The Alignment Concept For The Fermilab Recycler Ring Using Permanent Magnets

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ABSTRACT

Fermilab is constructing a new 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. This paper discusses the concepts to be employed to align these permanent magnets within the Recycler Ring with respect to the specified accuracy. The specified alignment tolerances and error budgets necessary for aligning the permanent magnets are also discussed. The major instrument used for the final magnet alignment is the Laser Tracker.

1. INTRODUCTION

The Recycler Ring is a new antiproton storage ring under construction 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 systems, leading to a major cost reduction. The Recycler Ring consists of 344 gradient magnets and 86 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 Main Injector

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

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

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 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 3 and 4 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 5 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 6 shows the plan and elevation tunnel view of a straight section. Figure 7 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 4.4958m magnetic length (add 88.9mm to each end for a physical length of 4.6736m) permanent magnets with a half-cell length of 17.288m.

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 0.508m (20in.) long permanent magnet quadrupoles. The overall magnet length is 0.6096m (24in.). The length between the pole tip end and the magnet end plate is 2in. (50.8mm).

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 3.0988m magnetic length (3.2766m physical length) permanent gradient magnets. The half-cell length is 12.966m.

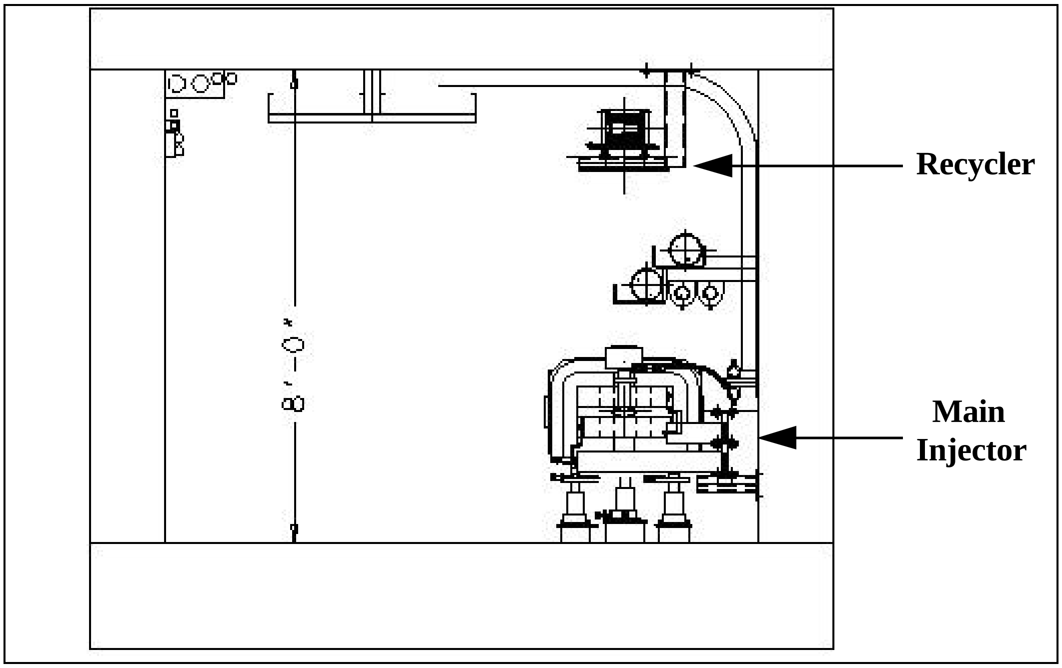

Figure 3. Tunnel cross-section in a standard arc cell showing a Main Injector dipole near the floor and a Recycler gradient magnet above it and near the ceiling [1].

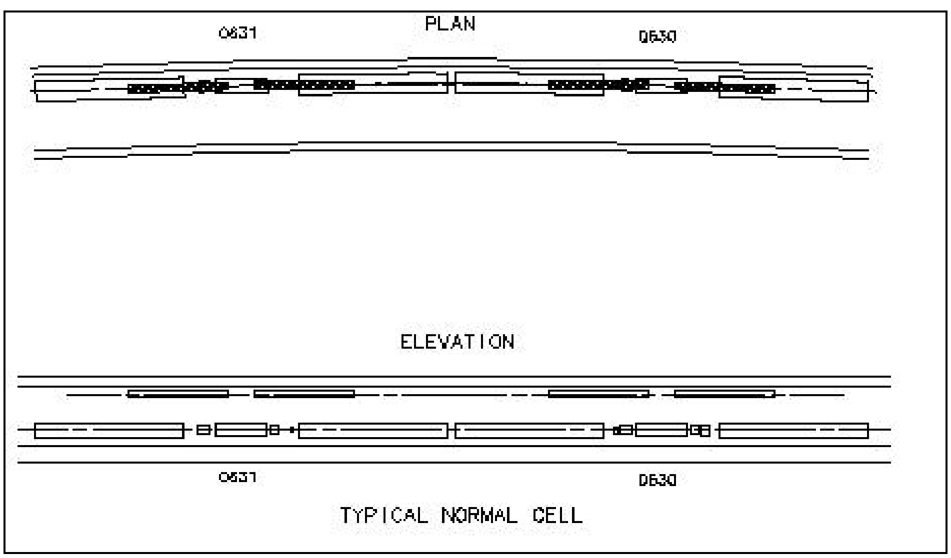

Figure 4. Plan and elevation views of both the Recycler and Main Injector beamlines. Note that the top magnets (shaded magnets in the plan view) are the Recycler gradient magnets [1].

