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Abstract – **Hybrid Permanent Magnet Quadrupoles are used in several applications for the Fermilab Recycler Ring and associated beam transfer lines. Most of these magnets use a 0.6096 m long iron shell and provide integrated gradients up to 1.4 T-m/m with an iron pole tip radius of 41.6 mm. A 58.4 mm pole radius design is also required. Bricks of 25.4 mm thick strontium ferrite supply the flux to the back of the pole to produce the desired gradients (0.6 to 2.75 T/m). For temperature compensation, Ni-Fe alloy strips are interspersed between ferrite bricks to subtract flux in a temperature dependent fashion. Adjustments of the permeance of each pole using iron between the pole and the flux return shell permits the matching of pole potentials. Magnetic potentials of the poles are adjusted to the desired value to achieve the prescribed strength and field uniformity based on rotating coil harmonic measurements. Procurement, fabrication, pole potential adjustment, and measured fields will be reported.**

I QUADRUPOLE REQUIREMENT FOR THE RECYCLER RING

The Fermilab Recycler Ring[1][2] will store anti-protons which have been recovered at the end of a colliding beams store in the Tevatron or have been accumulated in the 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. Since it 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 (18 cells) through the long straight sections. Gradient magnets[3] are used in the regular and dispersion suppressor cells. Quadrupoles are used in the normal long straight sections, in a special high beta long straight section which will support an upgrade to electron cooling, and in a phase trombone which will provide the only overall tune adjustment for the recycler.

Two quadrupole designs are needed to meet the transverse aperture requirements. In the high beta region, a symmetric quadrupole with 58.42 mm (2.3″) pole radius is required. Fig. 3 illustrates the body cross section of the large aperture (RQE) quadrupoles. Only a preliminary design of this magnet exists and it will not be discussed further.

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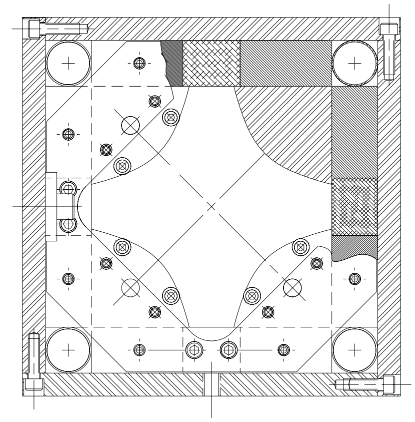

Figure 1: Cross section view of 42 mm aperture radius quadrupoles. One layer of 25.4 mm thick × 49.5 mm wide bricks drive each back side of each pole. A stainless steel tube in each corner holds iron washer packages captured on stainless steel rods which are used to tune magnet strength and field shape.

The balance of the quadrupoles can meet the aperture and strength requirements with a 41.73 mm (1.643″) pole radius and a 0.508 m (20″) pole length. Fig. 1 illustrates their cross section. Table 1 describes the required number of each series for which requirements are fully specified at this time. Additional 41.73 mm quadrupoles will fill other roles in the ring and transfer lines.

Series	# Req.	Pol	Ferrite Length	Comp #	$\int B'_y dl$ T
RQMF	20	F	15.125	42	1.3345
RQMD	22	D	14.625	41	-1.2862
RQSA	2	D	5	13	-0.4442
RQSB	2	D	3.6	9	-0.3259
RQSC	2	F	6	16	0.5403
RQSD	2	D	4.08	11	-0.3643

Table 1: 41.6 mm aperture radius quadrupoles series for the Recycler Ring. F polarity provides focusing in the horizontal plane. Material quantities selected to achieve the design strengths are shown in 4th and 5th columns. Ferrite of width ≈ 49.5 mm (1.95″) is used on each of the two sides of each pole in the length in inches shown. Compensator pieces are 1.25 mm thick × 25.4 mm wide × 50.8 mm long. Measurements of quadrupole strength temperature dependence are not complete at this time so compensator requirements may change.

