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Abstract – **Hybrid permanent magnets provide the magnetic fields for an anti-proton storage ring which is under construction at Fermilab. Using a combined function lattice, gradient magnets provide the bending, focusing and sextupole correction for the regular cells. Shorter magnets without sextupole are used in dispersion suppressor cells. These magnets use a 4.7 m (3 m) long iron shell for flux return, bricks of 25.4 mm thick strontium ferrite supply the flux and transversely tapered iron poles separated by aluminum spacers set the shape of the magnetic field. Central fields of 0.14 T with gradients of ≈6%/inch (≈13%/inch) are required. Field errors are expected to be less than 10^{-4} of the bend field over an aperture of ± 40 mm (horizontal) × ± 20 mm (vertical). Design, procurement, fabrication, pole potential adjustment, field shape trimming and measured fields will be reported.**

1 INTRODUCTION

The Fermilab Recycler Ring[1][2] will increase the number of anti-protons available for collisions in the Tevatron collider by recovering anti-protons remaining at the end of a colliding beams store in the Tevatron and by serving as a final accumulation depository beyond the Debuncher and Accumulator. The primary bending and focusing will be provided by hybrid permanent magnets using iron for pole tips and flux return and strontium ferrite as a flux source compensated for temperature dependence using a NiFe alloy. Fabrication will begin soon on the gradient magnets. This report will describe requirements, fabrication considerations and prototype studies.

2 GRADIENT MAGNET REQUIREMENTS FOR THE RECYCLER RING

Since the Recycler Ring is placed above the Fermilab Main Injector, its lattice is quite similar with 54 regular arc cells and 32 dispersion suppressor cells and uses a dipole-free FODO lattice through the long straight sections. Gradient magnets provide bending and focusing in the regular and dispersion suppressor cells. Sextupole for chromaticity correction is incorporated in the regular cell gradient magnets. Quadrupoles[3] are used in straight sections and for tune adjustment.

The field $B(r,\theta) = B_y + iB_x$ in a gradient magnet is described by

Series	# Req.	Length m	$\int B_y dl$ T-m	b_2 units	b_3 units
RGF	108	4.4958	0.61824	619.74	8.696
RGD	108	4.4958	0.61824	-598.09	-15.053
SGF	64	3.0988	0.41216	1275.96	0.0
SGD	64	3.0988	0.41216	-1303.08	0.0

Table 1: Quantities and design field components for Recycler Ring gradient magnets.

$$B(r,\theta) = B_1 \sum_{j=1}^{\infty} (b_j + ia_j) \left(\frac{r}{r_0}\right)^{j-1} e^{i((j-1)\theta)} \qquad (1)$$

where r and θ are polar coordinates, B_1 is the dipole field (at the magnetic center), r_0 is the reference radius which we take as 25.4 mm, b_j, a_j are the normal and skew harmonic components with dipole taken as $j = 1$. We report b_j, a_j in 'units' of 1×10^{-4}.

Table 1 describes the field specifications for the four gradient magnet designs. Figure 1 illustrates the body cross section of the regular cell horizontally focusing (RGF) magnet while Figure 2 illustrates the dispersion suppressor cell horizontally focusing (SGF) cross section. Except for the obvious left-right reflection (to change from horizontally focusing to defocusing) RGF and RGD magnets differ only in details of pole shape required to produce the specified gradient and sextupole harmonics. Similarly, the SGF and SGD designs differ only in pole shape details. The RGF and RGD pole shapes provide a sextupole component which is sufficient to compensate the natural chromaticity of the lattice.

The field error budget[4] for the Recycler Ring has been determined based on a combination of assumptions about fabrication capability with lattice considerations which included resonance width and tracking studies. Table 2 provides the error budget for gradient magnets in terms of limits on average values and RMS deviations about those averages. Poletip separation, angle, and curvature along with pole potential (ferrite total strength) set the design fields. Errors in the potential will be controlled by adjusting the ferrite quantity. End shims will be created with shapes to cancel the normal quadrupole, sextupole and octupole errors. Some correction for higher order field errors may be possible with end shims, but we expect the pole reproducibility to be adequate. Note that unlike an electromagnet in which a series coil connection assures an anti-symmetric pole potential distribution (average value of zero), in a hybrid permanent magnet, a small symmetric term is expected for an initial selection of magnetic materials. This contributes the most significant driving source for skew quadrupole.