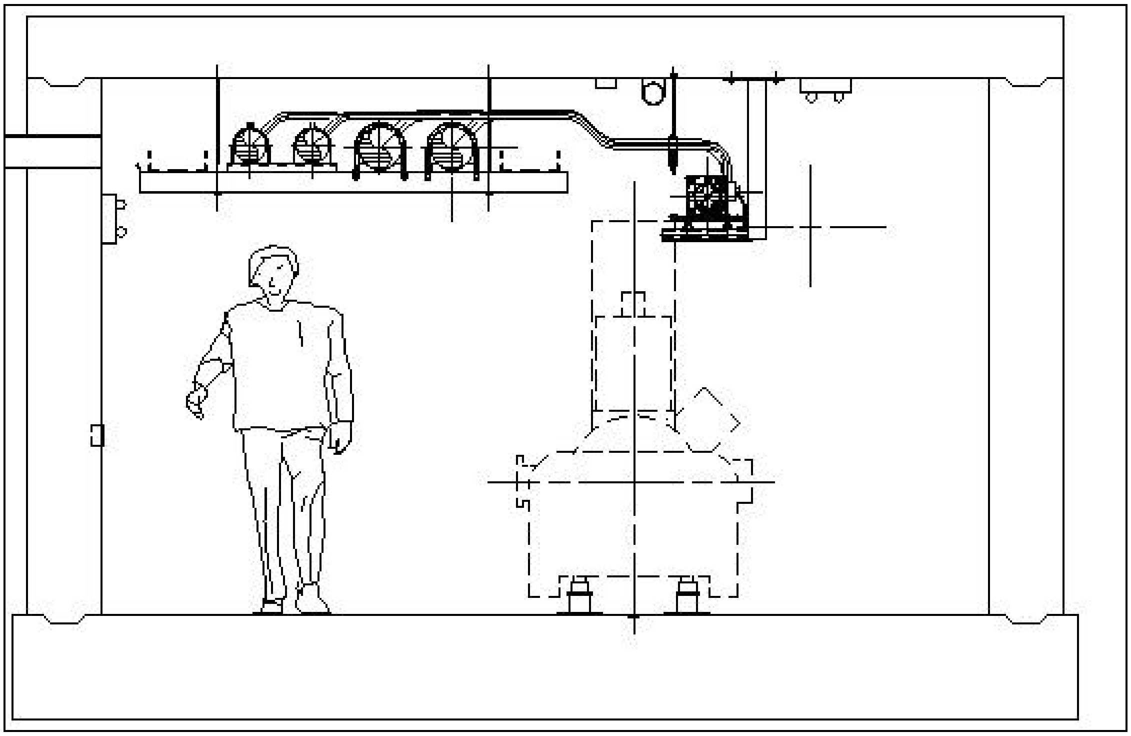

Figure 5. Tunnel cross-section at the MI-60 straight sections showing the Main Injector RF cavities with the Recycler ring quadrupoles above and to the radial outside [1].

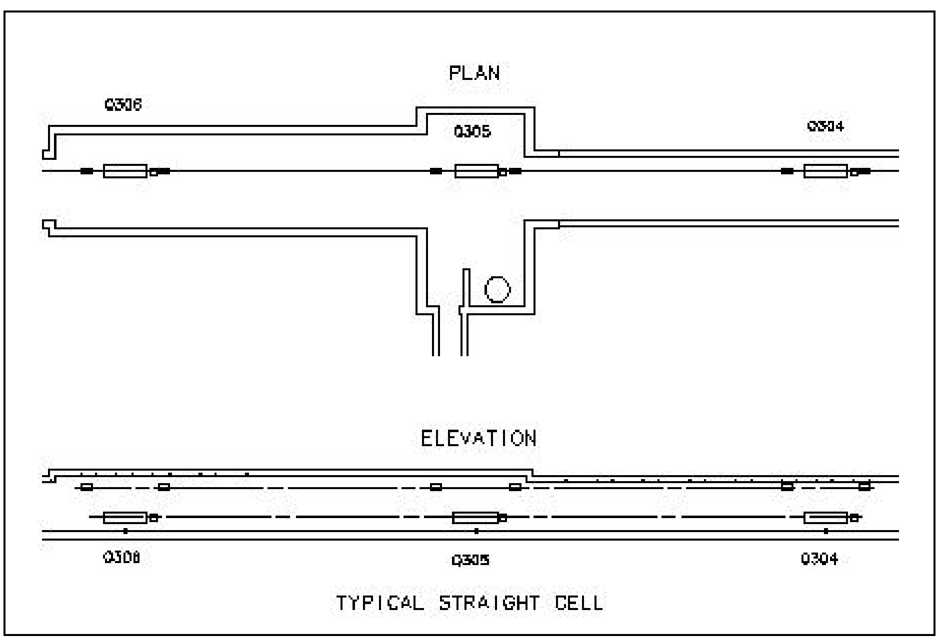

Figure 6. Plan and elevation views of the Main Injector (open frames) and Recycler (shaded rectangles) magnet deployments in a standard straight section [1].

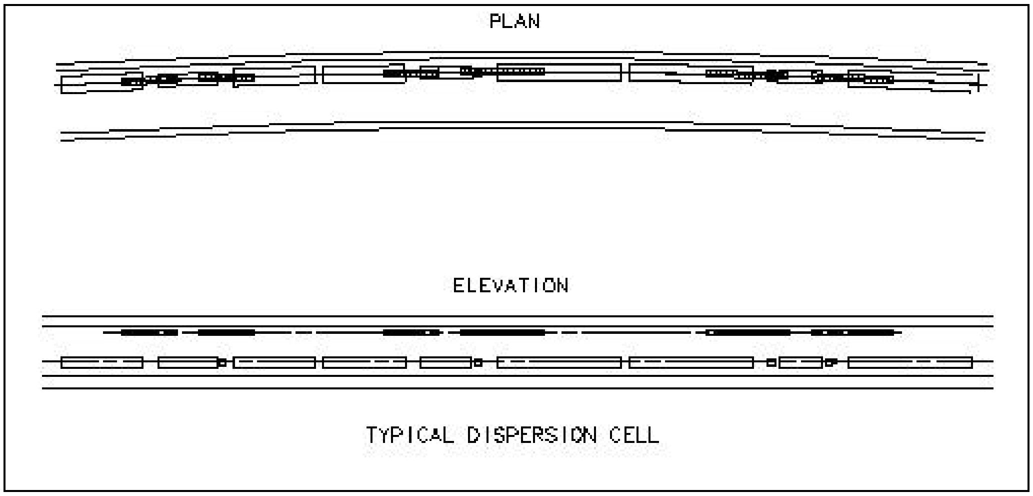

Figure 7. Plan and elevation views of the Main Injector (open frames) and Recycler (shaded rectangles) magnet deployments in a dispersion suppression cell [1].

