The Experience at Fermilab: Recycler Ring and Beam Lines based on PM Technology

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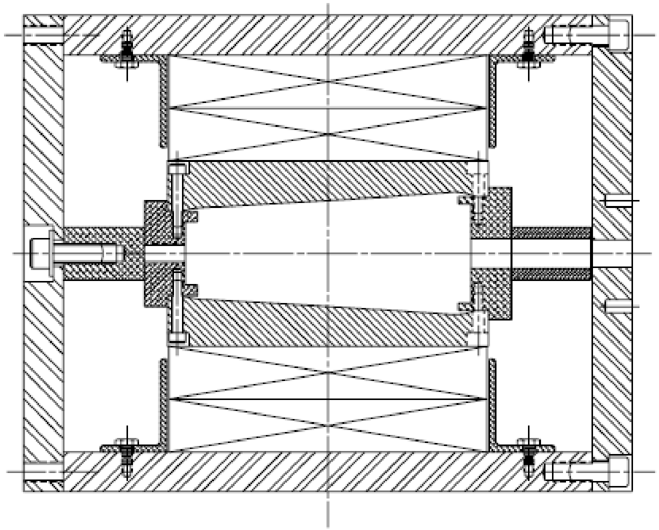
Outline

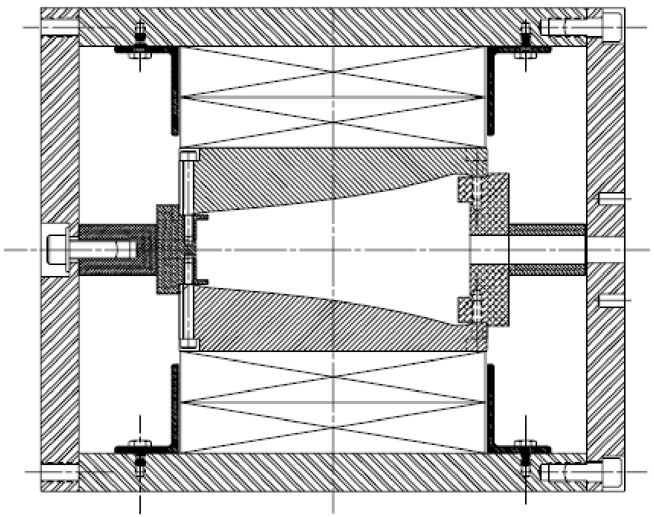
- Recycler permanent magnets
- NOvA beam line magnets
- Beam profile monitor magnets
- Summary
- References

Fermilab Recycler Ring Dipoles (1)

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) $\times$ ± 20 mm (vertical).**

Recycler Ring Dipoles (2)



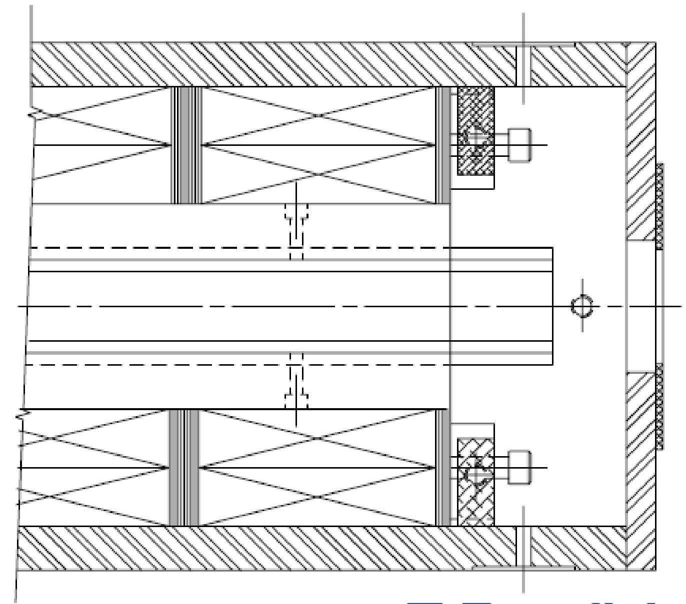


Dispersion suppressor gradient focusing/defocusing dipoles SGF/SGD

Ring gradient focusing/defocusing dipoles RGF/RGD

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.



Fermilab Recycler Ring Quadrupoles (1)

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.**

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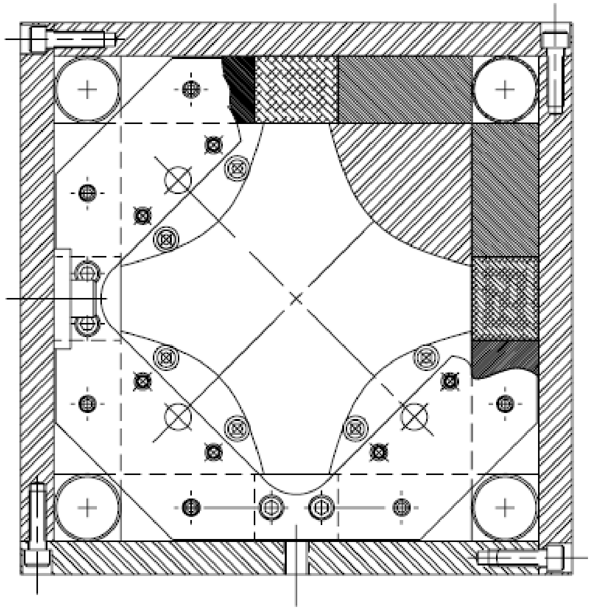
Recycler Ring Quadrupoles (2)