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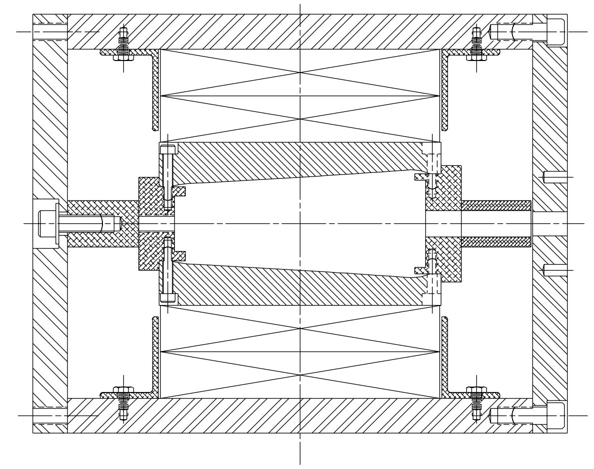

Figure 1: Cross section view of RGF gradient magnet. Iron pole tips are spaced by aluminum bars. Above and below the pole assembly, two ferrite bricks (each 25.4 mm thick by 152.4 mm wide) drive flux thru the gap. An iron shell provides flux return path and provides the mechanical support.

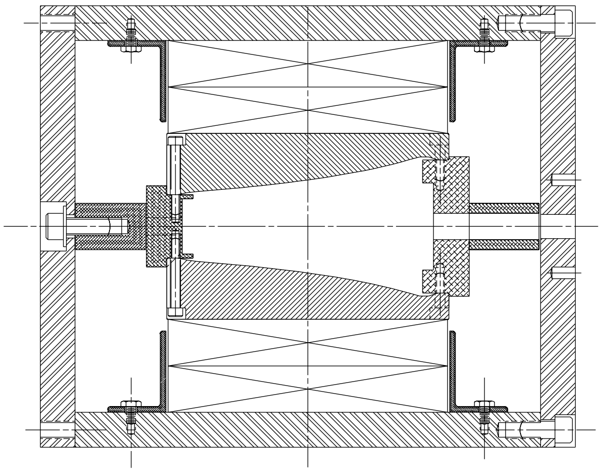

Figure 2: Cross section view of SGF gradient magnet. Most features are like the RGF but the larger slope on the pole face (to provide more quadrupole) requires a greater average iron thickness and thereby changes other dimensions.

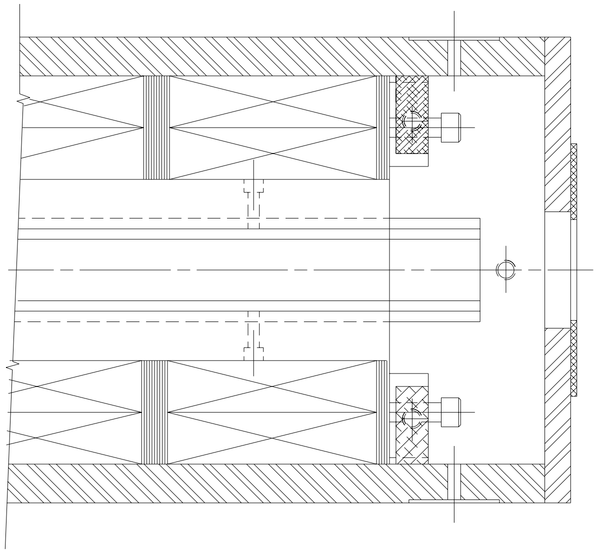

Figure 3: Side section view of RGF gradient magnet. 10 ± 1 compensator strips are between the 101.6 mm long ferrite bricks. The pole spacer extends beyond the pole so that survey positions can be referenced to the pole spacer through the holes shown.

Multipole	Normal		Skew	
Component	Sys.	Random	Sys.	Random
Quadrupole	1	1	1	1
Sextupole	0.5	1	-	0.5
Octupole	0.5	0.5	-	0.5
10-pole	0.2	0.5	-	0.5
12-pole	0.1	0.5	-	0.5
14-pole	0.1	0.5	-	0.5
16-pole	0.1	0.5	-	0.5
18-pole	0.1	0.5	-	0.5

Table 2: Field quality requirements for Recycler Ring gradient magnets. Limits are shown for deviations from values of normal quadrupole and sextupole shown in Table 1. Systematic (average) and Random (RMS deviations) limits are shown for other normal and skew moments. Except for the quadrupole, it is assumed that systematic skews assume the value determined by the random fluctuations.

3 CREATION OF PRECISE POLE TIP SHAPES

The design shape of the poles was varied to seek an optimum match of the B_y field component to the requirements of Table 1 over a 2.54 mm grid in a rectangular aperture ±20.3 mm high × ± 35.56 mm wide as calculated using a two-dimensional magnet design code (POISSON). The pole shape tolerance was specified to best match the requirement: deviations from a best fit over the central ± 42.5 mm (1.7$''$) are limited to ± 5 μm (0.0002$''$) with deviations of ± 25 μm (0.001$''$) over the remainder of the ± 76.2 mm (3$''$) width. Pole gap spacers are permitted variations of ± 50 μm (0.002$''$).