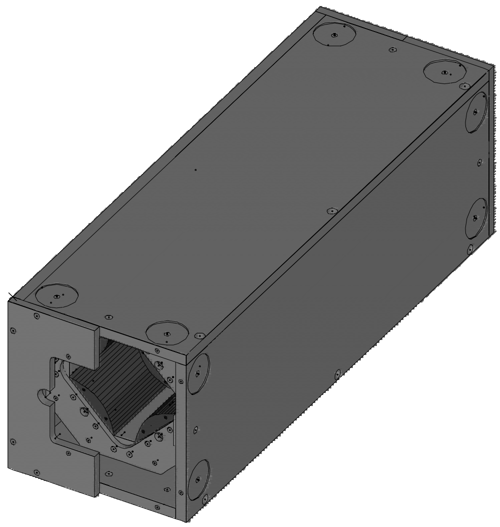

Figure 2: View of magnet assembly showing relation of pole, end collar, and flux return shell. Holes in the end of the pole are for screws which hold washers for tuning 8-pole and 12-pole field errors. Alignment nest mounting surface also shown at the end of the flux return shell.

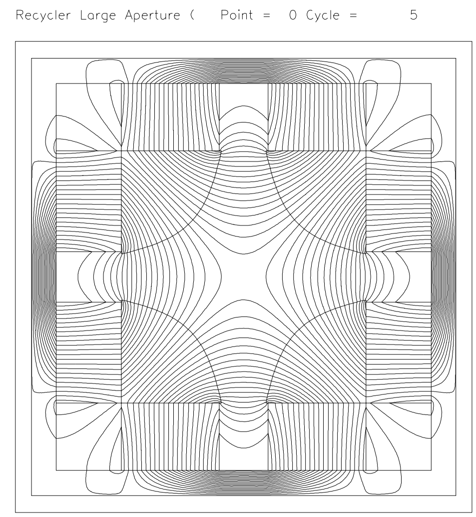

Figure 3: Cross section view of 58 mm aperture radius quadrupole. Shell forms a 0.3302 m (13″) square. Pole tip aperture radius is 58.42 mm (2.3″). Two 76.2 mm (3″) wide ferrite bricks drive each side of each pole.

II FERRITE AND TEMPERATURE COMPENSATOR

Commercial grades of strontium ferrite are well matched to the modest poletip fields required for this project. Temperature stability requirements demand compensation[4] of the ferrite temperature dependence by about × 40 to achieve $< 0.5 \times 10^{-4}$ /^{o} C. This is achieved using strips of NiFe alloy embedded between blocks of ferrite which drive the pole potential. As temperature increases, the ferrite supplies less flux while the temperature compensation alloy removes less flux. Procurement issues for the ferrite and compensator have been described elsewhere[5]. Since H_c of the ferrite decreases as the temperature falls, any ferrite which is driven too near H_c may be irreversibly demagnetized if the magnetic assembly is cooled. Uniformity of the bricks cannot be assured, so we cool assembled magnets below the permitted temperature (0^oC) for storage or transportation.

III POLE TIP AND FLUX RETURN SHELL

The focusing requirements for the regular aperture quadrupoles shown in Table 1 can be met with a single mechanical design for the iron and its support. The pole length is 0.508 m (20″) with a pole shape optimized from the hyperbolic shape to maximize the good field aperture. Poles are supported at the ends by pinning and bolting to a stainless steel end collar. Precision aluminum bars separate the poles. The flux return shell is made from 12.7 mm (0.5″) thick 1018 steel which has been ground flat (tolerance 0.63 mm) prior to the drilling and machining required to support the mechanical assembly. This shell is spaced by a single brick thickness (25.4 mm) from the pole tip. Using a 'windmill' pattern in which each side is resting on only one of the perpendicular edges, brick size variation and pole assembly tolerance are accommodated without incurring gaps in the flux paths. Gaps remain only due to size variations in bricks on one side. An overall magnet length of 0.6096 m (24″) leave 38.1 mm (1.5″) between the end of the pole and the magnet end plate. Rust protection is provided by electro-plating all iron pieces with zinc dichromate.

The pole pieces for prototype and transfer line quadrupoles[6] were fabricated by numerical machining. The larger quantity required for the Recycler Ring justified fabrication using an extrusion and two stage drawing technique. Bars of 1018 steel were extruded and drawn to a >6.1 m length and straightened. Final machining included cutting to length and drilling and tapping assembly and mounting holes. Tolerance on the pole shape was $\pm$ 25 $\times$ 10^{-6} m ($\pm$ 0.001″). Generally looser tolerances are required for other part shapes and hole placement.