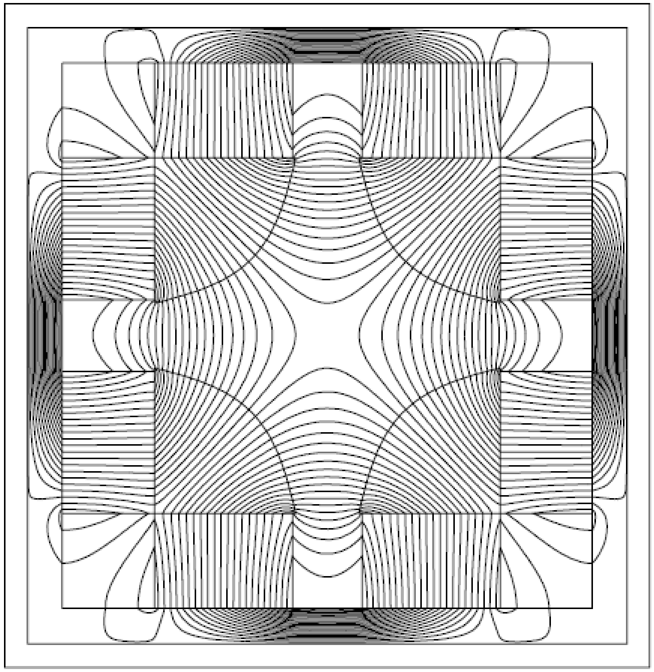


Figure 1: Cross section view of 42 mm aperture radius quadrupoles. One layer of 25.4 mm thick × 49.5 mm wide bricks drive each back side of each pole. A stainless steel tube in each corner holds iron washer packages captured on stainless steel rods which are used to tune magnet strength and field shape.

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

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 $\times$ 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.

Ferrite Magnetization and Shunting

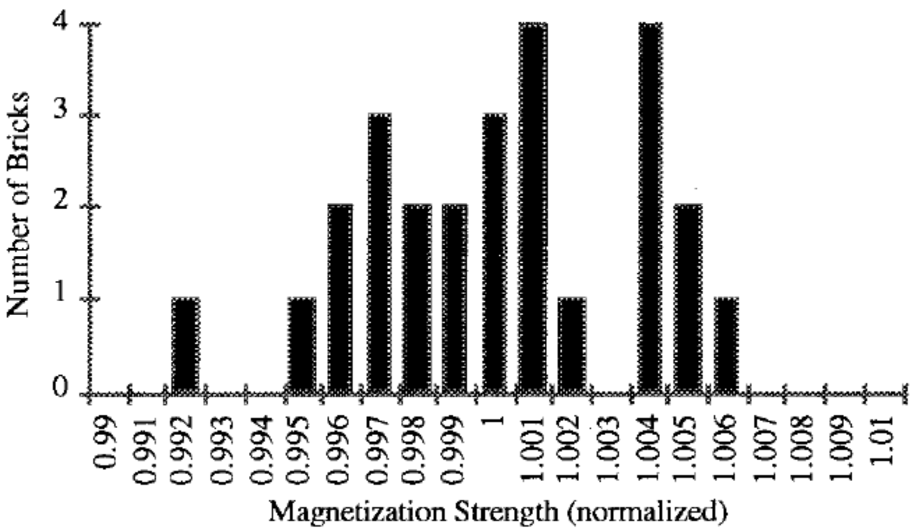


Figure 3: Histogram of the first 26 bricks tested with the MTF single brick field strength tester. The full spread of the bricks tested was 1.3% and the RMS spread was 0.3%. This measurement indicates that within a single lot of bricks we expect the variation to be less than the ±10% tolerance specified by the manufacturer.

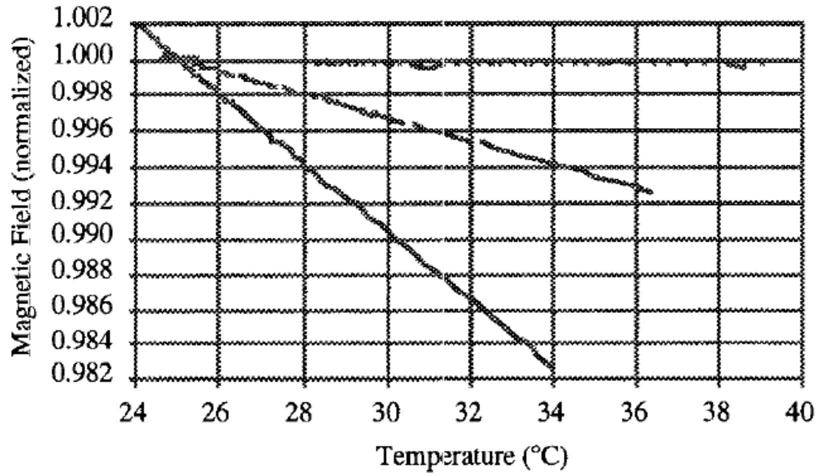
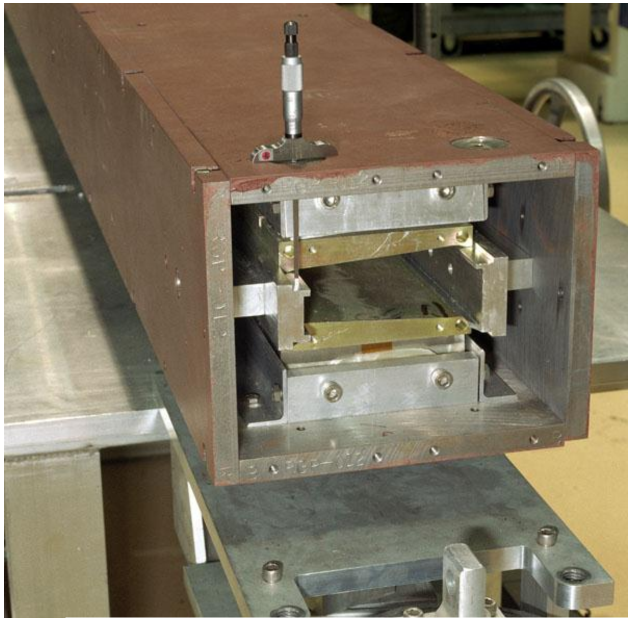


Figure 4 Cool-down curves showing variation of the magnetic field in a permanent magnet prototype with various size temperature compensation shunts. Bottom curve: uncompensated magnet showing the expected temperature coefficient of -0.19%/°C. Middle curve: first attempt at a temperature compensation shunt. Top curve: second attempt using a shunt of a larger size estimated from the performance of the first shunt. The temperature coefficient has been reduced by approximately two orders of magnitude, more than adequate for our application.