Four techniques have been examined for producing these shapes: stacked laminations, numerically controlled machining, form grinding, and extrusion/drawing. Various low carbon steels (*e.g.* 1008 or 1018) are used in all cases.

- Laminations were punched from 1.5 mm thick steel and stacked against a backing plate.
- Machining was used to shape hot rolled steel bars which were ground to produce flat surfaces. A CNC mill with 1$''$ diameter ball cutter, using transverse passes repeated

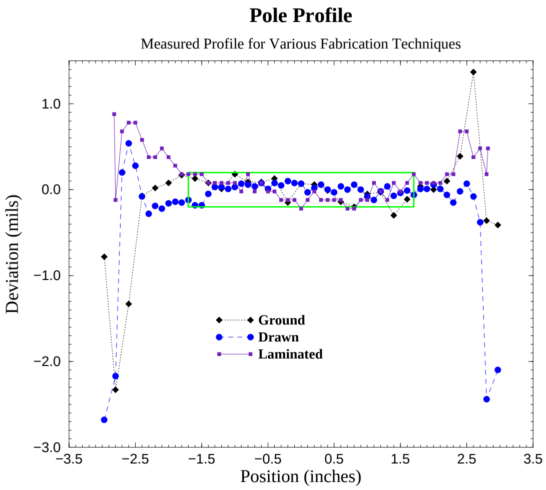

Figure 4: The profiles achieved with various fabrication techniques are shown. The difference between the measured and the specified shape are are presented after correction by a linear fit to the deviations weighted by the allowed deviation. Deviations are in mils with 1 mil = 0.001″ = 25.4 μm. Position is in inches with 1″ = 25.4 mm. Box indicates requirements for high precision region.

along the length produced the first prototypes.

- Form grinding employed a grinding cylinder which produced the required transverse shape with a grinding pass along the pole length. The shape of the grinder is maintained by dressing on a precision steel form with a cutting surface of embedded diamonds. It used similar steel to the machining technique.
- Two passes of drawing thru carbide dies produces the required shape from a bar which had been extruded to nearly the desired shape.

Each technique has successfully produced prototype quantities. Fig. 4 shows the precision achieved with the lamination, form grinding, and extrusion/drawing techniques for the RGF magnets. For the RGF and RGD magnets we are preparing for production based on the capability to produce production quantities to the required schedule and cost. We continue to explore the capability of both drawing and lamination techniques for the less rectangular shape of the SGF/SGD series.

4 MEASUREMENT AND TUNING FOR DIPOLE STRENGTH

Procurement issues for the ferrite and compensator have been described elsewhere[5]. For each design, the number of ferrite bricks (4″ × 6″× 1″) is selected to initially provide 1 - 2 % excess pole potential. Since H_c of the ferrite decreases as the temperature falls, any ferrite which is driven too near H_c may be demagnetized if the magnetic assembly is cooled. Uniformity of the bricks cannot be assured, so we cool all assembled magnets below the temperature (0^o C) which will be permitted in storage or transportation.

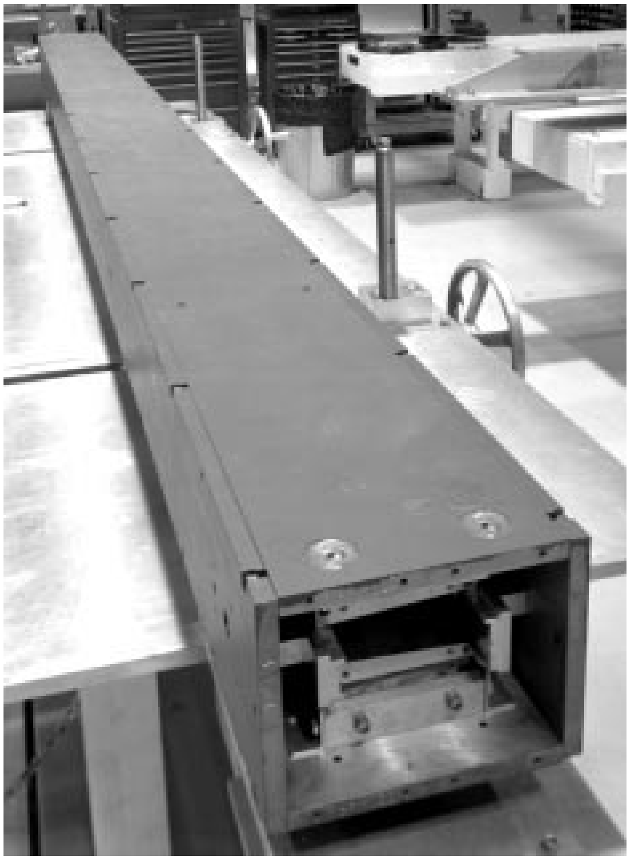

Figure 5: View of gradient magnet on assembly table.