IV PRODUCTION

The production proceeded with parallel efforts on the fabrication of a series with large quantities along with efforts to build and tune a series with only two magnets required. Assembly kits were created by withdrawing parts from inventory. Standard 4″x6″x1″ bricks were first cut in half to ≈ 2″x6″x1″ bricks which are used either at that length or in shorter lengths as specified. Bricks were magnetized in an automated system and stored for assembly. Fabrication consists of

- assembling the pole assembly with end collars and spacer bars (see Fig. 4),

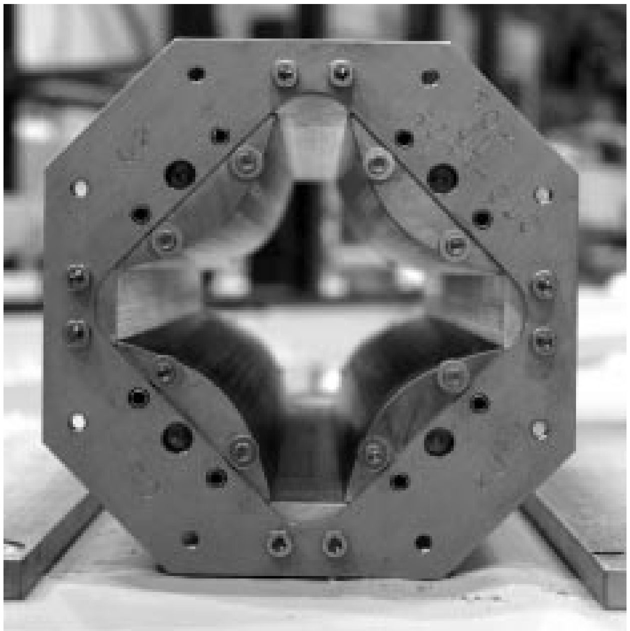

Figure 4: Photo of end of quadrupole pole assembly. Stainless end collar, aluminum pole spacers and iron poles with 12-pole tuning washers in place are visible.

- exciting one side at a time by placing the required bricks and compensator packs followed by the flux return plate,
- rolling the assembly to the next side for exictation until 4 sides are complete,
- finally installing the stainless tubes which hold tuning washers and the end plates.

Note that for this size of ferrite brick, the magnetic forces present permit fully magnetized bricks to be installed manually by persons of ordinary strength, although care is required. Preliminary tuning (see below) is followed by inserting the assembly in a refrigerator which cools the entire magnet to $\sim 0^o C$. Strength measurements at $0^o C$. and room temperature establishes that temperature compensation had been accomplished. Following the room temperature compensation test, a final adjustment of tuning washers is made to restore any deviations from the preliminary adjustment which are induced by the cooling.

V MEASUREMENT AND TUNING FOR QUADRUPOLE STRENGTH AND FIELD SHAPE

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

$$B(r, \theta) = B_2 r_0 \sum_{j=1}^{\infty} (b_j + i a_j) \left(\frac{r}{r_0}\right)^{j-1} e^{i((j-1)\theta)} \qquad (1)$$

where r and θ are polar coordinates, B_2 is the quadrupole harmonic field, 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}.

The field error budget[7] for the Recycler Ring has been determined based on a combination of assumptions about fabrication capabilities with lattice considerations which included resonance width and tracking studies. The average quadrupole strengths are required to match the design within 5×10^{-4} with a sigma about that mean of 8×10^{-4}. All higher order multipoles (sextupole through 18-pole) are required to have normal and skew harmonics with sigma of less than 1.5 units. The systematic (average value) normal components are required to be less than 0.5 units. The average skew is assumed to be zero within the tolerance of the sigma for random variation.

Control of the gradient strength along with the normal and skew sextupole and skew octupole is achieved by tuning the pole potential. Note that, unlike an electromagnet quadrupole in which a series coil connection assures an anti-symmetric pole potential distribution (average value of zero), in a hybrid permanent magnet, the desired antisymmetric source distribution would only be achieved by precisely matching materials. The symmetric contribution to the pole driving terms provides the most significant driving source for skew octupole.

