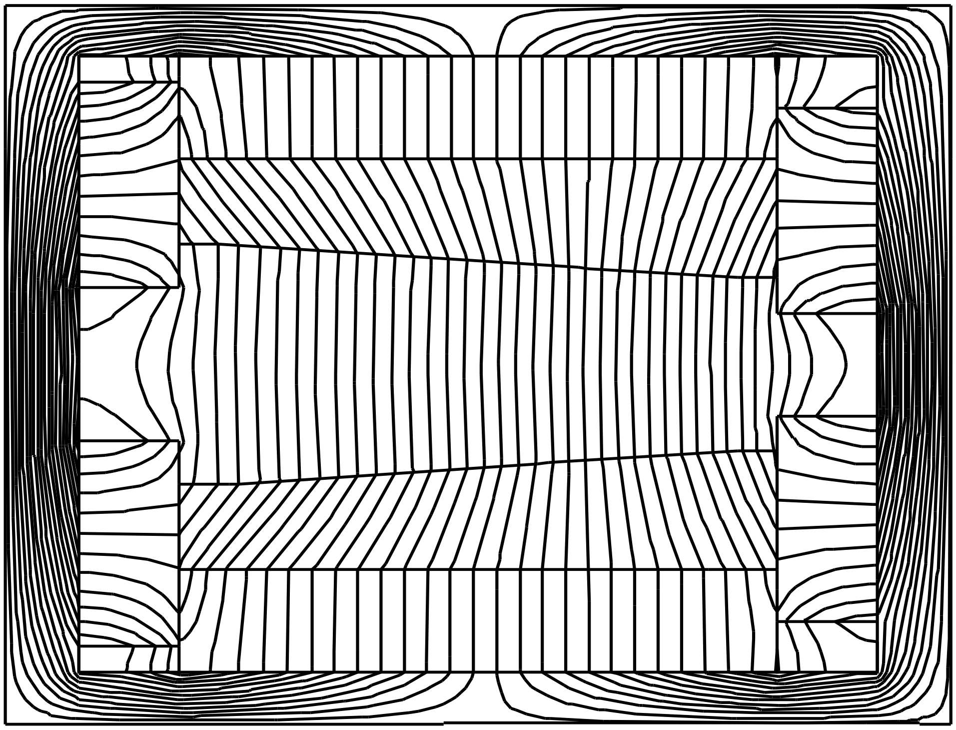

Figure 3.1A-5 - POISSON Field Map of PDG Gradient Dipole

Dipole Magnet (PDD and PDV) Design

The two straight dipoles PDD and PDV are identical in cross section and differ in length and integrated strength. A cross section of the magnet is shown in Fig. 3.1A-6, and a field map in Fig. 3.1A-7. The PDD (a.k.a. “Double-Double Dipole” or “Horizontal Bend Dipole”) provides the same 20mrad bend as the gradient magnet in a shorter package due to the higher 2.3 kG bend field. This higher strength is achieved by stacking the ferrite bricks two deep behind the poles and at the sides of the magnet. This shorter length provided a substantial amount of free space in the lattice to allow for the installation of additional correctors, instrumentation, etc. at a later date. The PDV magnets (a.k.a. “Vertical Bend Dipoles” or “PB2 Dipoles”) are longer versions of the PDD which are mounted on their sides to provide the bends in the vertical drop region of the 8 GeV line.

The PDD and PDV bend dipoles have a completely 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.

