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Survey and Alignment Of The Fermilab Recycler Antiproton Storage Ring

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ABSTRACT

In June of 1999 Fermilab commissioned a newly constructed antiproton storage ring, the "Recycler Ring", in the Main Injector tunnel directly above the Main Injector beamline. The Recycler Ring is a fixed 8 GeV kinetic energy storage ring and is constructed of strontium ferrite permanent magnets. The 3319.4-meter-circumference Recycler Ring consists of 344 gradient magnets and 100 quadrupoles all of which are permanent magnets. This paper discusses the methods employed to survey and align these permanent magnets within the Recycler Ring with the specified accuracy. The Laser Tracker was the major instrument used for the final magnet alignment. The magnets were aligned along the Recycler Ring with a relative accuracy of ±0.25 mm.

1. INTRODUCTION

The Recycler Ring is a newly constructed antiproton storage ring in the Fermilab Main Injector (FMI) tunnel directly above the Main Injector beamline, near the ceiling (Figure 2).
The FMI is a new 150 GeV accelerator also under construction and is situated southwest of the Tevatron, interacting with the Tevatron near the F-0 straight section (Figure 1).

2. THE RECYCLER RING

The purpose of the Recycler Ring is to improve the luminosity, or collision rate, in the Tevatron collider. Luminosity is defined as the number of particles per square centimeter per second. The Recycler Ring is a fixed 8 GeV kinetic energy storage ring with a circumference of 3319.400 meters built only with strontium ferrite permanent magnets. Some of the advantages of permanent magnets are that they do not require power supplies, power cabling, cooling water system, and electrical safety system, resulting in major cost reduction. The Recycler Ring consists of 344 gradient magnets and 100 quadrupole magnets, all of which are permanent magnets, to provide bending and optical focusing. The construction of the ring depends on the alignment of the magnets with a high degree of accuracy [1].

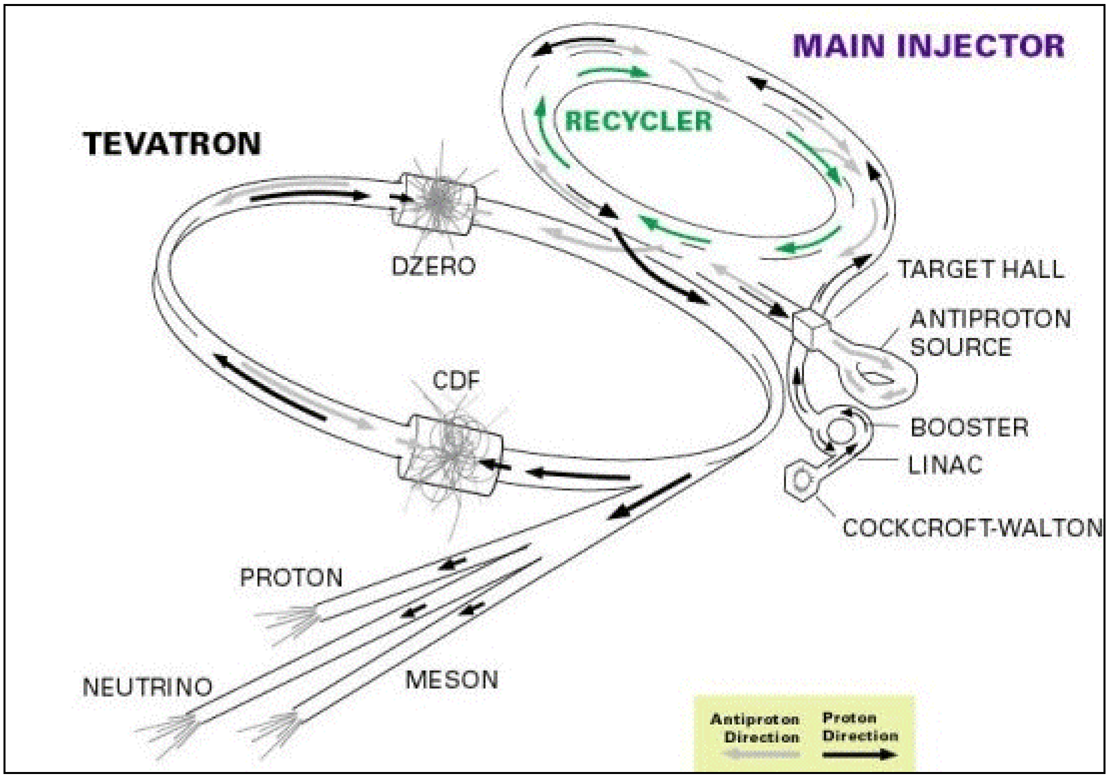

Figure 1. Fermilab's Accelerator Chain

The luminosity of the Tevatron Collider is determined by the number of antiprotons available for collisions. The central purpose of the Tevatron Collider is to collide protons and antiprotons at high luminosity in order to accumulate as much integrated luminosity as possible in as little time as possible. The role of the Recycler Ring is to provide more antiprotons for the Tevatron collider, which proportionally increases the luminosity. This is accomplished by acting as a high reliability post-Accumulator and receptacle for recycled antiprotons from previous Collider store. Prior to the development of the Recycler ring, the peak luminosity goal of the Fermi III upgrade program was $8x10^{31}cm^{-2}sec^{-1}$. With the construction of the Recycler ring, a typical peak luminosity of $2x10^{32}cm^{-2}sec^{-1}$ is expected [1]. Successful prototype efforts have been made for the permanent magnet 8 Gev transfer line to the FMI.

2.1 The Recycler Ring Transfer Lines

In addition to the Recycler Ring, there are three 8 GeV proton and antiproton transfer lines (Figure 3). The MI-32 Proton and MI-40 proton injection and abort lines are used during commissioning and tune-up. The MI-22 and MI-32 antiproton transfer lines between the Main Injector and the Recycler are used for normal Tevatron Collider operations. The MI-22 and MI-32 straight sections link both rings, MI and RR, together for injection and extraction of both antiprotons and protons [1].

Figure 2. Recycler gradient models hang from the ceiling above Main Injector magnets.