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

The gradient magnet is a 1.45kG gradient dipole with a 2in. gap at the center, a 5.5in. horizontal aperture and a 3.5in. horizontal field aperture. The overall dimensions are 9.0in. high by 11.5in. wide by approximately 15ft long. The magnet weight is 2700lb. The gradient magnets are straight and the sagitta of the beam inside a magnet is 10mm. The Recycler beam dimension is about 2.25in. vertically and 3.75in. horizontally. Figure 8 shows the basic design of the gradient permanent magnet. 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.

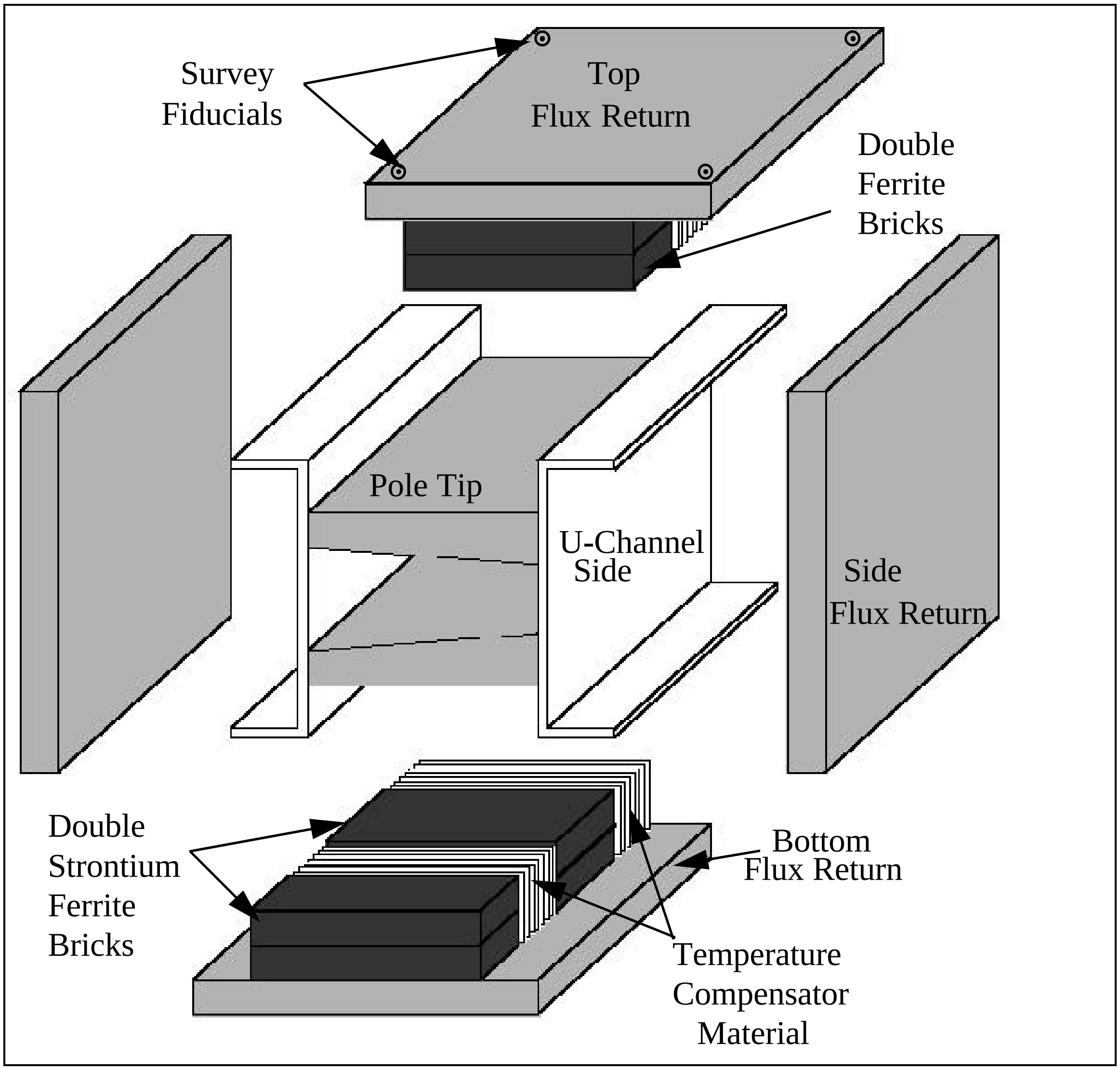

Figure 8. Components of the gradient permanent magnet [1].

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 will be measured by using a Tangential Coil Probe. Mechanical measurements will be made using a Depth Micrometer.

Figure 9. Assembled gradient magnet showing the survey fiducials

3.2 Quadrupole Magnets

The permanent magnet quadrupole has a 1.643in. (41.73mm) pole tip radius [1]. The magnetic length for all the Recycler quadrupole magnets are 0.508m (20in.) long. The overall physical dimensions are 8.25in. high by 8.25in. wide by 24.75in. long. The quadrupole magnet weighs 200lb. The field shaping is provided by machined steel pole tips and the field is driven by 1in. (25.4mm) thick strontium ferrite bricks. The magnet is surrounded by a 0.5in. (12.7mm) 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 cross-section of a rectangular quadrupole magnet and Figure 11 shows the assembled quadrupole magnet. There are 86 quadrupole magnets in the Recycler Ring and they are used in the straight sections.