Measurements of the dipole component of the field with a flip-coil in the center of the aperture are used to confirm the temperature compensation and for strength trimming. Strength adjustment is achieved by replacing full bricks with partial bricks in a fashion which enhances the initial top-bottom and end-to-end symmetry of the magnet.

5 FIELD SHAPE TRIMMING

We expect body harmonic errors to be at most several units of quadrupole error from angles created by pole and spacer tolerance, sextupole error of 1 - 2 units due to pole shape variation, and a unit or less of octapole. End corrections are applied by varying the pole length as a function of horizontal position. An end corrector is fabricated from a length of the design pole shape which is machined to vary its length at different transverse locations. An end angle produces a quadrupole correction. A parabolic endpiece produces a sextupole correction. But neither correction is pure so a linearization is required based on difference measurements using the nominal quadrupole, sextupole and octapole correctors. Corrections which are top - bottom symmetric will modify only the normal harmonics. Corrections for higher order skew harmonics have not been developed. The skew quadrupole is controlled by adjustments of the pole potential (varying the number of bricks).

Magnet production will employ a rotating coil harmonic measurement[6] to assess the field errors. After initial strength trimming, the harmonic errors will be used to design end shims (for both poles at one end) to correct the integrated field shape. These shapes will be cut from the stock pole shape and bolted to the magnet prior to final strength trimming. Custom shims will be fabricated for each magnet unless it is determined that corrections are sufficiently similar from magnet to magnet as to not require it.

6 LONGITUDINAL UNIFORMITY

The longitudinal uniformity of the magnetic potential of the pole is established by the distribution and strength of ferrite and compensator materials. The finite permeability and remanance of the iron creates potential differences near the end since flux must be transported to the pole end. The design must include space for bricks beyond the average required number to assure the capability of adequate magnet strength with below average bricks. Symmetric non-uniformities primarily affect Recycler focusing properties while asymmetric non-uniformities modify both the bend center and the focusing. Figure 6 illustrates effects of moving or removing half bricks. We will clearly need smaller fractional bricks.

7 STATUS AND PROSPECTS

Measurements of transverse shape have confirmed that the design produces the desired field quality when the steel shapes match the specifications. Prototype quantities of the extruded/drawn steel indicate that this technique can produce the pole shape needed. Details of longitudinal brick placement and end shimming are being worked out now in preparation for final assembly.

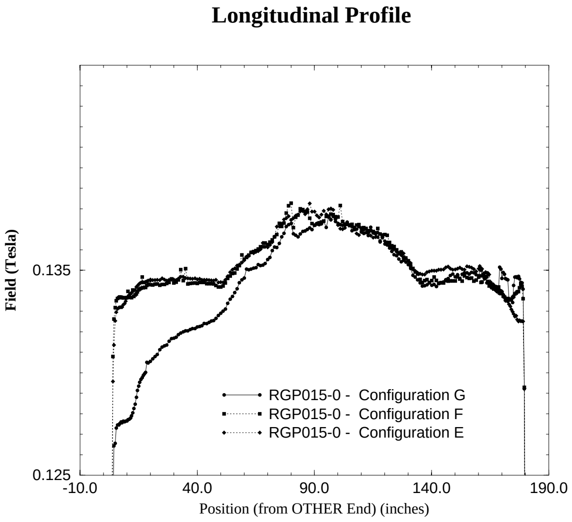

Figure 6: The magnetic field profiles resulting from various brick configurations on RGP015, a protype RGF magnet. In configuration E, a half brick is missing adjacent to the pole and $\approx 2''$ from the pole end in 4 locations. Configuration F moves the missing brick to $\approx 6''$ from the pole end. Configuration G removed a half bricks top and bottom from the left end.

Both the extrusion/drawing and the lamination option are still being considered for the SGF and SGD magnets. Production decisions will await further testing. Meanwhile, materials are being delivered for fabrication of RGF magnets. Production rates of 3 per day are expected before January 1998. All magnets of all four series are required during summer 1998.

8 ACKNOWLEDGMENTS

We thank our support staff. The assembly and testing crew at Fermilab Building MP9 lead by Glenn Smith and the staff of the Magnet Test Facility have provided careful work on these magnets. Greg Kobliska has vigorously persued pole fabrication options resulting in the present satisfactory set of choices. Arnie Knauf has provided design/drafting for all the designs under consideration.

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