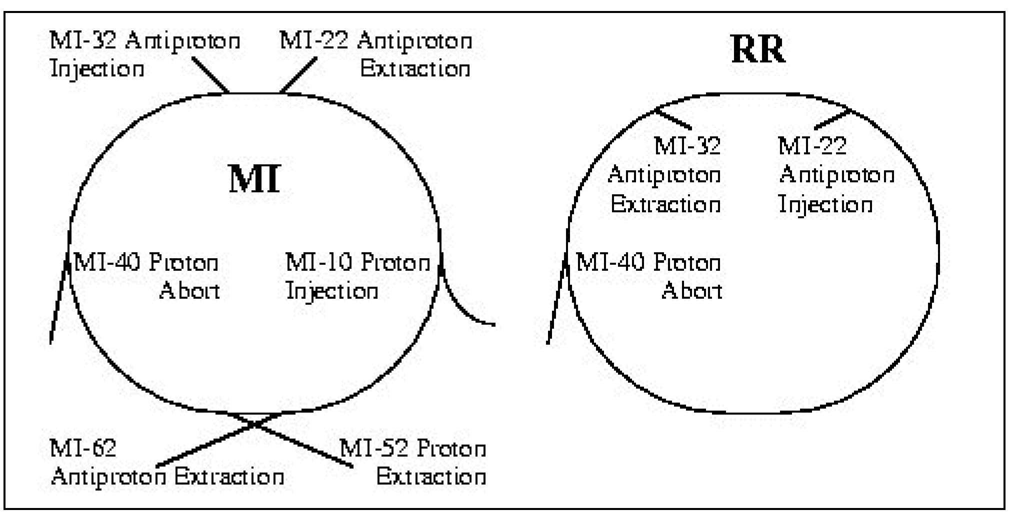

Figure 3. Sketch of the Main Injector (MI) and Recycler Ring (RR) beam transfer lines.

2.2 The Recycler Ring Lattice

The Recycler Ring lattice is identical to the Main Injector lattice with two 4.4958 m long 1.45kG gradient magnets in each half of the cell. The center of the Recycler Ring vacuum chamber is placed over the Main Injector at a distance of 7 feet from the floor. The Recycler Ring is designed to have exactly the same radius as the Main Injector. Figures 4 and 5 show the beam's eye, plan, and elevation views of both the Recycler and the Main Injector in a standard arc cell. The Main Injector beamline and Recycler Ring beamlines are exactly 56.00 inches apart. The only location in the tunnel where the Recycler Ring is not directly over the Main Injector is at MI-60 RF straight section [1]. The Recycler Ring swings to the radial outside by 18 inches at that straight section. These radial variations are adjusted so that the circumference of the Recycler Ring is exactly the same as that of the Main Injector. Figure 6 shows the sketch of the Recycler Ring position at MI-60 near the RF cavities. The other Recycler Ring straight sections are identical to those of the Main Injector. Figure 7 shows the plan and elevation tunnel view of a straight section. Figure 8 shows the plan and elevation views of the dispersion suppression cells which surround the Recycler Ring straight sections.

The Recycler lattice is a strong focusing FODO lattice made up of either two gradient magnets or two quadrupole magnets (in the dispersion free straight sections) above each Main Injector quadrupole. The Recycler Ring lattice consists of a total of 104 cells and is made up of three basic cell structures [1]:

1) Arc cells - there are 54 arc cells, each containing four 4.4958 m magnetic length (add 88.9 mm to each end for a physical length of 4.6736m) permanent magnets with a half-cell length of 17.288 m.

2) Straight section (dispersion free) cells - there are three lengths of straight sections; four 3 half-cell, two 4 half-cell, and a two 8 half-cell to make a total of 18 straight section cells, each made up of four 0.508 m (20 in.) long permanent magnet quadrupoles. The overall magnet length is 0.6096 m (24 in.). The length between the pole tip end and the magnet end plate is 2 in. (50.8 mm).

3) Dispersion suppression cells - there are 32 dispersion suppression cells which consist of a dispersion suppression insert (2 cells) on either side of each straight section. The dispersion suppression insert is made up of eight 3.0988 m magnetic length (3.2766m physical length) permanent gradient magnets. The half-cell length is 12.966 m.

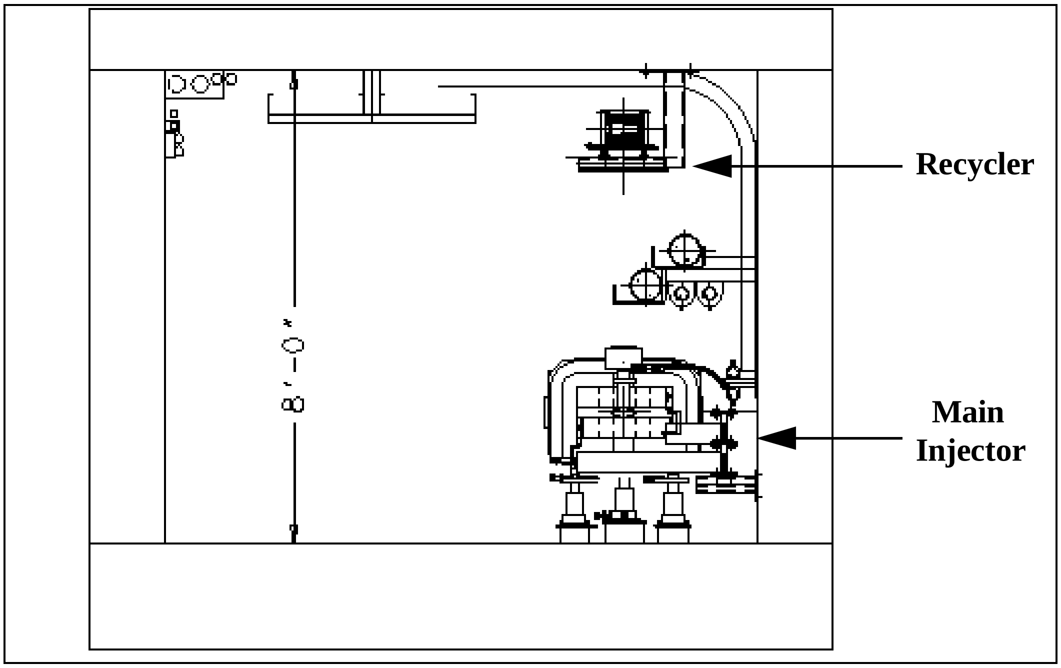

Figure 4. Tunnel cross-section in a standard arc cell showing a Main Injector dipole near the floor and a Recycler gradient magnet above it and near the ceiling [1].