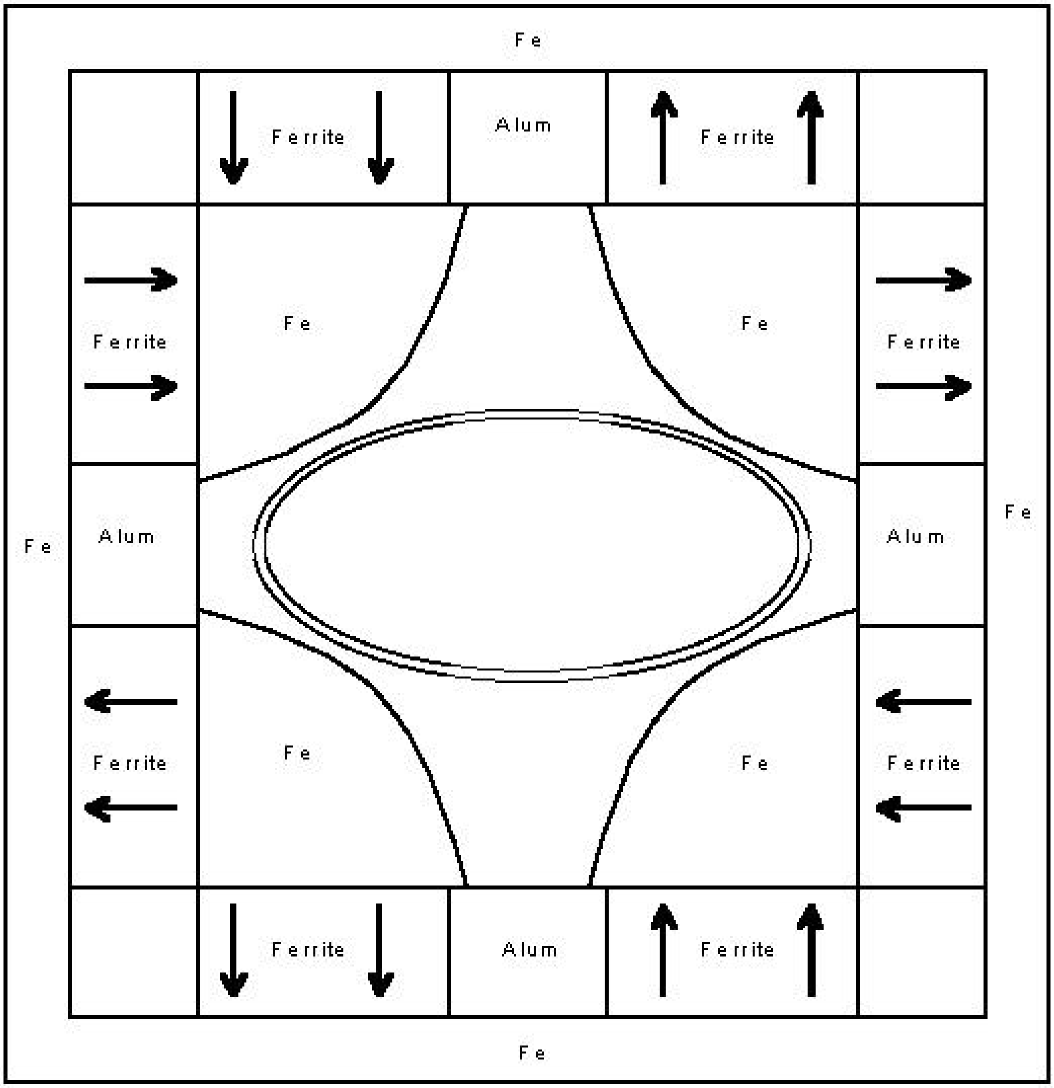

Figure 10. Cross-section of a rectangular quadrupole magnet [1].

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.

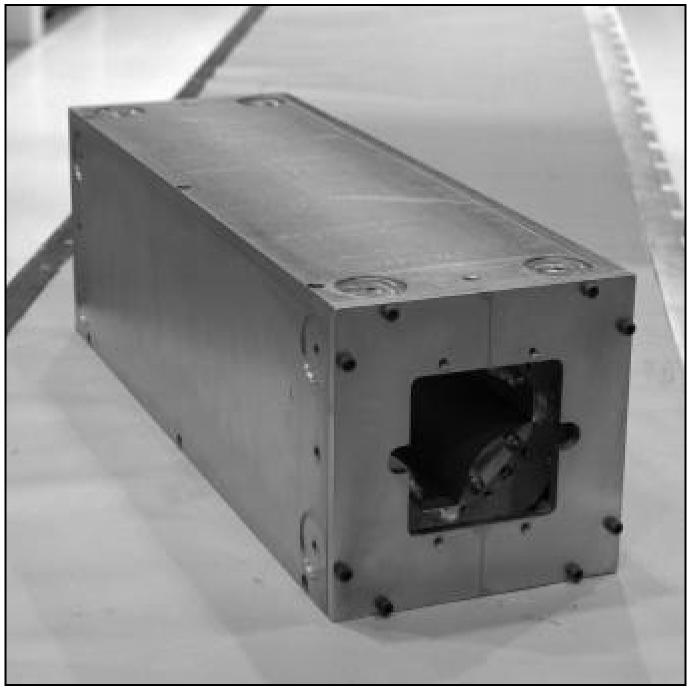

Figure 11. Assembled quadrupole magnet showing the survey fiducials

4. ALIGNMENT TOLERANCES

The desired absolute and relative alignment tolerances for the 344 gradient and 86 quadrupole permanent magnets are the same as those for the Main Injector [5]. All values are specified at the one-sigma (1σ) level.

4.1 Absolute and Relative Tolerances

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 ±2mm of the ideal position [5].

The circumference tolerance is defined as ±5mm (to be redefined possibly to ±10mm) with little or no effect on the performance of the machine.