Recycler Dipoles Fabrication



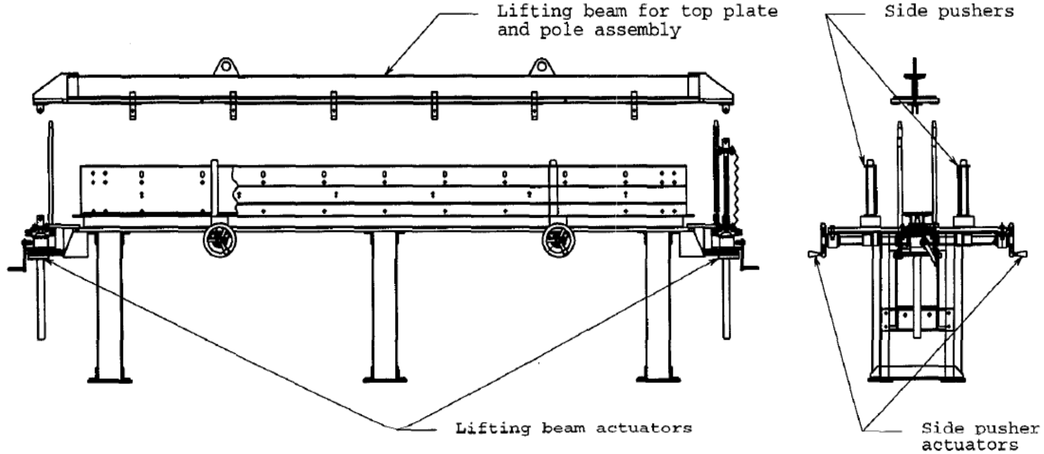
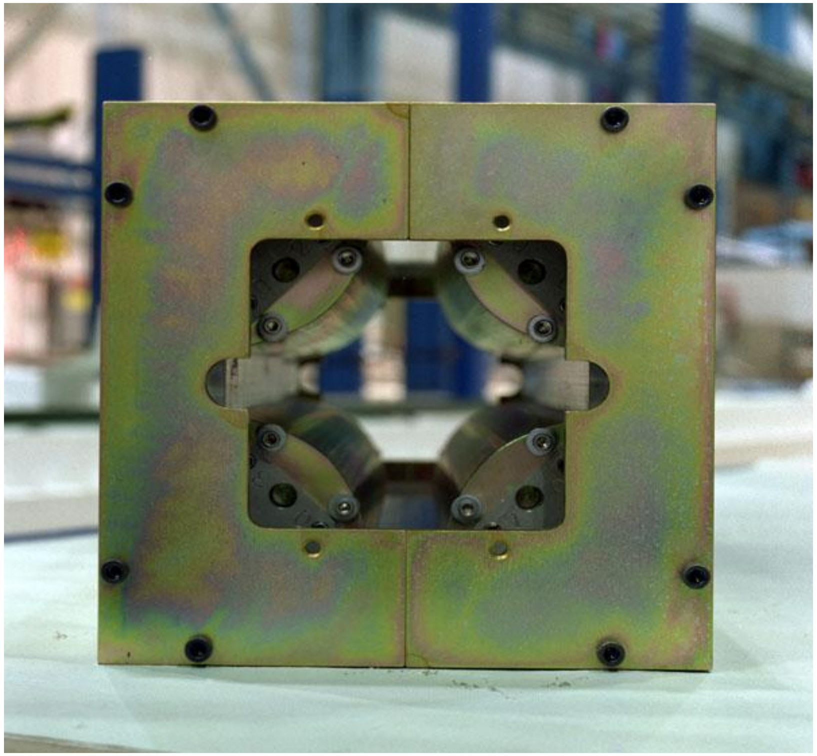
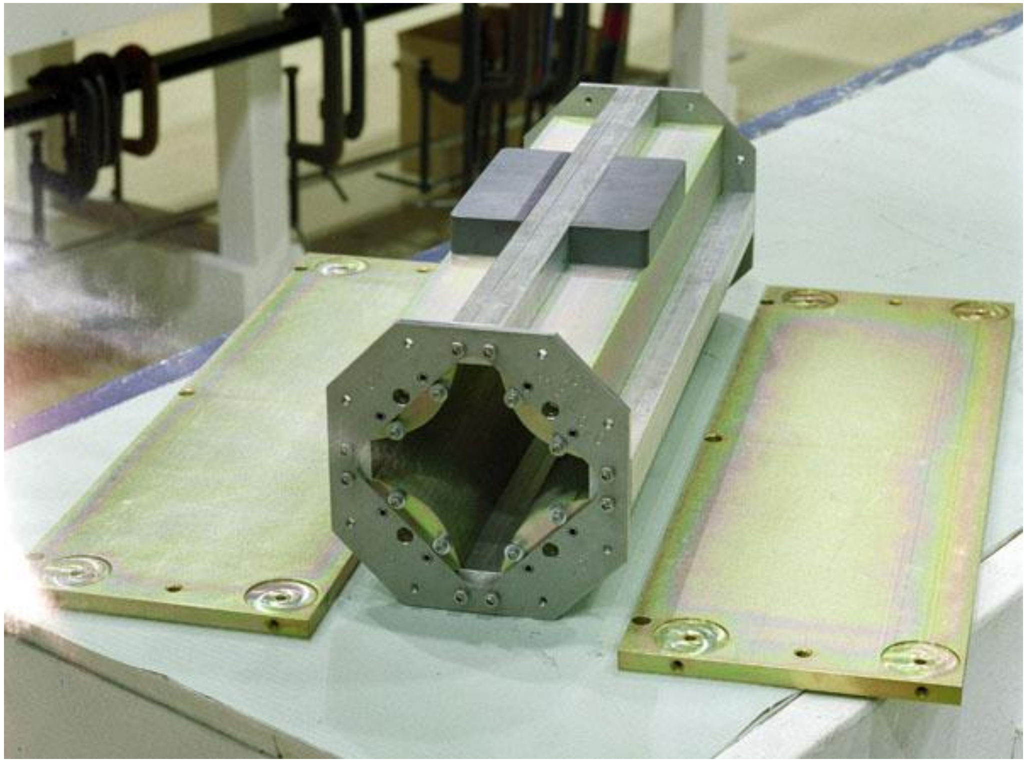