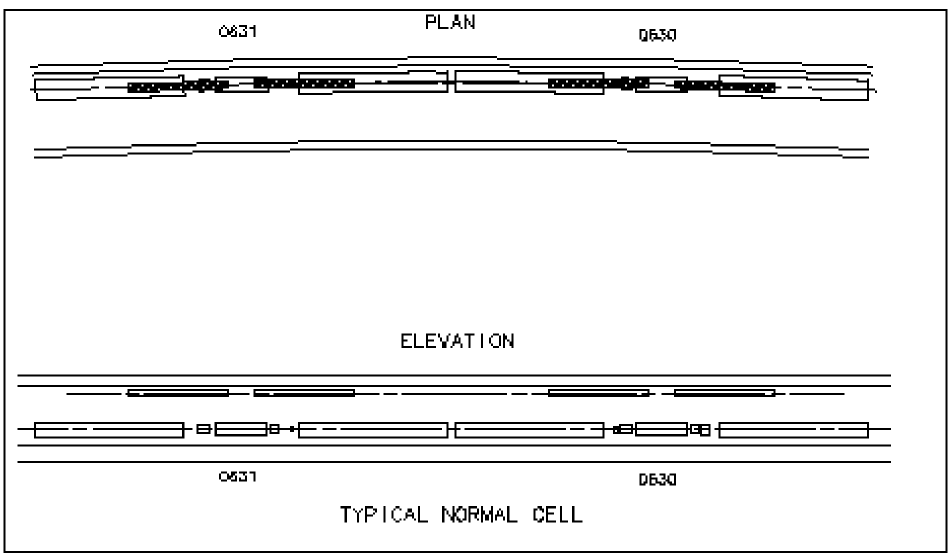

Figure 5. Plan and elevation views of both the Recycler and Main Injector beamlines. Note that the top magnets (shaded magnets in the plan view) are the Recycler gradient magnets [1].

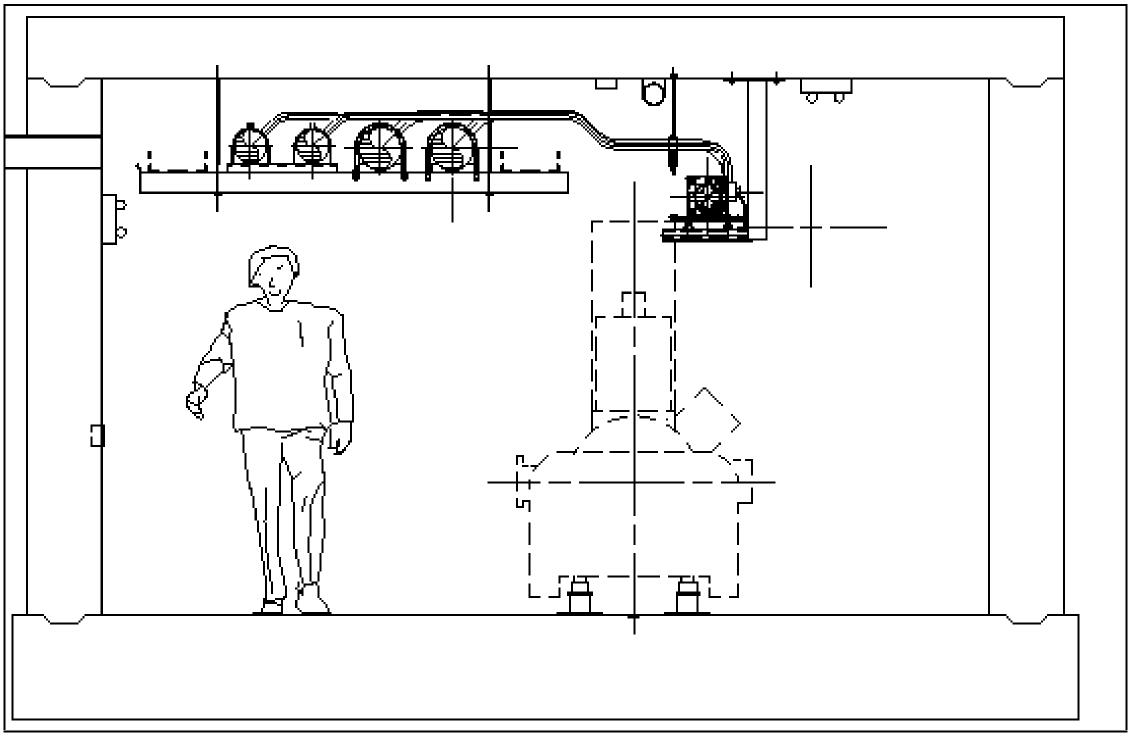

Figure 6. Tunnel cross-section at the MI-60 straight sections showing the Main Injector RF cavities with the Recycler ring quadrupoles above and to the radial outside [1].

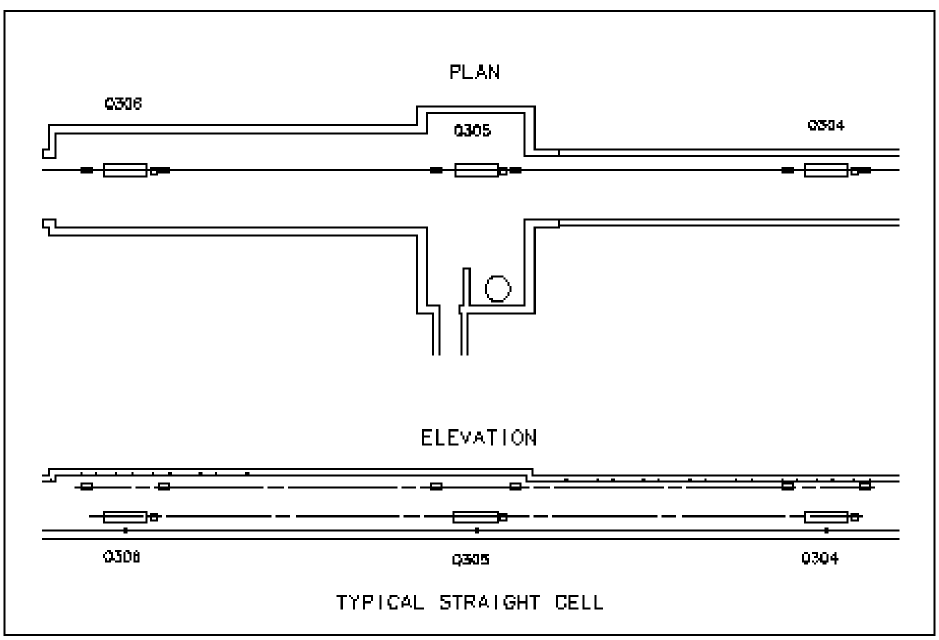

Figure 7. Plan and elevation views of the Main Injector (open frames) and Recycler (shaded rectangles) magnet deployments in a standard straight section [1].