The normal octupole error is driven by assembly asymmetries. The lowest harmonics allowed for a symmetric quadrupole are 12-pole and 20-pole. The pole shape removes these in the body field provided the poles are precisely placed at the correct radius. End field contributions for 20-pole are insignificant but the 12-pole end contribution of 7 units is compensated using steel washers, two stacks on each end of each pole, secured by #6 USC steel screws at angles of $\pm 20.56^o$ from the pole centerline. Antisymmetric placement (with respect to the pole centerline) of washers in these stacks is used to trim the normal octupole term due to pole assembly asymmetries. Fig. 4 shows the end configuration.

For each design, a combination of ferrite brick sizes and compensator strip quantities is selected to provide 1 - 2 % excess pole potential. These quantities are shown in Table 1. The magnetic potential of the pole can be reduced by increasing the permeance between the pole and the flux return shell. We accomplish this by placing steel washers in the corner regions at the centerline of each pole (see Fig. 1). Varying the number of washers in 4 corner locations allows control of the integrated gradient strength, the normal sextupole, the skew sextupole, and the skew octupole. Since most of the flux is carried between the poles, changes of potential on one pole are not independent of changes on adjacent poles. The coupling from the non-adjacent pole is quite small.

Measurements with a Rogowski Coil can be used to determine pole potentials. The precision required precluded measurements except where special holes at pole ends reduced errors due to coil placement. Since bricks are not available to uniformly drive the pole, potential drop along the pole precluded precise measurements with this technique. An automated rotating coil harmonics measurement system[8] provides both strength and shape measurements in a format well suited to tuning the poles.

	RQMF		RQMD	
	Ave	Std.Dev.	Ave.	Std.Dev.
$B2$	1.334E+00	4.2E-04	1.286E+00	4.38E-04
$\delta b2$	-1.59E-04	3.2E-04	5.12E-05	3.4E-04
b3	1.52E-05	7.65E-05	-1.16E-06	5.53E-05
a3	-6.23E-06	1.06E-04	8.01E-06	6.07E-05
b4	7.77E-05	2.20E-04	-2.32E-06	2.62E-04
a4	-3.33E-06	1.20E-05	-3.11E-06	2.11E-05
b5	2.01E-05	2.58E-05	-3.21E-05	3.76E-05
a5	2.49E-05	5.18E-05	2.35E-05	4.65E-05
b6	-4.60E-05	2.78E-05	-4.14E-05	2.34E-05
a6	1.97E-06	9.55E-06	3.62E-06	1.68E-05

Table 2: Measured results at room temperature for 19 of 20 RQMF and all 22 RQMD magnets. B2 in the measured quadrupole integrated strength in T-m/m while $1 + \delta b2$ is B2 divided by its design value. These are values obtained from preliminary tuning of pole tip strengths before magnets were cooled to 0^o C. Note that the harmonic values are expressed as not as ‘units’ but directly as field ratios.

The tuning algorithm is described by the equation

$$\begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{pmatrix} = \begin{pmatrix} 0.329 & 1.135 & -1.135 & -13.33 \\ 0.329 & -1.135 & -1.135 & 13.33 \\ 0.329 & -1.135 & 1.135 & -13.33 \\ 0.329 & 1.135 & 1.135 & 13.33 \end{pmatrix} \begin{pmatrix} \delta b_2 \\ b_3 \\ a_3 \\ a_4 \end{pmatrix} \tag{2}$$

where w_1, w_2, w_3, w_4 indicate the changes in the number of washers to be placed behind the pole in quadrant 1-4 respectively. $\delta b_2, b_3, a_3, a_4$ are the measured values of the relative strength error, and the normal and skew sextupole and the skew octupole normalized harmonic components. Two or three adjustment cycles converges to a solution which matches the strength and harmonic requirements.

VI RESULTS

Initial assembly and trimming of the magnets shown in Table 1 has been completed. Resulting magnet properties are summarized in Table 2. 12-pole trimming washers were installed on the assumption that all magnets were alike. This has provided satisfactory trimming of the 12-pole component but adjustments to place these washers in asymmetric positions for normal octupole trimming will be required for a fraction of the magnets. Trimming of the strength, b_3, a_3, and a_4 was successfully carried out. This will be re-confirmed after the magnets have been cooled, then measured cold and warm for temperature compensation.

Fabrication and testing of these quadrupole has proceeded with satisfactory results. We believe that the quadrupole requirements for the Recycler Ring will be fully satisfied by these magnets.

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