Figure 3: Permanent magnet assembly tooling

Magnets assembled from 4 sub-assemblies: top, bottom, and two sides by using special non-magnetic tooling (left).

Recycler Quadrupole Fabrication





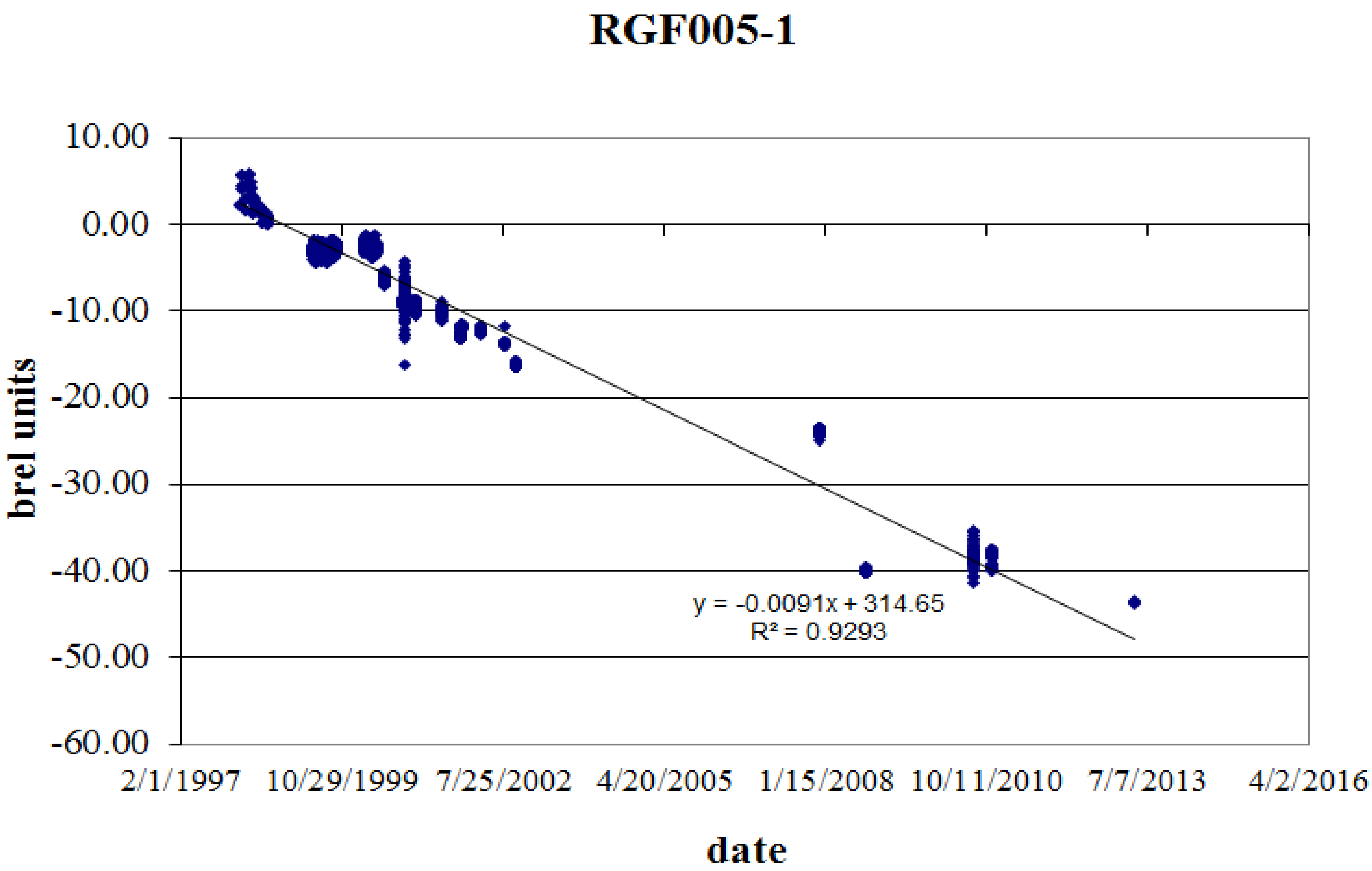
1. Assembling the pole assembly with end collars.
2. Exciting one side at a time by placing the required bricks and compensator packs followed by the flux return plate.
3. Rolling the assembly to the next side for excitation until 4 sides are complete
4. Finally installing the stainless tubes which hold tuning washers and the end plates.

Magnets Construction Facility

Recycler Magnets in the Tunnel

The Main Injector Tunnel showing Main Injector (blue magnets on the bottom) and Recycler (green magnets on the top).

RGF Gradient Dipole Strength vs. Time



The Recycler magnets strength drops with the rate 3 units/year.