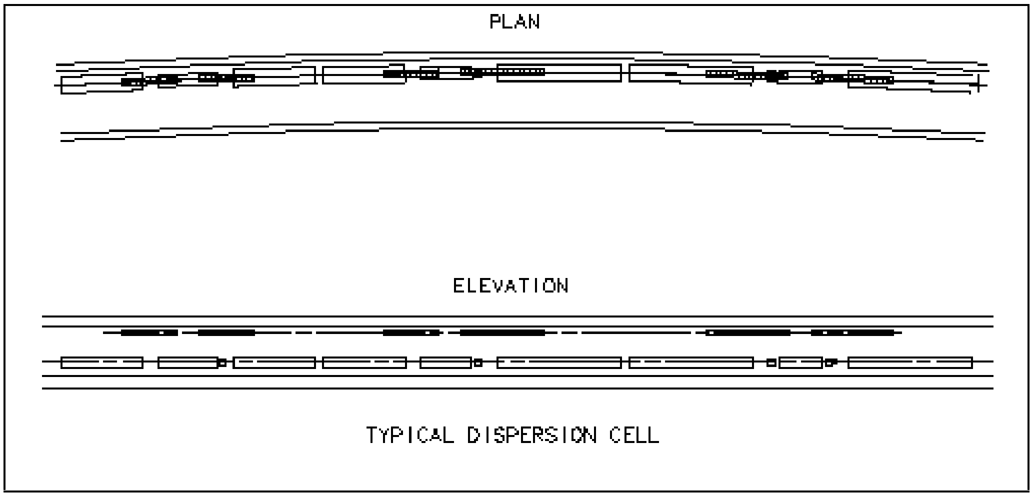

Figure 8. Plan and elevation views of the Main Injector (open frames) and Recycler (shaded rectangles) magnet deployments in a dispersion suppression cell [1].

3. PERMANENT MAGNETS

3.1 Gradient Magnets

The gradient magnets provide the bending and focusing for the normal arc and dispersion suppression cells. There are four different kinds of gradient magnets in the Recycler ring lattice. Their magnet type specifications are:

1. RGF: Focusing gradient magnets in the normal arcs; Pole length is 177 in. (4.4958 m) and physical length is 184 in. (4.6736 m). Magnet count is 108.
2. RGD: Defocusing gradient magnets in the normal arcs; Pole length is 177 in. (4.4958 m) and physical length is 184 in. (4.6736 m). Magnet count is 108.
3. SGF: Focusing gradient magnets in the dispersion suppression cells; Pole length is 122 in. (3.0988 m) and physical length is 129 in. (3.2766 m). Magnet count is 64.
4. SGD: Defocusing gradient magnets in the dispersion suppression cells; Pole length is 122 in. (3.0988 m) and physical length is 129 in. (3.2766 m). Magnet count is 64.

The gradient magnet is a 1.45kG gradient dipole with a 2 in. gap at the center, a 5.5 in. horizontal aperture and a 3.5 in. horizontal field aperture. The overall dimensions are 9.0 in. high by 11.5 in. wide by approximately 15 ft long. The magnet weight is 2700 lb. The gradient magnets are straight and the sagitta of the beam inside a magnet is 10 mm. The Recycler beam dimension is about 2.25 in. vertically and 3.75 in. horizontally. The field is driven by the permanent magnet material and the field shape is determined by the steel pole tips. The permanent magnet material is a Type 1008 Strontium Ferrite. The size of the ferrite brick material is a rectangle 4″x 6″x 1″ thick. A double layer of bricks are stacked on the top, double bricks on the bottom, and no bricks on the sides.

The magnets are assembled by pinning and bolting the pole tips to the aluminum U channel side to hold them in place to make a box structure. The bricks are placed on the back of the pole tips interleaved with the strips of temperature compensator. The bricks are held in place by the magnetic forces. The top and bottom flux return plates are then lowered on to the assembly, and the side flux returns are moved into place and bolted to the top and bottom plates. The steel end plates are bolted to the flux return. The magnet's field strength and shape are measured for each magnet after assembly. The field strength was measured by using a Tangential Coil Probe. Mechanical measurements were made using a Depth Micrometer.

Figure 9. Assembled gradient magnet showing the survey fiducials

3.2 Quadrupole Magnets

There are many different strengths of quadrupoles magnets in the Recycler ring lattice. The permanent magnet quadrupole has a 1.643 in. (41.73 mm) pole tip radius [1]. The magnetic length for all the Recycler quadrupole magnets are 0.508 m (20 in.) long. The overall physical dimensions are 8.25 in. high by 8.25 in. wide by 24.75 in. long. The quadrupole magnet weighs 200lb. The field shaping is provided by machined steel pole tips and the field is driven by 1 in. (25.4 mm) thick strontium ferrite bricks. The magnet is surrounded by a 0.5 in. (12.7 mm) thick steel flux return and the field at the ends of the magnet is terminated by a "flux clamp" end plates. Figure 10 shows the assembled quadrupole magnet. There are 100 quadrupole magnets in the Recycler Ring and they are used in the straight sections.

3.3 Beam Position Monitors

The Beam Position Monitors (BPMs) and other instrumentations are not permanent magnets but they still have to be aligned. The Recycler contains 416 BPMs, one horizontal and one vertical in each half cell. The BPM records the exact location of the antiproton beam within the beam pipe. This information is very crucial to the successful operation of the Recycler.