Table 1 defines the relative alignment tolerances (1σ) of the gradient and quadrupole permanent magnets to adjacent components [5].

Table 1. Alignment Tolerances

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

The Laser Tracker will be used in order to achieve these alignment tolerances. The relative alignment tolerances for the pre-alignment of the permanent magnets with optical tooling technique is ±0.5mm. The tolerance for the stand placement is ±6mm.

5. THE CONTROL NETWORKS

Previous alignment tasks were solved by establishing a geodetic control network defined by concrete monuments around the Recycler/FMI ring (Figure 12). A Local Tunnel Coordinate System (LTCS) was specifically defined for the FMI [6]. The adjustment of the network had been completed in the LTCS reference system. The geodetic control network could be upgraded in the near future. 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 13). 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.

6. 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 will be determined after the magnet has 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 14).

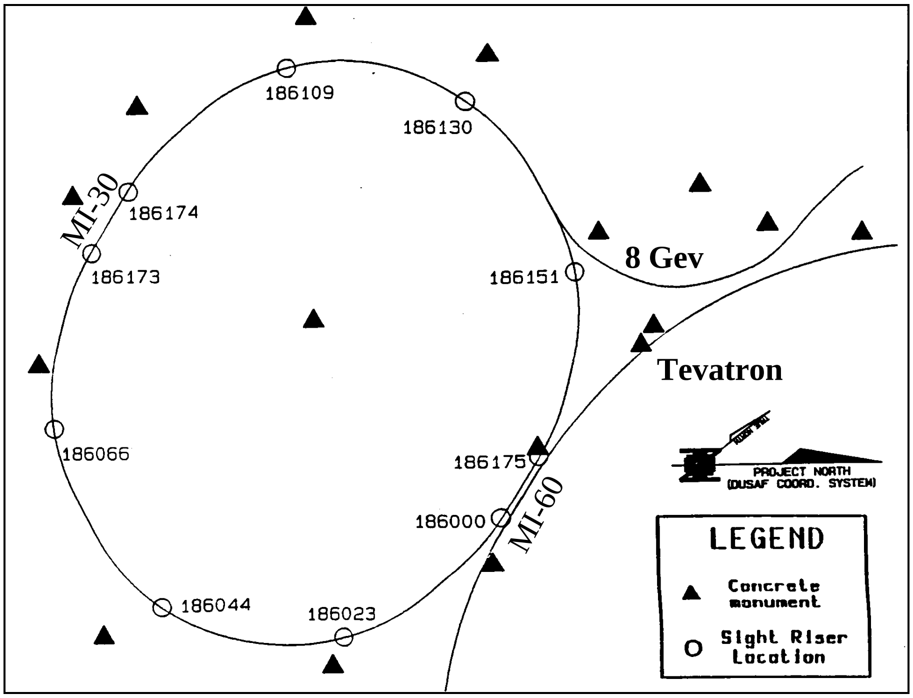

Figure 12. Geodetic Control Network

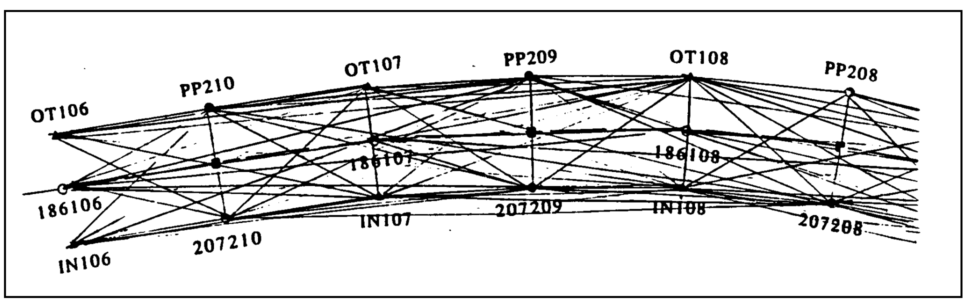

Figure 13. Tunnel Control Network

There are 8 survey fiducial points ("nests") at the corner of each magnet; four on top and four at the bottom. Each fiducial is located between the pole tip end and the flux return end (Figure 14). The fiducials are the same as those for the transfer line gradient magnets in the 8 Gev transfer line. At the center of each fiducial is a 0.25in. hole that precisely fits a Laser Tracker SMR (Spherically Mounted Retroreflector) nest (Figure 17). The center of this hole defines the location of the fiducial point. The fiducial center of the gradient magnet is typically located longitudinally 2.25in. from the tip of the top flux return and transversely 1.75in. 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 1.5in. from the end of the side flux return. The x, y, z coordinates for each of the fiducials will be supplied to the alignment group in the beam lattice coordinate system. The coordinate system is defined such that z is the vertical above the beamline, y is longitudinal along the beamline, and x is transverse to the beamline. Beam right is positive. The Main Injector and the Recycler Ring beamlines are separated by exactly 56.00 inches.

First, x, y and z will be 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 ±0.0125mm. Mechanically, x, y and z are designed to better than ±0.125mm. Second, corrections will be 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 are 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 7.46mm and for the short gradient magnet the constant is 3.29mm.