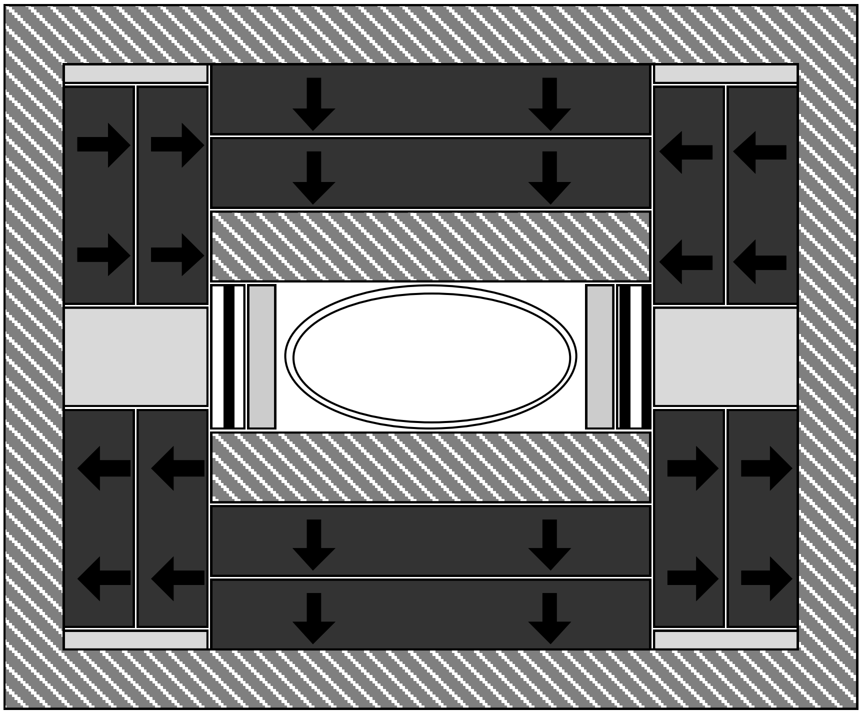

Figure 3.1A-6 - 8 GeV Line Dipole (PDD and PDV) Cross Section

A significant design choice for the PDD and PDV dipoles was the placement of the compensator material at the edges of the magnet gap region. (The compensator alloy is interspersed with the ferrite bricks behind the pole tips in the gradient magnet, as well as subsequent Recycler prototype magnets). The advantages of the gap compensator 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 be replaced and the compensation adjusted after assembly of the magnet. The disadvantage of the gap compensator is a slight sensitivity of the field shape to both compensator placement and temperature. Both effects are at the level of a few “units” in extreme cases, and thus are adequate for the 8 GeV transfer line magnets but undesirable for the Recycler storage ring magnets.

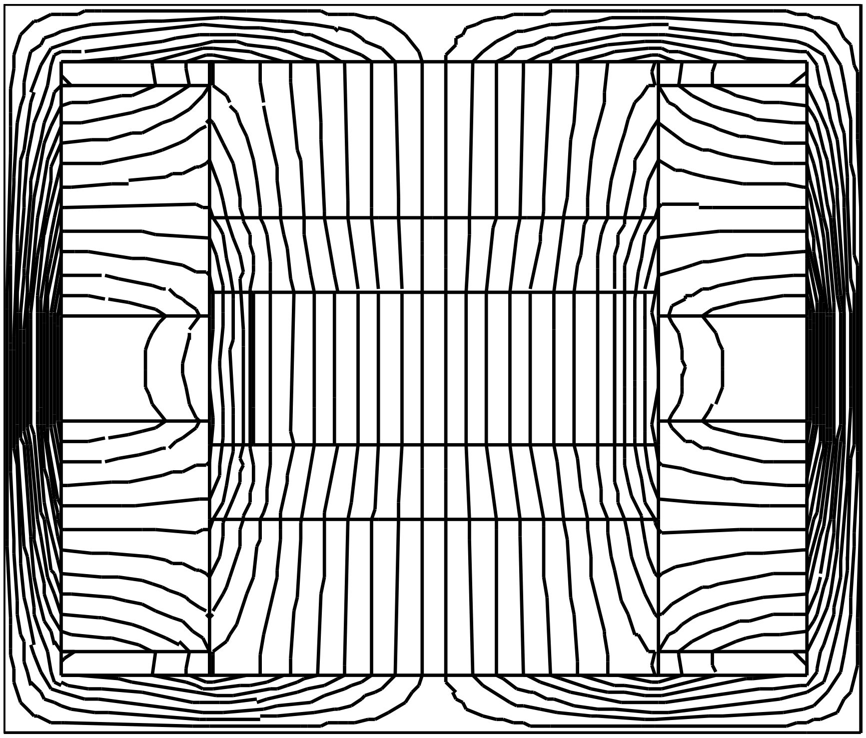

Figure 3.1A-7. POISSON Field Map of PDD and PDV Dipoles

Permanent Magnet Quadrupole Design

Nine permanent magnet quads are used in the FODO cells of the reverse bend section of the 8 GeV Line. The pole tip radius is 1.643”, the same as the Main Ring/Main Injector quadrupoles. The magnetic (pole tip) length is 20” and the overall length (steel-to-steel including flux clamp end plates) is 24.5”. The integrated gradient is [1.481 T-m/m].