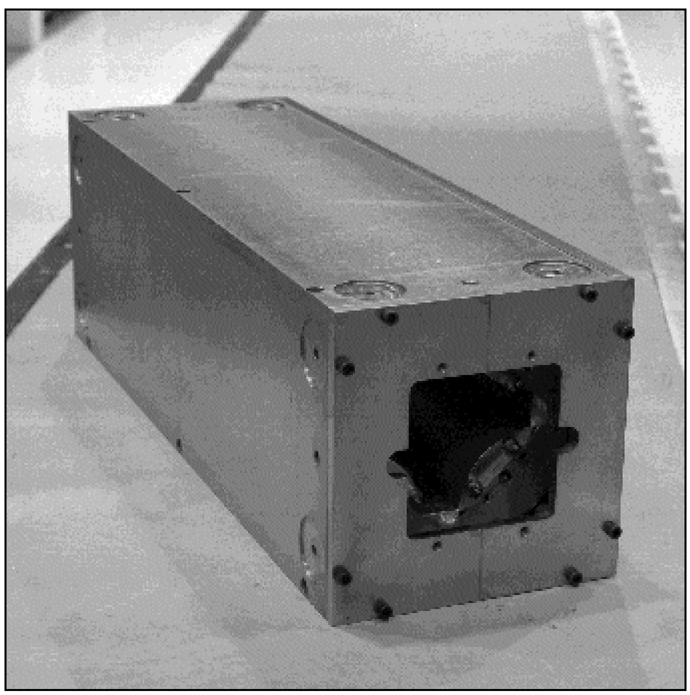

Figure 10. Assembled quadrupole magnet showing the survey fiducials

4. SURVEY AND ALIGNMENT OF THE RECYCLER RING

4.1 Local Tunnel Coordinate System

The Local Tunnel Coordinate System (LTCS) was established to meet the stringent accuracy requirements of the FMI project. Its origin and rotation axes are located at a point, CFMI, which lies at the centroid of the FMI Plane [6]. The coordinates (XYH) in the LTCS are defined in the FMI Plane. The FMI Plane is that plane defined by the nominal designed orthometric heights (H) of cell boundaries 308, 522, and 620. To convert the LTCS coordinates to global geodetic coordinates the FMI Plane must be tilted by a small angle to a projection plane There are two different versions of LTCS.

4.1.1 LTCS:XYZ

The LTCS:XYZ coordinate system corresponds to the lattice version of the LTCS. The X-Y plane of the LTCS is coincident with the FMI plane. It is a right-handed Cartesian coordinate system defined as follows:

Origin - CFMI (Centroid of the FMI Plane)
Y-axis - NORTH axis rotated by Geodetic Azimuth α from the Geodetic North.
X-axis - EAST axis. Positive to the right and perpendicular to the Y-axis.
Z-axis - Positive up at CFMI and perpendicular to both X- and Y-axes.

The parameters that define the LTCS:XYZ coordinate system origin at CFMI are defined in [6].

4.1.2 LTCS:XYH

The actual working plane of reference for the FMI tunnel is the FMI Plane. LTCS:XYH is a right-handed Cartesian coordinate system based on a Double Stereographic Projection [6]. The (XYH) coordinates in this system are identical to the (XYZ) coordinates in the LTCS:XYZ system at the origin, where H is the orthometric height.

4.2 The Control Points

The control network consists of a geodetic control network defined by concrete monuments around the Recycler/FMI ring (Figure 11). A Local Tunnel Coordinate System (LTCS) was specifically defined for the FMI [6]. The adjustment of the network was done in the LTCS reference system. The geodetic control coordinates were transferred to the tunnel by the establishment of a Tunnel Control System (TCS). TCS consists of a secondary tunnel constraint network which was established to include the sight riser drop points in the tunnel. A final tunnel control network was then established. The tunnel control network is a system of braced quadrilaterals between the floor monuments in the tunnel, the sight riser drop points, and the bench marks (tie rods) (Figure 12). There are a total of 10 sight risers, 231 floor monuments, and

208 tie rods around the ring. The entire tunnel control network was measured with the Laser Tracker.

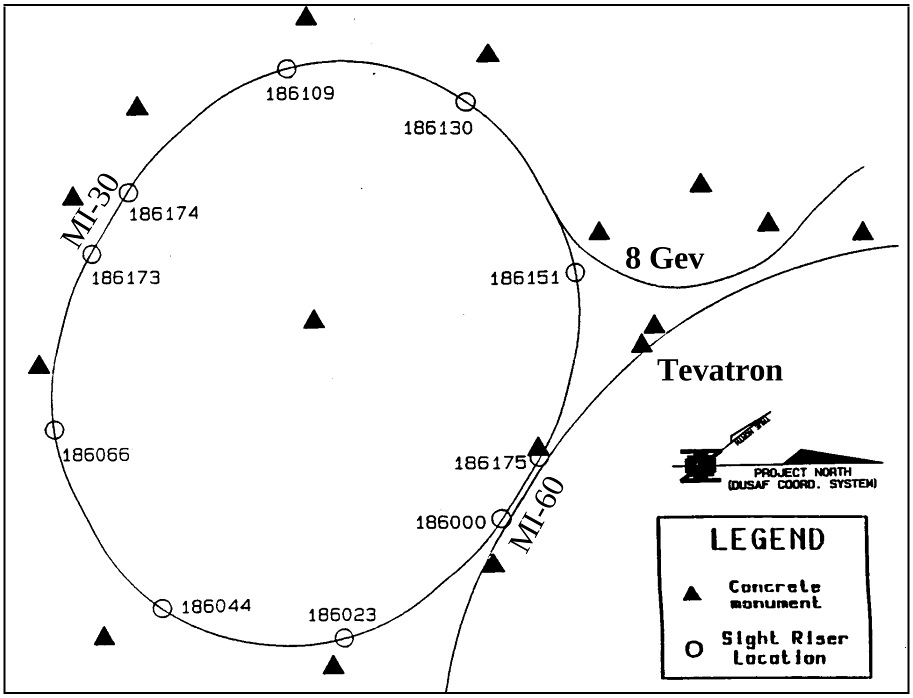

Figure 11. Geodetic Control Network

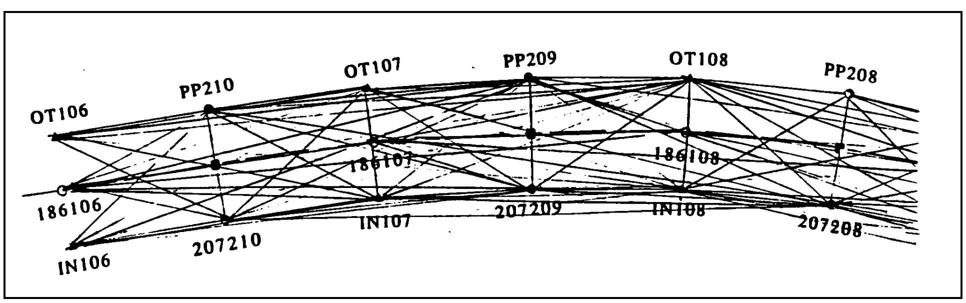

Figure 12. Tunnel Control Network

4.3 Absolute and Relative Alignment Tolerances

The desired absolute and relative alignment tolerances for the 344 gradient and 100 quadrupole permanent magnets are the same as those for the Main Injector [5]. All values are specified at the one-sigma (1σ) level. The absolute placement tolerances require the positioning of each beam component on the local projection around the FMI ring within a horizontal and vertical envelope of ±2 mm of the ideal position [5]. The circumference tolerance is defined as ±5 mm. Table 1 defines the relative alignment tolerances (1σ) of the gradient and quadrupole permanent magnets to adjacent components [5]. The tolerance for the stand placement is ±6 mm.