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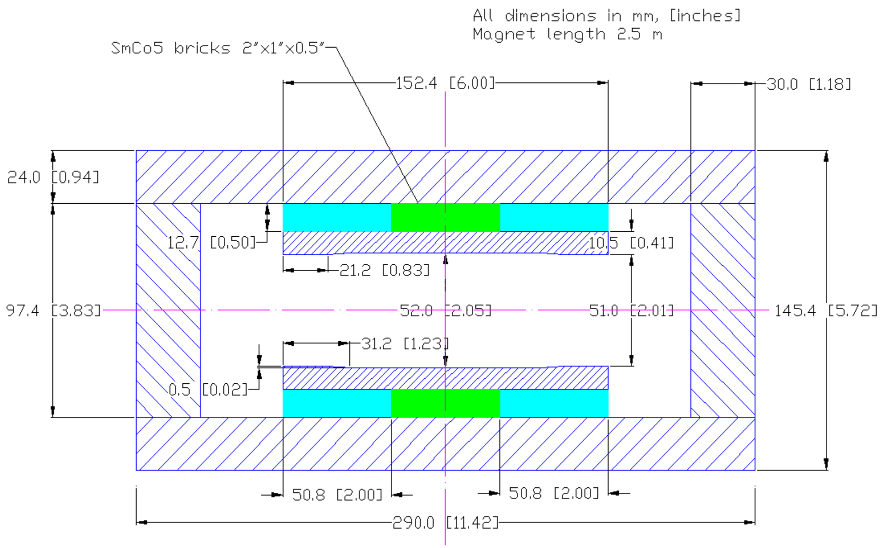
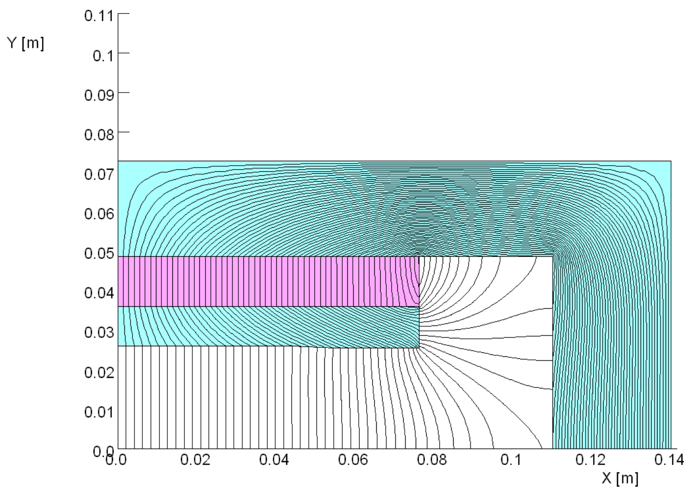
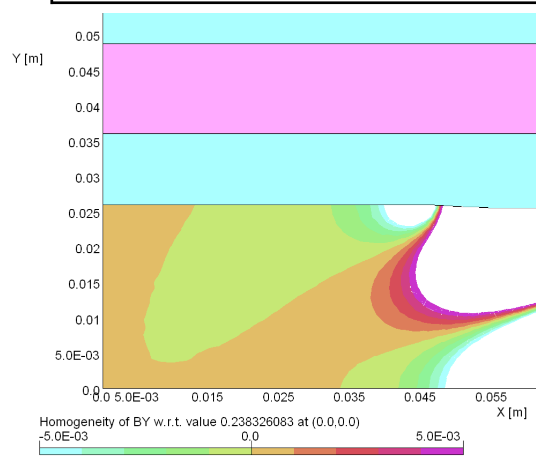
NOvA/ANU Permanent Magnet Dipole (PDS)



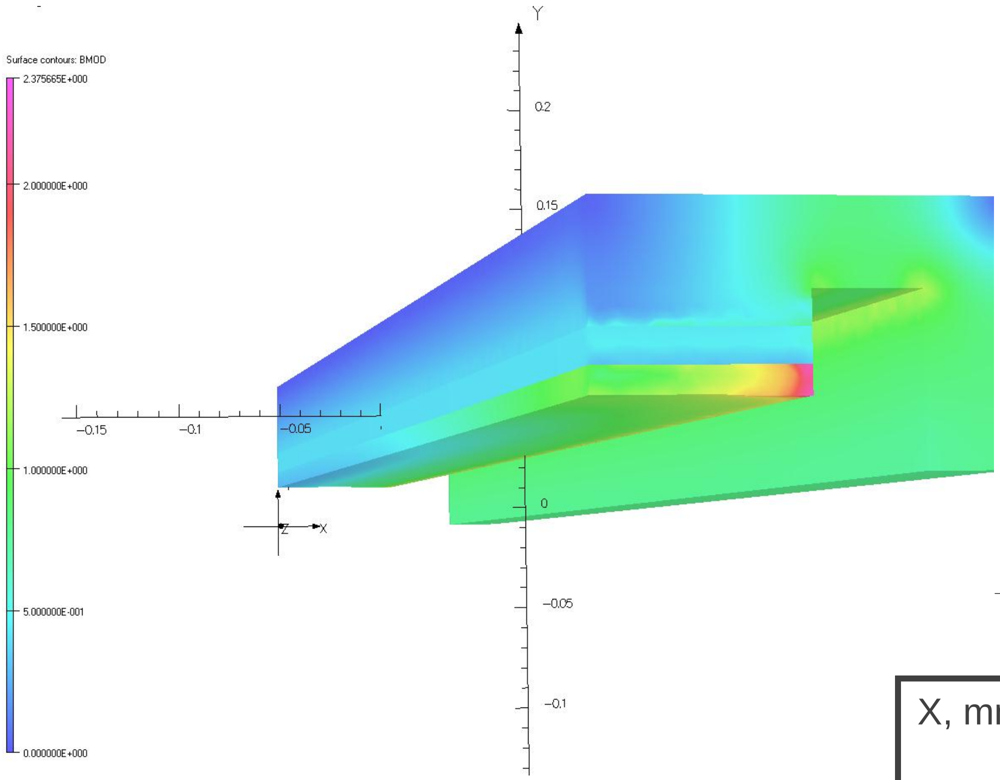
Integrated strength, T-m	0.56954
Distance between beams, mm	159
SmCo5 residual flux density Br, T	> 0.8
SmCo5 coercive force Hc, kA/m	>600
Air gap, mm	52
Magnet length, m	< 2.5
Magnet width, mm	< 400
Magnet height, mm	<159