The quadrupole (Fig. 3.1A-8) has a hybrid design analogous to the gradient dipole. The field shaping is provided by machined steel pole tips and the field is driven by strontium ferrite bricks. Temperature compensation of the ferrite is provided by interspersing strips of compensator alloy between the bricks along the length of the magnets. Solid “bar stock” construction is used throughout. The pole tips are supported at the ends by pinning and bolting into stainless steel support plate. A steel flux return shell surrounds the magnet, and “flux clamp” end plates are used to terminate the field at the ends of the magnet.

The magnetic strengths of the pole tips in the magnet are trimmed by placing variable number of steel washers in the corners of the magnet behind each pole tip. This trimming takes place using a "Rogowski Coil" to measure the magnetic potential of each pole tip. The field shape (mainly the systematic 12-pole from the magnet ends) can then be trimmed out by adding steel washers to bolts at the ends of the pole tips.

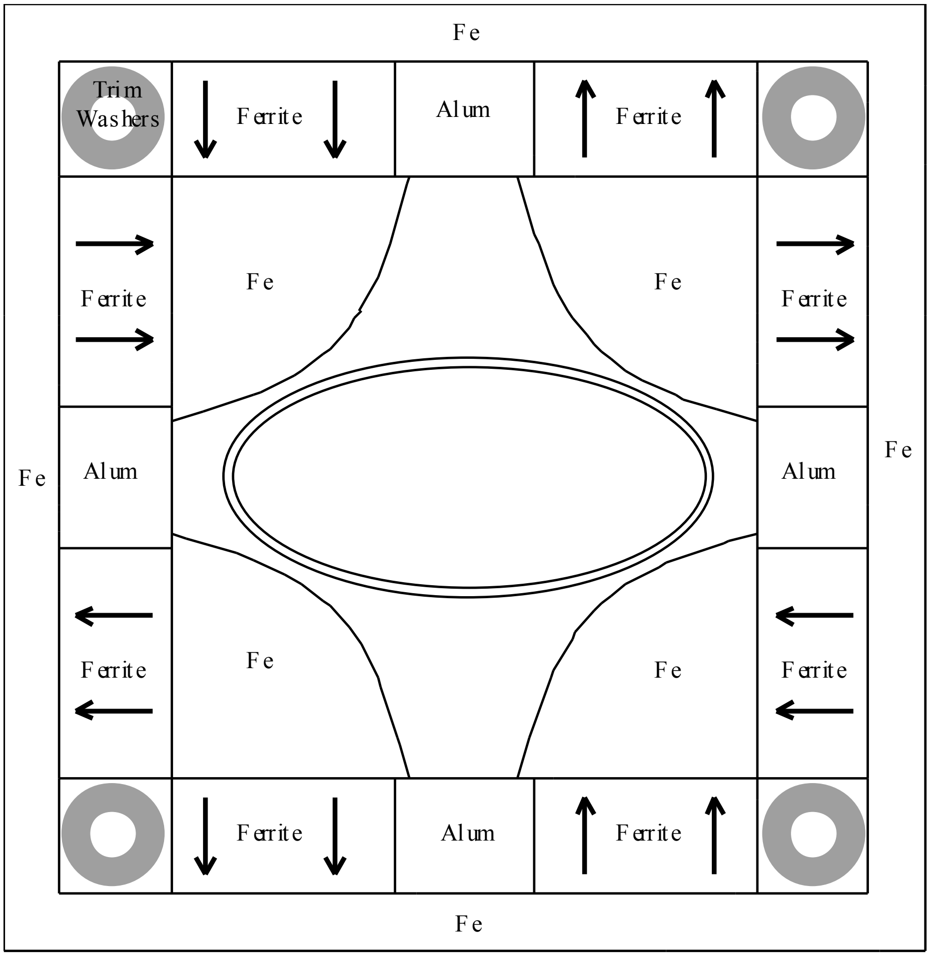

Figure 3.1A-8. Cross section of 8 GeV Quadrupole Magnet.