Table 1. Alignment Tolerances

Magnet type	Horizontal/Vertical	Beam Direction	Roll Angle
Quadrupoles	±0.25 mm	±3 mm	±0.5mrad
Dipoles	±0.25 mm	±3 mm	±0.5mrad
Beam Position Monitors	±0.25 mm	±3 mm	

4.4 The Survey Method

The Laser Tracker was used to achieve the alignment tolerances. The Laser Tracker, SMX Tracker4000 and its associated software Insight™, was used for the final magnet alignment using the established floor control points. The Laser Tracker is a device that makes three-dimensional measurements. It uses a laser distance meter, two precision angle encoders and a proprietary software to calculate, store and display the three-dimensional position of a mirrored target situated over the desired point or feature. Table 2 shows the specifications for the Tracker4000 [8]. A Geodimeter Total Station was used to stake the ceiling for the magnet installation in the ring. Optical tooling (Brunsons) techniques were used to pre-align the magnets. The relative alignment tolerances for the pre-alignment of the permanent magnets with optical tooling technique was ±0.5 mm.

Table 2. Tracker4000 Specifications

Category		**Radial**	**Transverse**
Resolution		0.16 microns	0.25 arcseconds
Repeatability	Near ±	1 micron	3 microns
	Far ±	1 micron/meter	1 micron/meter
Accuracy	Near ±	2 microns	12 microns
	Far ±	0.8 micron/meter	5 microns/meter
Working Volume		34 meters	270° horizontal 120° vertical

4.5 Magnet Fiducialization

The goal of the permanent magnet fiducialization is to relate all its magnetic measurements and the magnetic center to the survey fiducials, which are mechanical points accessible to subsequent survey measurements. The mechanical center of the permanent magnet was determined after the magnet had been assembled. The labeled (lead end) of the gradient magnet is downstream of the beam direction, which is the same as that of the Main Injector (Figure 13).

There are 8 survey fiducial points ("nests") at the corner of each gradient magnet; four on top (H,A,R,J) and four (E,D,N,M) at the bottom. Each fiducial is located between the pole tip end and the flux return end (Figure 13). The fiducials are the same as those for the transfer lines gradient magnets in the 8 Gev transfer line. At the center of each fiducial is a 0.25 in. hole that precisely fits a Laser Tracker SMR (Spherically Mounted Retroreflector) nest (Figure 16). The center of this hole defines the location of the fiducial point. The fiducial center of the gradient magnet is typically located longitudinally 2.25 in. from the tip of the top flux return and transversely 1.75 in. from the end of the side flux return. The fiducial center of the quadrupole magnet is typically located longitudinally 1 in. from the tip of the top flux return and transversely 1.5 in. from the end of the side flux return. There are 8 survey fiducial points ("nests") at the corner of each quadrupole; four on aisle side (B,C,K,L) and four (E,D,N,M) at the bottom.

A local magnet model coordinate system was defined such that its origin is at the upstream magnetic center, y connects the two geometric centers positive downstream, x is positive right and perpendicular to y, and z is positive up (Figure 13).

First, x, y and z were measured with reference to the origin at the mechanical (or geometric center) center of the lead end of the magnet, using a Depth Micrometer with an accuracy of ±0.0125 mm. Mechanically, x, y and z are designed to better than ±0.125 mm. Second, corrections were applied, if any, to convert x, y, z from the local mechanical coordinate system to the local magnetic coordinate system with the origin at the magnetic center. For the gradient magnet, the mechanical center is very near the longitudinal magnetic center. Third, corrections were applied to convert x, y, z from the local magnetic coordinate system to the beam lattice coordinate system. The longitudinal magnetic center and the beam center are different by a constant in the transverse x direction; for the long gradient magnet the constant is 7.46 mm and for the short gradient magnet the constant is 3.29 mm. The geometric center is the same as the magnetic center for the quadrupole permanent magnet. It gets installed on the magnetic center and beam center. The longitudinal magnetic center was determined using the Tangential Coil Probe. A database was created for model coordinates of the fiducials for all the magnets in the ring.

The magnets were placed in the beam line such that Y is longitudinal along the beamline, X is transverse to the beamline, and Z is the vertical positive above the beamline. Beam right is positive. The X, Y, Z coordinates for entrance and exit points for all magnets were supplied to the alignment group in the beam lattice coordinate system. A software was written to compute the fiducial coordinates in the beam lattice coordinates system.