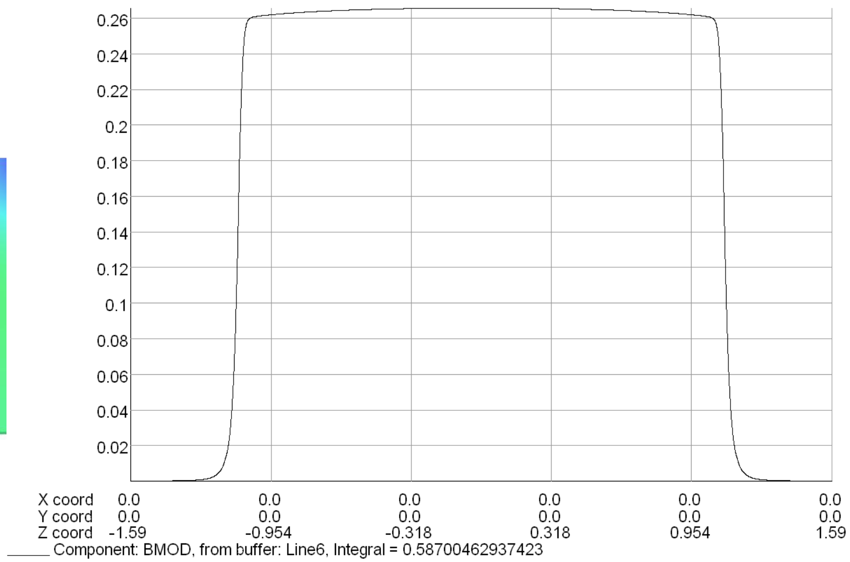




Field homogeneity (+/- 0.5% max) in the magnet gap

2.3 m Long PDS Magnet



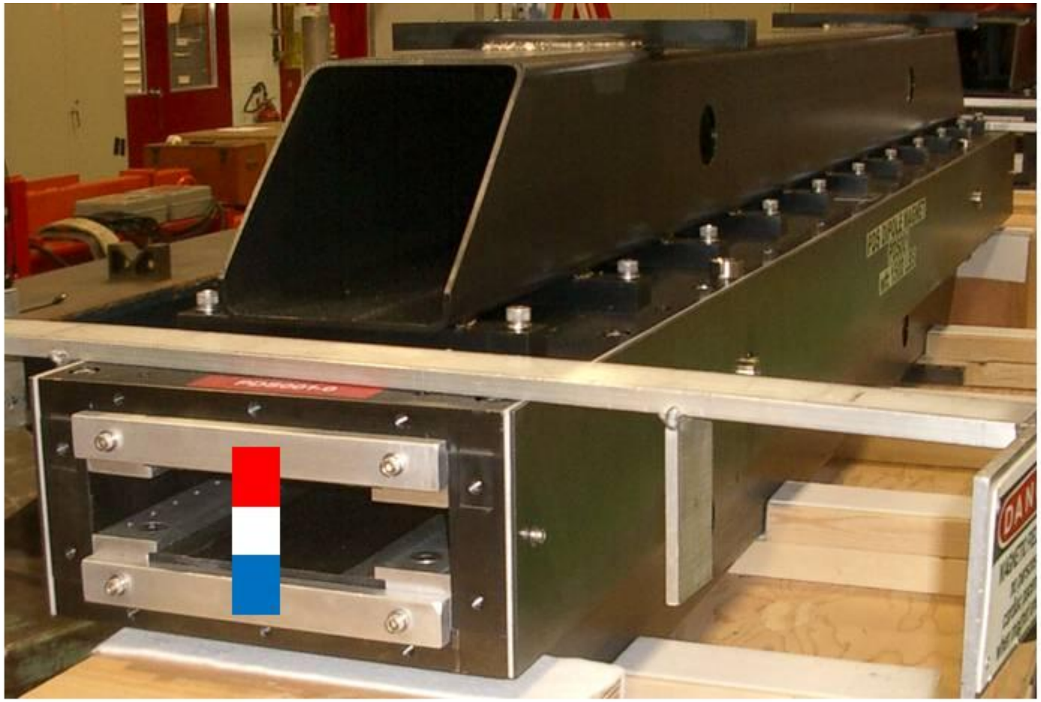


X, mm	Integrated field for 86” magnet, T-m	Homogeneity, %
0	0.587005	0
20	0.586953	-0.009
25.4	0.586886	-0.02
30	0.58685	-0.026
38.1	0.586733	-0.046

The PM bricks length is 1” .

~ 90” long magnet will have enough strength to cover possible deviations in PM properties.