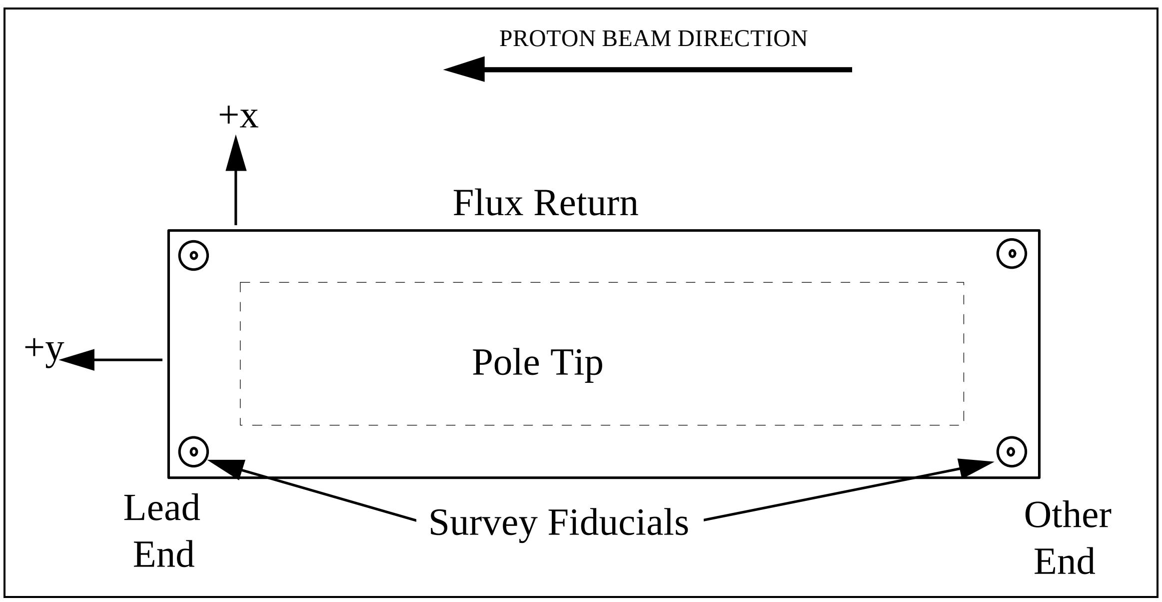

Figure 14. Survey fiducials location. The pole tip is 177" long. The distance from the Pole Tip to the tip of the Flux Return is 3.5″.

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 will be determined using the Tangential Coil Probe.

6.1 Magnet Stands

The magnet stands will hang below the ceiling to support and hold the 2700lb. gradient magnets and the 200lb. quadrupole magnets. In most location around the Recycler Ring the stands will be bolted to the unistrut sections welded to the iron bars captured in the concrete tunnel walls. In other locations a more elaborate stand will be built. The magnet stand has three legs with adjustment screws. The screws each have a ±1in. 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 will be specifically built for the beam pipe due to the long distances between the magnets.

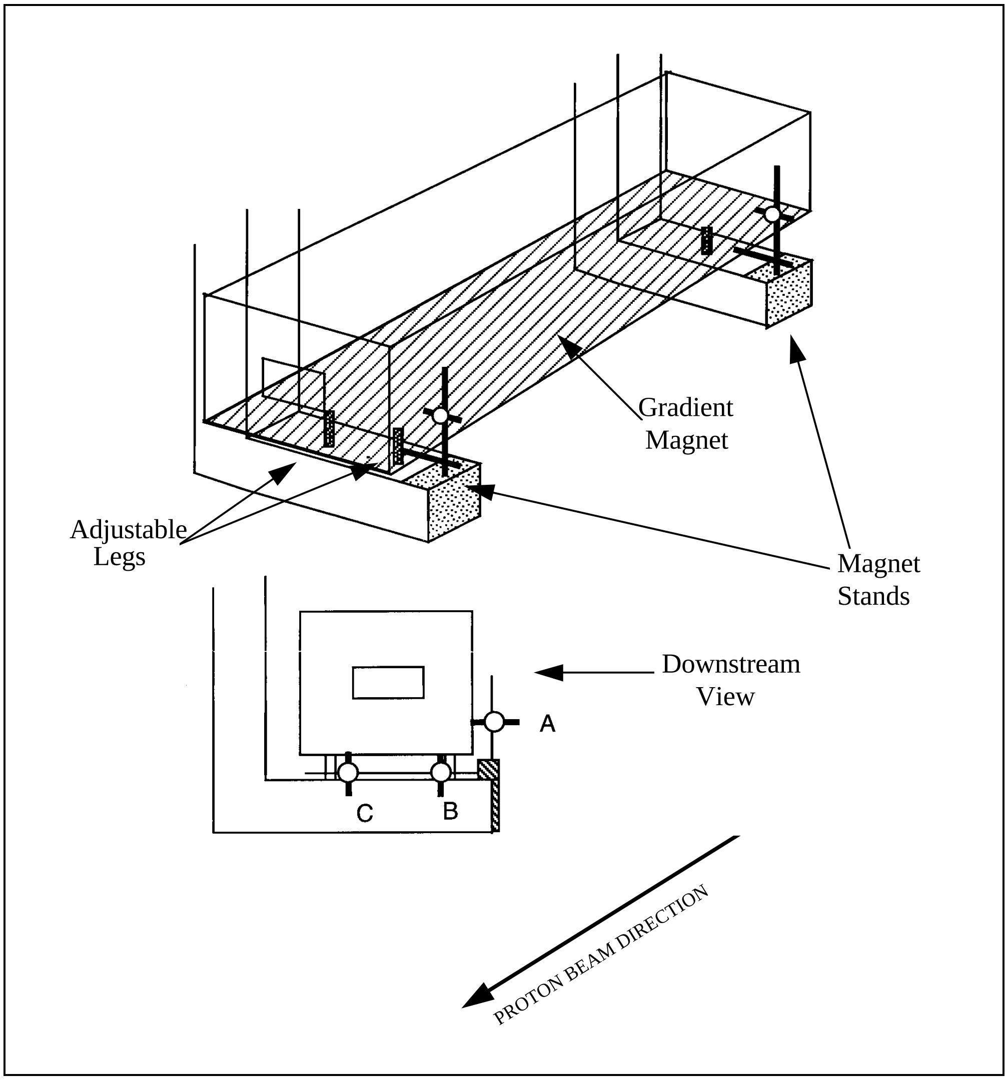

Figure 15. Magnet stands with three adjustable legs.