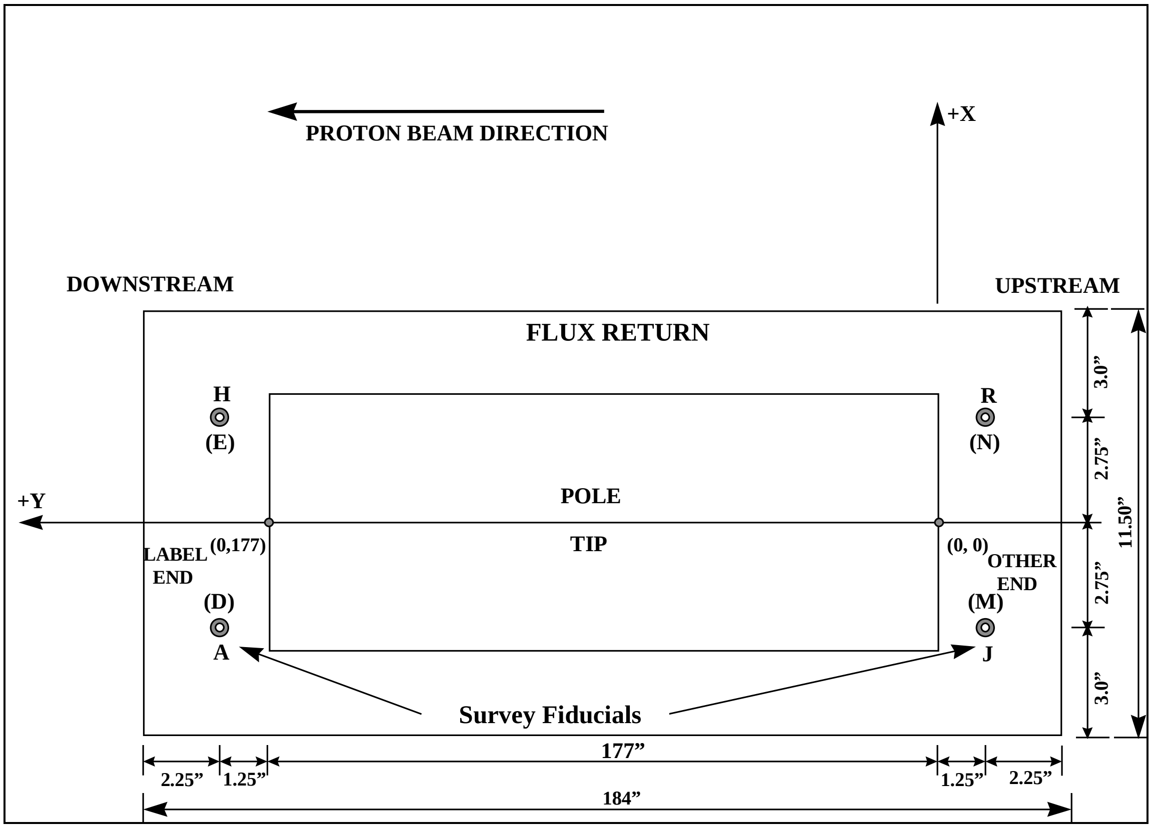

Figure 13. Survey fiducials location. The pole tip is 177" long. The magnet model coordinate system is shown, Z is up.

4.6 Magnet Stands

The magnet stands were hung below the ceiling to support and hold the 2700 lb. gradient magnets and the 200 lb. quadrupole magnets. In most locations around the Recycler Ring, the stands were bolted to the unistrut sections welded to the iron bars captured in the concrete tunnel walls. In other locations where there are no unistruts, more elaborate stands were built. The magnet stand has three legs with adjustment screws. The screws each have a ±1.0 inch freedom of adjustment. The stands can be adjusted in three rotations (roll, pitch and yaw) and two translations (z-vertical and x-transverse). There is no adjustment in the beam (y-longitudinal) direction. The BPMs have their own specifically built stands. Different stands were specifically built for the beam pipe due to the long distances between the magnets.

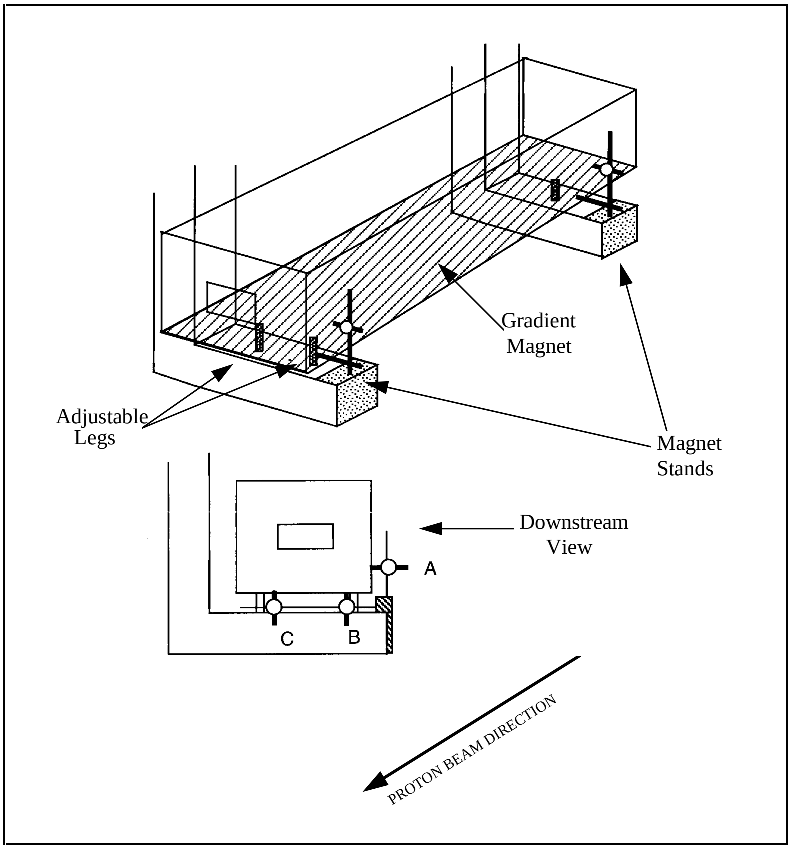

Figure 14. Magnet stands with three adjustable legs.

4.7 Magnet Alignment

4.7.1 Pre-Alignment

Prior to any alignment, the magnet stands, the permanent magnets, and the BPMs were installed. Using the beam lattice, the entrance and the exit y-coordinates of all gradient magnets, quadrupole magnets, and BPMs were marked on the ceiling to within 3 mm. The positions of the magnet stands were also marked on the ceiling. This was very critical since the magnet stands have no adjustment in the beam direction. The magnet stands were installed as marked on the ceiling. The magnets were then placed at the beam height on the stands as marked on the ceiling. A Geodimeter Total Station was used for these operations. After magnet installation, each magnet was rough aligned to the beam lattice using the optical tooling techniques. Using the coordinates of the established floor control points and the beam lattice coordinates of the magnets, offsets were computed to the four fiducials at the bottom of all the gradient magnets and the quadrupole magnets around the ring. These offsets were then be used to place the magnets along the beamline around the whole ring.

4.7.2 Final Alignment

The Laser Tracker, SMX Tracker4000 and its associated software Insight™, was used for the final magnet alignment using the floor control points. First, the ideal coordinates of fiducials for all the magnets were imported into the SMX software. Second, after the normal calibration, the Laser Tracker was positioned at a point nearly perpendicular to a line connecting two gradient magnets (Figure 15). In the straight sections the Laser Tracker was positioned at a point nearly perpendicular to a line connecting two quadrupole magnets. Third, the Laser Tracker was oriented into the Tunnel Control System by best fitting to several floor control points and tie-rods. From this setup, measurements were made to four fiducials (E,D,N,M) at the bottom of the two gradient magnets or the quadrupole magnets. Four additional measurements were made to the side fiducials (B,C,K,L) for the quadrupole. The magnets were moved to their ideal nominal position to within the specified tolerance by using the "Watch Window" capability in the Laser Tracker software. Figure 16 shows the view of the permanent magnet and the fixtures from the tunnel floor.