Magnetic Measurements - Field Strength

Several types of field strength measurements were performed on the 8 GeV line magnets. In the MP9 magnet factory the strength trim and temperature compensation trim were performed via a flip coil or Rogowski coil for the dipoles and quads respectively. A manual flip coil with non-precise positioning was used for the straight dipoles, and a motorized flip coil suspended from the survey fiducials was used for the gradient magnets. The magnets were then shipped to Fermilab's Magnet Test Facility (MTF) where the strength and field shape were measured using rotating coils and (for a limited subsample of production magnets) a stretched-wire system.

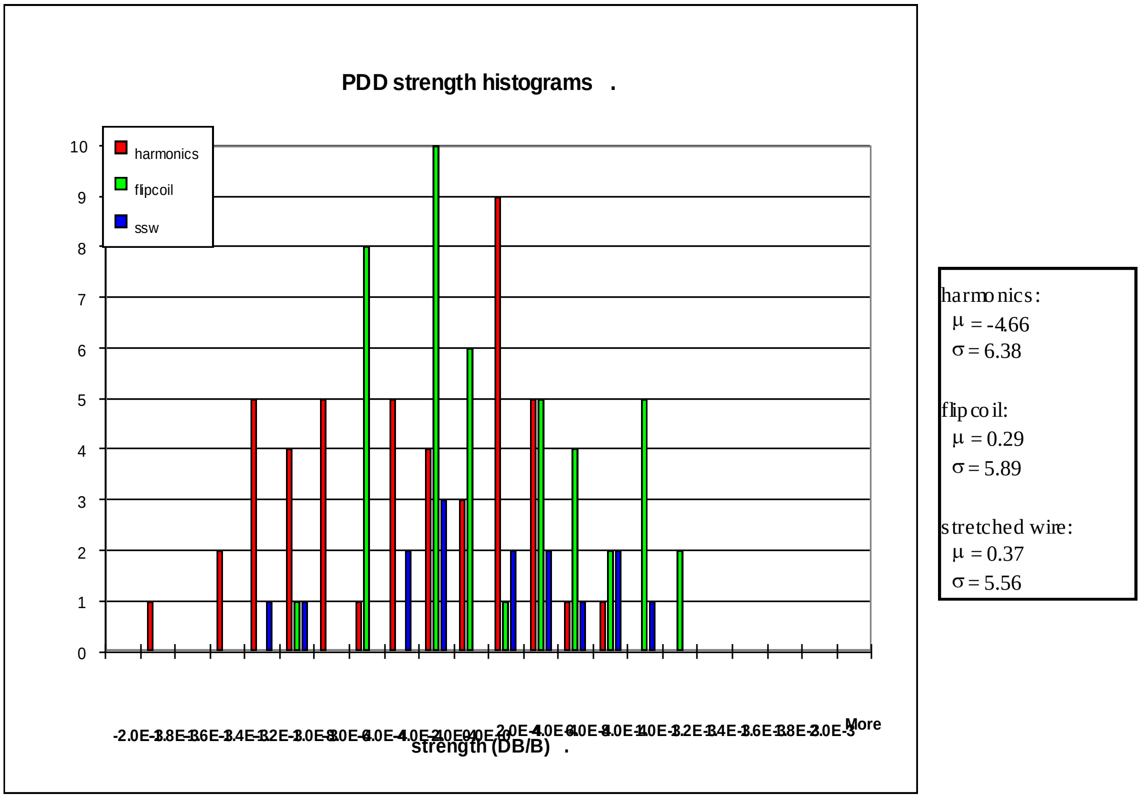

Figure 3.1A-9. Distribution of PDD strengths measured with the harmonics probe at MTF, the manual flip coil at the MP9 magnet factory, and the single stretched wire system at MTF.