PDS Permanent Beam line Magnet

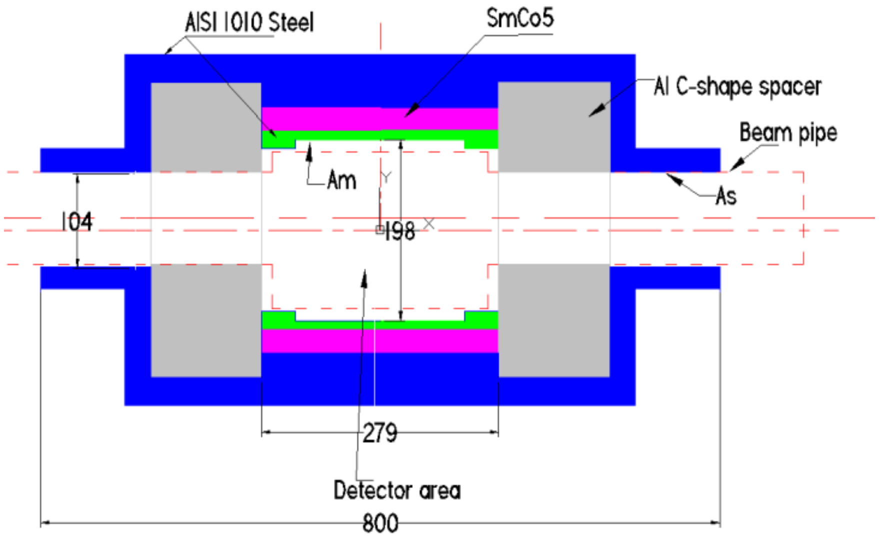


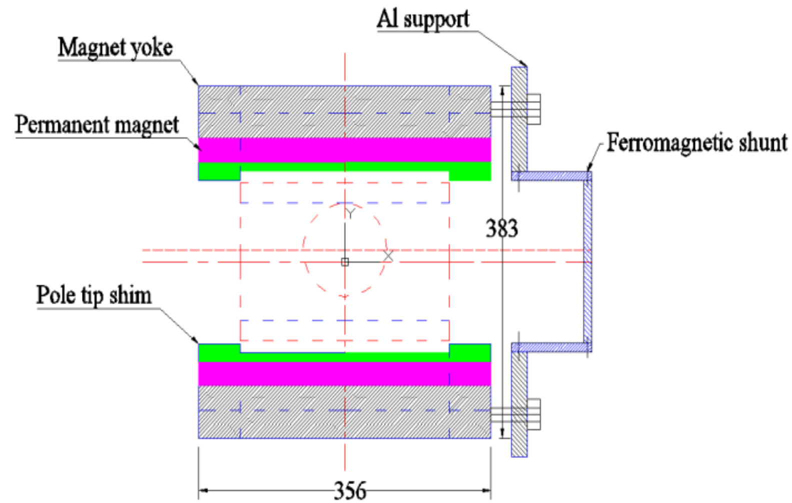
Several PDS magnets were built in industry, tested at Fermilab, and installed at NOvA beam line.

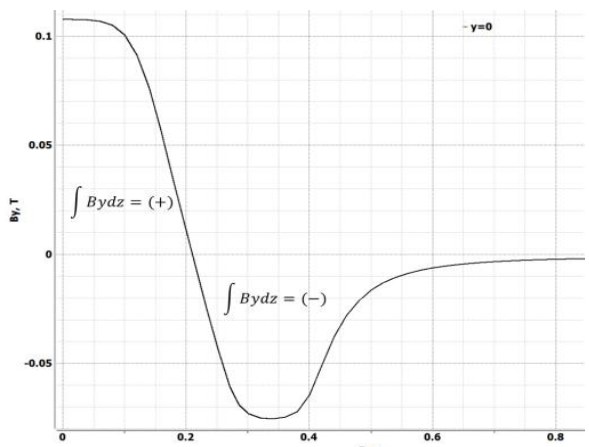
Permanent Magnet for the Beam Profile Monitor

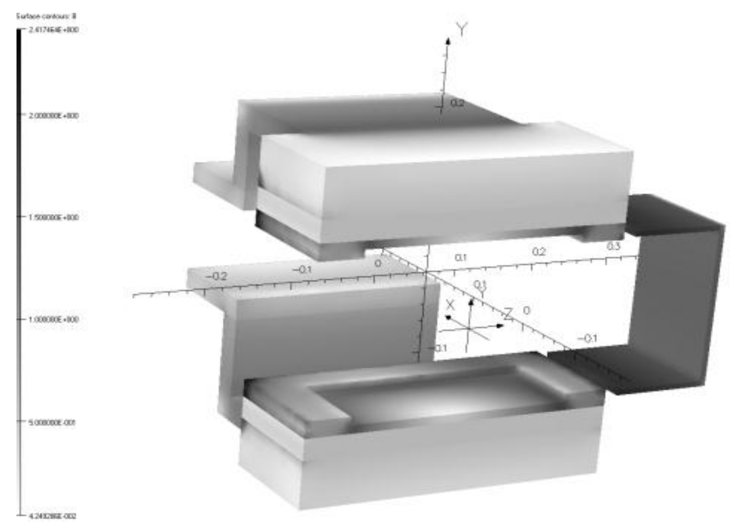
Abstract— **The ionization beam profile monitor system for the Main Injector Ring is under construction at Fermilab. The beam profile detector unit is installed inside the main magnet gap. The magnet has a novel configuration previously used for this type of application in the Main Injector. However this magnet is far more compact with a higher quality field. Most flux from the main gap returns symmetrically along the beam pipe through two side gaps. It provides nearly full compensation to yield integrated magnetic field close to zero, and helps eliminate distortions of the circulating proton beam. The permanent magnet poles are assembled from SmCo5 bricks (0.5”x1”x2”) which have a good thermal stability, and a reasonable cost. Further integrated field reduction is obtained by the use of a ferromagnetic plate which shunts the main gap. The plate position and flux shunting are adjusted in conjunction with magnetic measurements. Three permanent magnets were successfully fabricated and measured.**