7. MAGNET ALIGNMENT

7.1 Pre-Alignment

Before any alignment can be performed, the magnet stands, the permanent magnets, and the BPMs have to be installed. This will be accomplished as follows:

1) Using the beam lattice, the entrance and the exit y-coordinates of all gradient magnets, quadrupole magnets, and BPMs will be marked on the ceiling to within 3mm.

2) The positions of the magnet stands will also be marked on the ceiling. This is very critical since the magnet stand have no adjustment in the beam direction. Therefore, the stands must be placed right the first time.

3) The magnet stands will be installed as marked on the ceiling.

4) The magnets will then be placed at the beam height on the stands as marked on the ceiling.

A Geodimeter Total Station will be used for these operations. Once all the magnets have been placed on the stands a pre-alignment of the magnets will be performed. This is done by rough aligning the magnets 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 will be computed to the four fiducials at the bottom of all the gradient magnets and the quadrupole magnets around the ring. These offsets will then be used to place the magnets along the beamline around the whole ring.

7.2 Final Alignment

The Laser Tracker, SMX Tracker4000 and its associated software Insight™, will be 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 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 [9]. The Laser Tracker will be positioned and oriented into the Tunnel Control System at a point nearly perpendicular to a line connecting two gradient magnets (Figure 16). In the straight sections the Laser Tracker will be positioned at a point nearly perpendicular to a line connecting two quadrupole magnets. From this setup, measurements to all eight fiducials at the bottom of the two gradient magnets or the quadrupole magnets will complete an observation session. The magnets will be moved to their desired nominal position to within the specified tolerance by using the “Watch Window” capability in the Laser Tracker software. Figure 17 shows the view of the permanent magnet and the fixtures from the tunnel floor.