A manually operated Rogowski coil was used to measure the strengths and temperature coefficients of the four independent pole tip potentials of the quadrupoles. These measurements were used to trim the strengths of each pole in the quad, by installing a variable number of washers on a threaded rod behind each pole tip.

Magnetic Measurements -Temperature Coefficients

Figures 3.1A-10 and 3.1A-11 show the distributions of temperature coefficients for the PDD and PGD magnets, respectively. Magnets outside the acceptance tolerances had the number of compensator strips changed, their strength re-trimmed, and the compensation remeasured.

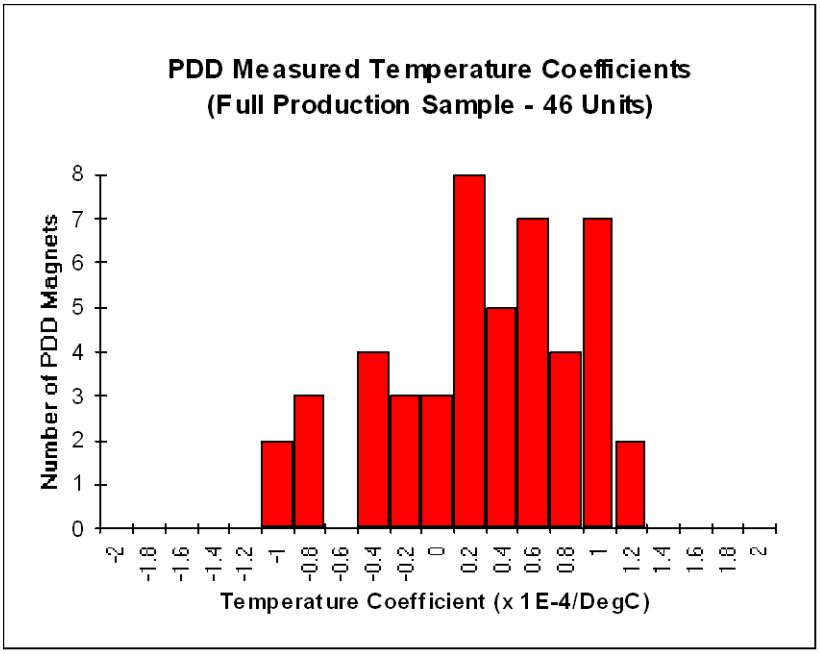

Figure 3.1A-10. Temperature Coefficients measured for the production run of PDD magnets. The mean is 0.15 units/°C, the standard deviation is 0.60 units/°C, and the acceptance tolerance was 1.2 units/°C.

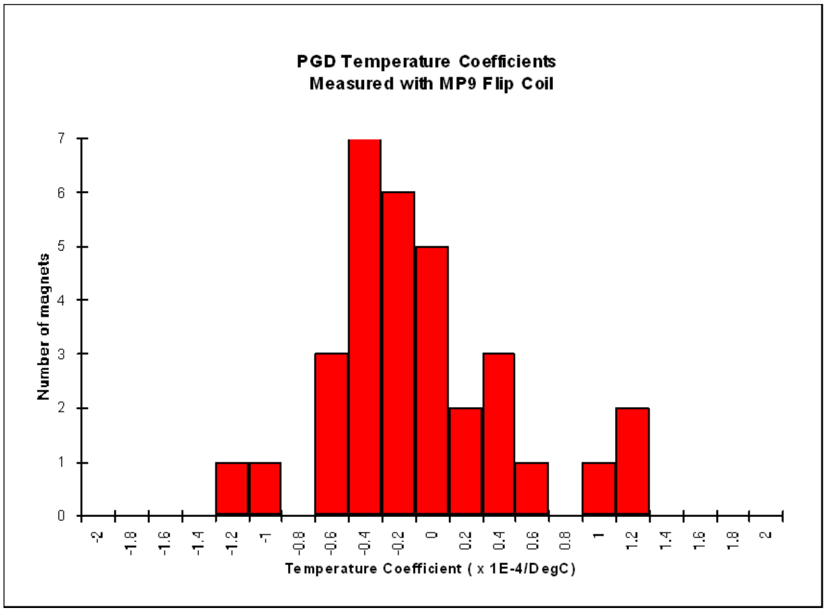

Figure 3.1A-11. Temperature Coefficients measured for the first 37 magnets of the production run of PGD magnets. The mean is 0.18 units/°C, the standard deviation is 0.55 units/°C, and the acceptance tolerance was 1.3 units/°C.