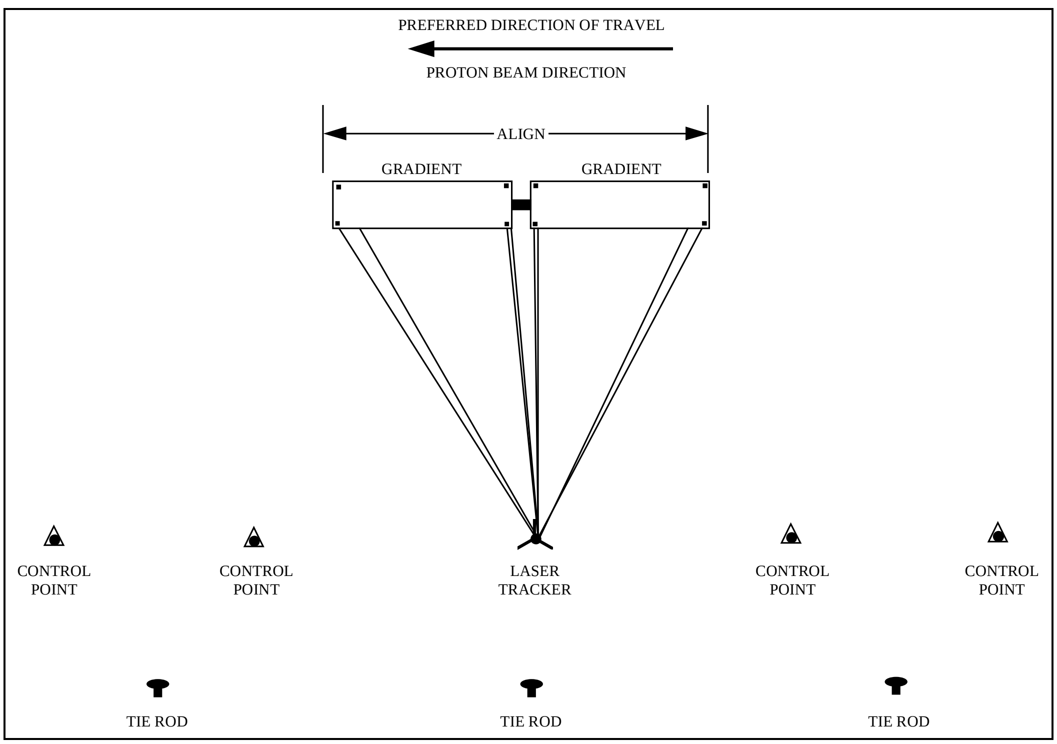

Figure 15. Magnet Alignment Procedure

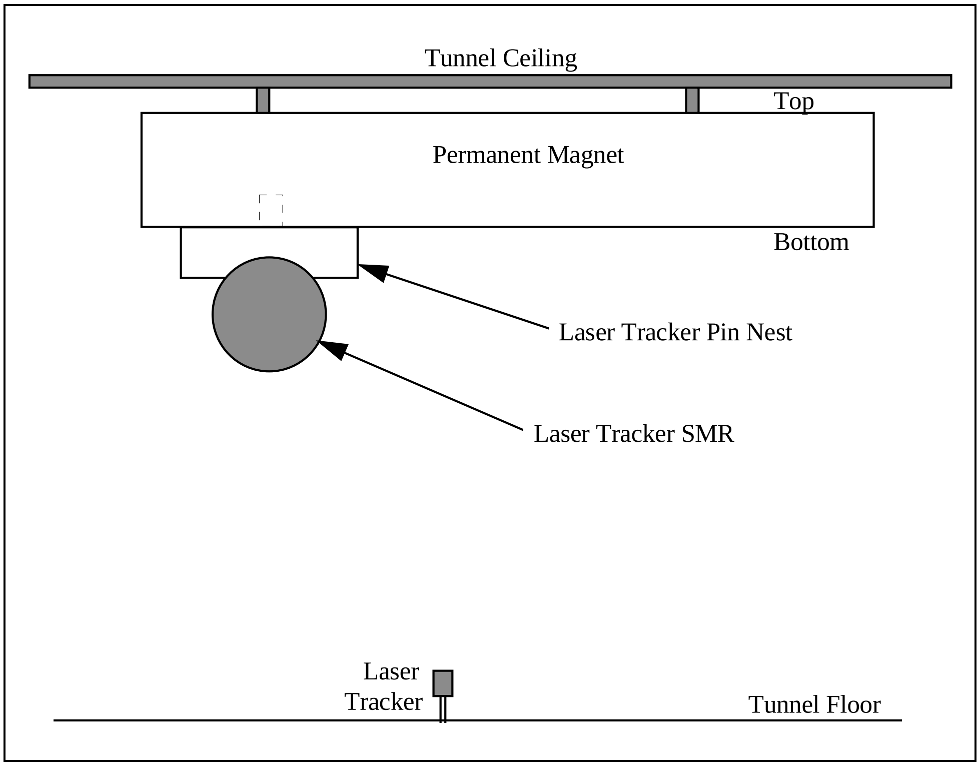

Figure 16. View of permanent magnet and fixtures from tunnel floor.

Figure 17. Laser Tracker alignment of quadrupole

4.7.3 Data Post-Processing

After data collection, data analysis was done by computing the differences (dX, dY, dZ) between the measured and the ideal coordinates of each magnet. These differences were then transformed to the resulting offsets to the beamline (Ox, Oy, Oz). Ox is the radial transverse offset, Oy is the along beam offset, and Oz is the vertical offset. The roll and twist for each magnet were then computed from the offsets. This information is passed on to the Recycler collaboration in a spreadsheet.

5. CONCLUSION

A Recycler Ring has been constructed at Fermilab in the Main Injector tunnel directly above the Main Injector beamline. The 3319.4-meter-circumference Recycler Ring consists of 344 gradient and 100 quadrupole magnets all of which are permanent magnets. These permanent magnets aligned with respect to the specified accuracy of ±0.25 mm using the Laser Tracker. The Recycler Ring was fully commissioned in June of 1999.

6. ACKNOWLEDGMENT

I would like to thank the Alignment group members who participated in the Recycler project. Thanks to my son, O.J. Oshinowo and my friend, Kelly Prude for proofreading this paper.

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