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

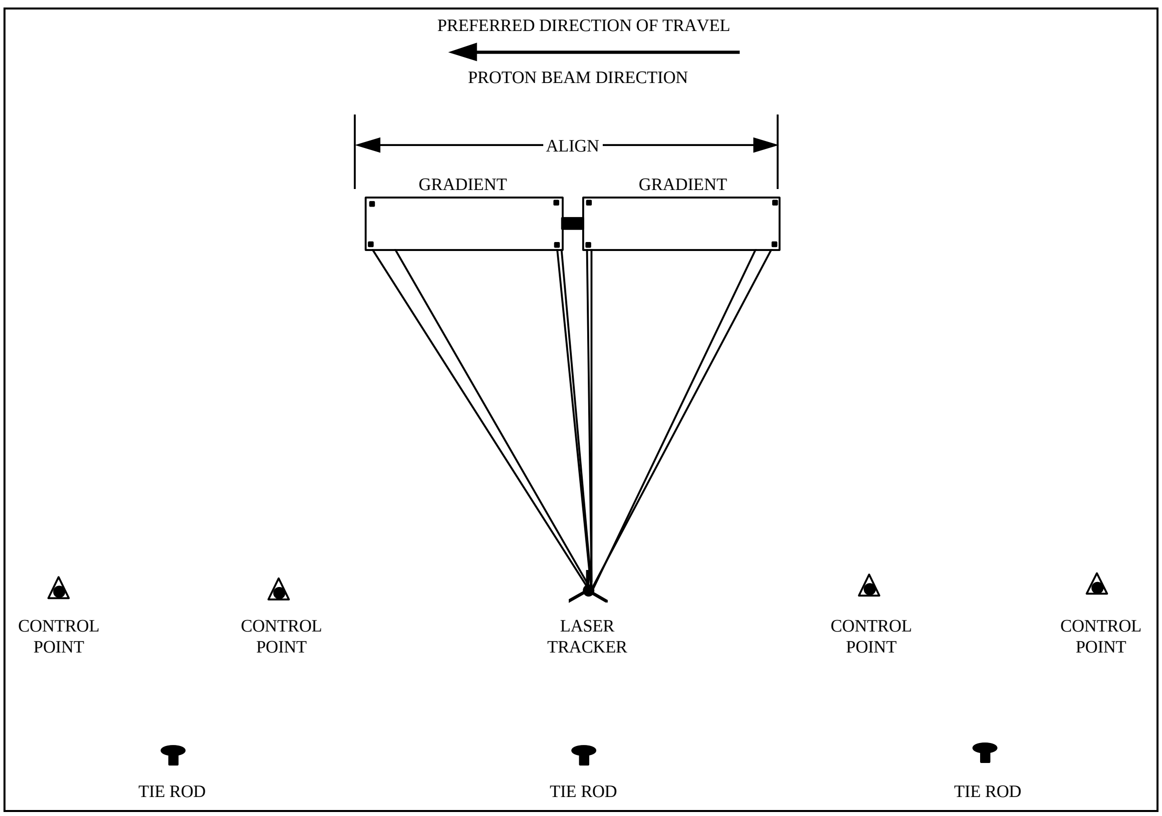

Figure 16. Magnet Alignment Procedure

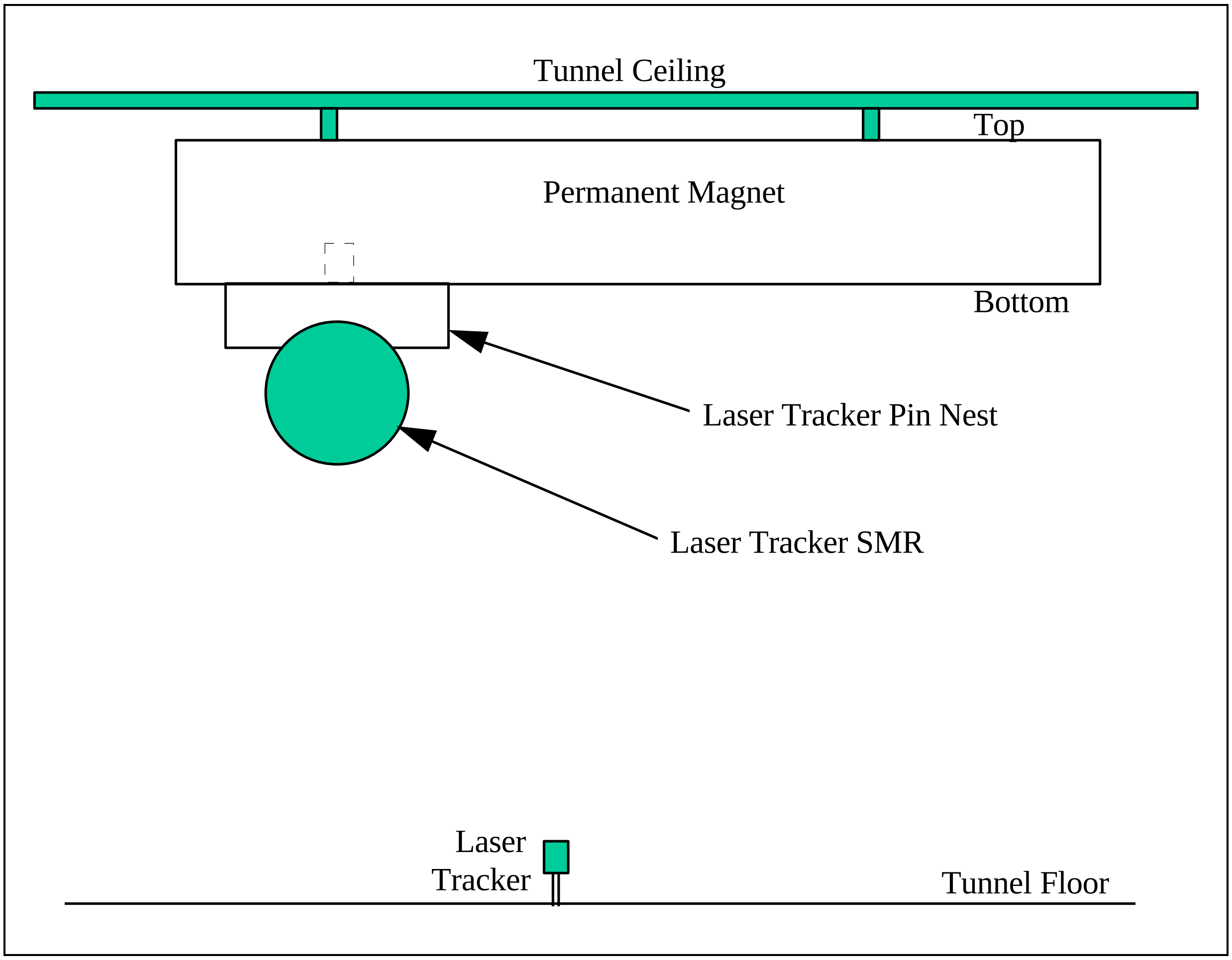

Figure 17. View of permanent magnet and fixtures from tunnel floor

8. ERROR ANALYSIS OF MAGNET ALIGNMENT

The analysis of the magnet alignment error budget emphasizes the individual contribution of the alignment component error and assigns their allowable magnitude. The magnitudes of the error are based on measurements, analyses, simulations, and what is considered reasonable assumptions. There are four characteristics of alignment component errors which independently affect the total radial standard deviation of a magnet alignment [7][8]:

$$\sigma_{Mag\_Align} = \pm\{\sigma_n^2 + \sigma_m^2 + \sigma_f^2 + \sigma_s^2\}^{1/2}$$

where

σ_n = standard deviation of the relative errors in the network (relative transversal errors between points)

σ_m = standard deviation of the errors in measurement from control points to fiducials

$= \pm\{\sigma_{nm}^2 + \sigma_{LT}^2\}^{1/2}$

σ_{nm} = standard deviation of nest to control monument repeatability

σ_{LT} = standard deviation of the Laser Tracker measurement for aligning components from one setup

σ_f = standard deviation of the errors in measurement from fiducials to magnet

σ_s = standard deviation of the errors in resolution of the stands adjustment

Taking the largest values that have been determined for any of the components in the analysis, the resulting standard deviation at the one-sigma (1σ) level is calculated as follows:

$\sigma_n = \pm 0.000158\text{m}$

$\sigma_m = \pm 0.000046\text{m}$

$\sigma_{nm} = \pm 0.000008\text{m}$

$\sigma_{LT} = \pm 0.000045\text{m}$

$\sigma_f = \pm 0.000035\text{m}$

$\sigma_s = \pm 0.000025\text{m}$

$$\sigma_{Mag\_Align} = \pm\{0.000158^2 + 0.000046^2 + 0.000035^2 + 0.000025^2\}^{1/2}$$

$$= \pm 0.000170\text{m}$$

The value of the resulting standard deviation is less than 0.25mm specified accuracy.

9. RECYCLER COMMISSIONING AND ALIGNMENT PLAN

The current working schedule to completion of the Recycler Ring and alignment project are as follows [2]:

April 1997 Start Recycler construction.

Fall 1997 Start magnet stands and permanent magnets installation.

March 1998 Partial turn Recycler operations, start commissioning. Since a turn implies one complete revolution of beam around the Recycler Ring, therefore a partial turn means that part of Recycler is under vacuum.

June 1998 First (single) turn Recycler operations. The requirement for this commissioning stage is for the magnets and vacuum systems to be completely installed. One of the purposes of this commissioning stage is to align the magnets in the Recycler in order to optimize the closed orbit. The beam is aborted after one complete revolution around the ring.

Fall 1998 Multiple (5000) turn Recycler operations. Beam storage is achieved during this operation. One of the goals of this commissioning stage is to establish that the machine has a stable closed orbit.

March 1999 Complete Recycler installation and commissioning.

The Recycler Ring project is on schedule for completion.

10. CONCLUSION

A Recycler Ring is being 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 86 quadrupole magnets all of which are permanent magnets. These permanent magnets will be aligned with respect to the specified accuracy by using the Laser Tracker. The Recycler Ring will be fully commissioned in March of 1999.

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