Magnetic Measurements - Field Quality

The field quality specification for acceptance of 8 GeV line dipoles and gradient magnets was set to 10 units of total field defect (By vs. X on the midplane) as measured at MTF by a single harmonics probe measurement 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 design good-field aperture of 1.75”(v) x 3.5”(h). This specification represents a compromise between the minimum field quality required for adequate performance of a transfer line (where a field defect of ~0.5% would be adequate) and the Recycler permanent magnet field quality (which must be in the range of a 1-2x10^{-4} over a 1” aperture).

The basic manufacturing strategy was to specify machining tolerances of typically ±0.003” for the iron pole tips of the magnets, which is sufficient to guarantee roughly 0.1% field defect over the aperture. Mechanical provisions were made for end shims on the ends of the pole tips which can be used to null out up to ~10 units of integrated field defect in the magnets. The end shims were not found to be necessary to meet the 8 GeV line field quality specifications. (This procedure was successfully used for the Recycler prototype magnets). The dominant source of field error arises from assembly tolerances in the parallelism of the pole tips, which produces a gradient error of roughly 1 unit per mil of mismatch between the side supports of the pole tips.

Table 3.1A-3. Measured systematic and random multipoles (in Fermilab units @1”) for the production run of PDD dipoles.

	Normal		**Skew**	
Pole	mean	std dev	mean	std dev
Quadrupole	-0.10	1.74	-2.65	3.66

Sextupole	-1.43	0.87	-0.24	2.75
Octupole	0.00	0.15	-1.09	1.34
10-pole	-0.73	0.56	-0.04	0.50
12-pole	-0.03	0.08	-0.10	0.14
14-pole	-0.12	0.18	0.00	0.08

Magnet Measurements - Quadrupoles

For the quadrupoles the field strength and shape specifications were driven by the requirement that the integrated field errors for a half-cell containing quadrupoles should be smaller than those of cells containing gradient magnets. As a result the field tolerances were considerably relaxed due to the 12x smaller normalization amplitude for the harmonics of the quads compared to the bend magnets. For example, a barely allowable 10-unit gradient error in the dipoles corresponds to a 120 unit strength error in the quadrupoles. The situation for higher multipoles is similar. In actual production the strength and multipole distributions [Fig.3.1A-12] were tighter than this. In addition, the assignment quadrupoles in the line paired one weak with one strong quadrupole, further attenuating any effects of quad strength variation.

Figure 3.1A-12. Field strength distribution for 8 GeV line Quadrupoles.

REFERENCES

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[1] Type 8 Strontium Ferrite data sheets & specs from Arnold, Crucible, Hitachi. Hitachi (Ardsmore, MI) was the low bidder on the ferrite for the 8 GeV line.

[2] The Technical Division assembly drawing package numbers for the 8 GeV line permanent magnets are: PGD (gradient magnet): ME-338124 , PDD (Horizontal dipole): ME-341007, PDV (vertical bend dipole) ME-341022, Quadrupole (PQP) : ME-341045.

[3] Dallas 1995 PAC papers on permanent magnets by Bertsche & Ostiguy, Foster & Jackson.

[4] Carpenter Technologies Compensator 30 type 4 data sheets from; Telecon data sheet, Eagle Alloys, Sumitomo Heavy metals.

[5] Hank Glass, Presentation in the collected transparencies from the Main Injector Magnet Physics (MIMP) meetings.

[6] Hank Glass, Presentation in the collected transparencies from the Main Injector Magnet Physics (MIMP) meetings.