Permanent Magnet Configuration and Field









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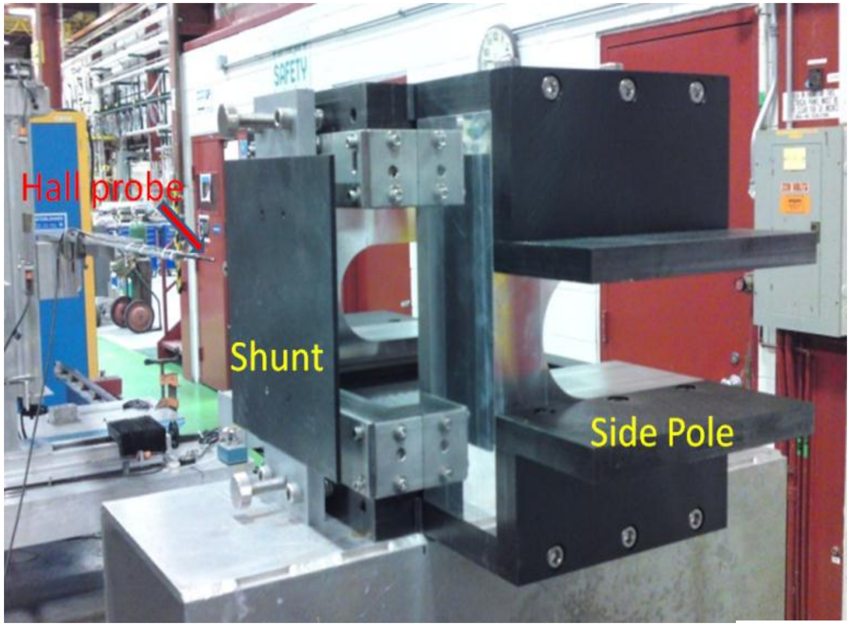
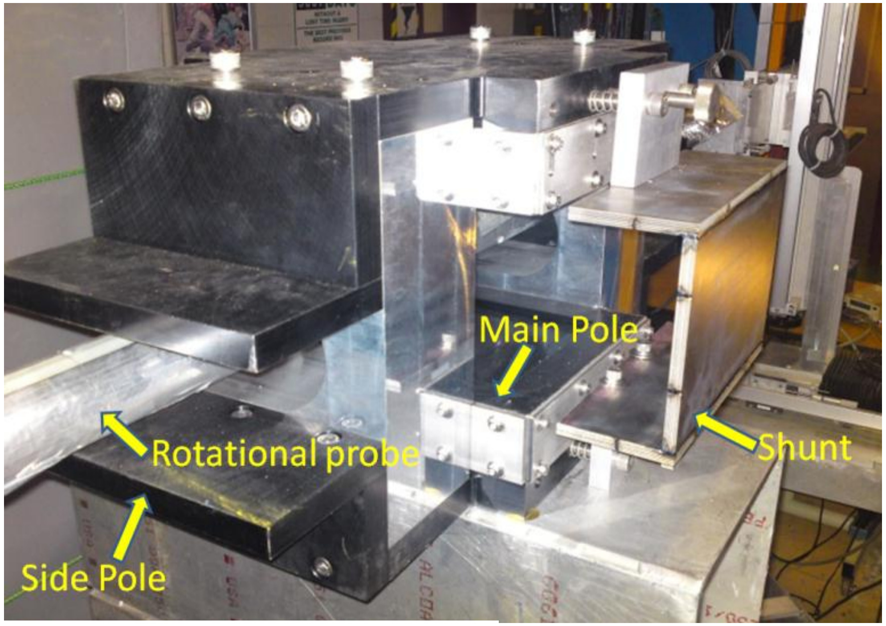
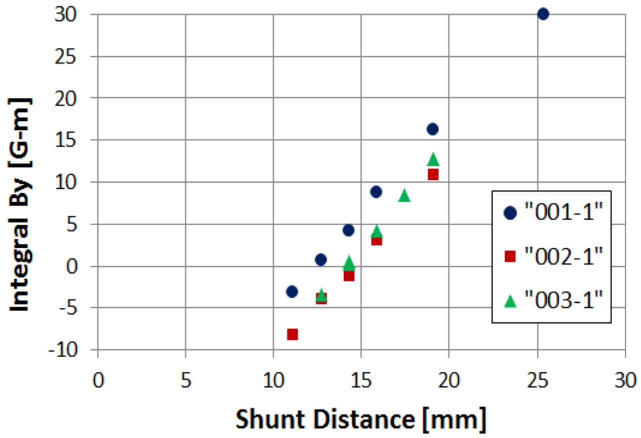
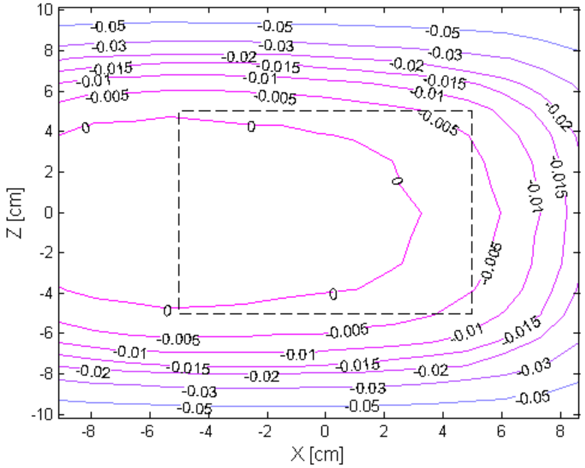
PDS Magnet Test









ΔBy/By$_0$ contours; the variation within the ±5 cm uniform field region (dashed rectangle) in X-Z is within 1%

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Summary

- Various permanent magnets were developed, installed, and are successfully working at Fermilab accelerator complex.
- There were also built and tested 6 various models of adjustable PM quadrupoles for the NLC project with gradients up to 100 T/m and an aperture 12.7 mm.
- The cost efficient approach was used for Recycler magnets based on the ceramic strontium ferrite.
- SmCo5 permanent magnets are more compact than ferrite based, and provide better thermal stability.
- Special attention MUST be paid on PM magnets assembly tooling, and safety for technicians.
- Because PM magnets produce the fixed and properly calibrated magnetic field must be excluded: large external fringe fields deviations, temperature variations, high radiation above the carefully specified values.

Recycler References

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