Magnet Alignment For The Fermilab Main Injector Project

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ABSTRACT

The Fermilab Main Injector (FMI) is a new 150 GeV particle accelerator. This paper discusses the magnet alignment algorithm, application software, and procedures employed to align the magnets within FMI Ring with respect to the specified accuracy. The specified alignment tolerances and error budgets necessary for aligning the magnets are also discussed. The major instrument used for the final magnet alignment is the Laser Tracker.

1. INTRODUCTION

The purpose of the Fermilab Main Injector (FMI) Ring is to replace and improve upon the performance of the now defunct Main Ring by simultaneously enhancing both the Fermilab collider and the fixed target programs. The Main Injector will supply a larger flux of protons for antiproton production, more intense proton bunches for use in the collider, and a higher efficiency acceleration of antiprotons. The FMI is situated southwest of the Tevatron Ring, interacting with the Tevatron near the F-0 straight section (Figure 1). Since the Main Ring has now been turned off, the FMI will perform all duties previously required of the Main Ring. Thus,
the Main Ring operations ceased following the start of commissioning of the FMI. This is expected to yield a concurrent reduction in the background rates seen in the colliding beam detectors. The performance of the FMI, as measured in terms of protons per second delivered to the antiproton production target or total protons delivered to the Tevatron, is expected to exceed that of the Main Ring by a factor of two to three. In addition the FMI will provide high duty factor 120 GeV beam to the experimental areas during collider operation, a capability which did not exist in the Main Ring [1].

2. THE FERMI MAIN INJECTOR RING

The FMI ring, which is irregularly oval in shape, has a circumference of 3319.419 meters. It consists of 344 dipole magnets and 208 quadrupole magnets (Figure 2). The MI-60 straight section is parallel to the Tevatron F0 straight section and the two beamlines are separated by 11.823m horizontally. The design location of the MI-60 reference point is 13.222m downstream from the F0 TeV point, and is offset from the TeV straight section by 11.823m [1][3].

Figure 1. Fermilab Main Injector

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

2.1 The FMI Lattice

The standard cell of the FMI is a FODO design but with two dipoles between the quadrupoles as shown in Figure 3. The FMI ring lattice consists of a total of 104 cells. It incorporates two different types of cells, the normal 17.2886m FODO cells and the 12.9665m FODO dispersion suppression cells. The dispersion suppression cells feature shorter dipoles and match the horizontal dispersion to zero in the straight sections. There are 72 normal cells (54 in the arcs and 18 within the straight sections) and 32 dispersion suppression cells.

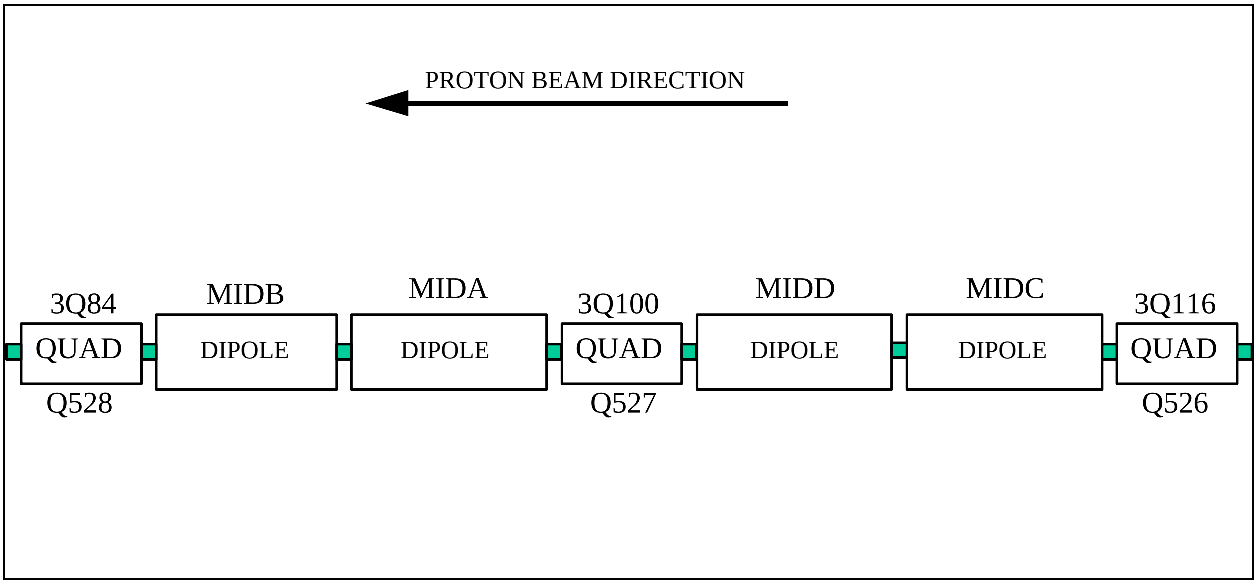

Figure 3. Layout of Dipoles and Quadrupoles in the Lattice.

3. THE FMI MAGNETS

3.1 Dipole Magnets

There are four different kinds of dipole magnets in the FMI ring lattice. Their magnet type specifications are:

1) IDA magnets - Type A - Length is 6.096m (240in.). Magnet count is 108 and magnet weight is 40,000lb.
2) IDB magnets - Type B - Length is 6.096m (240in.). Magnet count is 108 and magnet weight is 40,000lb.
3) IDC magnets - Type C - Length is 4.064m (160in.). Magnet count is 64 and magnet weight is 27,000lb.

4) IDD magnets - Type D - Length is 4.064m (160in.). Magnet count is 64 and magnet weight is 27,000lb.

The difference between Type A and Type B is that the jumper between top and bottom coils are at opposite ends in order to facilitate the electrical connections in the tunnel. The same difference exists between Type C and Type D. The magnets are not straight and have a sagitta of 16mm for Types A and B, and 7mm for Types C and D.

3.2 Quadrupole Magnets

There are three different kinds of quadrupole magnets in the FMI ring lattice. Their magnet type specifications are:

1) IQD magnets (3Q116) - Length is 2.945m (116in.). Magnet count is 48 and magnet weight is 12,000lb.
2) IQC magnets (3Q100) - Length is 2.539m (100in.). Magnet count is 32 and magnet weight is 10,300lb.).
3) IQB magnets (3Q84) - Length is 2.134m (84in.). Magnet count is 128 and magnet weight is 8,740lb.

The magnets are straight and they have no sagitta. The majority of the quadrupole magnets in the project are reused Main Ring quadrupoles. The Main Ring quadrupoles that will be reused in the Main Injector ring are the 3Q84 quadrupoles. The new quadrupoles are the IQCs and IQDs.

3.3 Magnet Stands

The magnet stands are installed and bolted into the concrete tunnel floor to support hold the 40,000lb. dipole and the 12,000lb. quadrupole magnets. The magnet stand has three legs with adjustment screws. Dipoles and quadrupoles have three axis adjustments: ±0.75″ in the transverse and longitudinal directions and ±2.00″ in the vertical direction..

4. ALIGNMENT TOLERANCES

The desired absolute and relative alignment tolerances for the 344 dipole magnets and the 208 quadrupole magnets have been defined earlier in the project by the FMI design committee [4]. 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 [4].

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 dipole and quadrupole magnets to adjacent components [4].

Table 1. Alignment Tolerances

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

The Laser Tracker will be used in order to achieve these alignment tolerances. The relative alignment tolerances for the pre-alignment of the 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 FMI ring (Figure 4). A Local Tunnel Coordinate System (LTCS) was specifically defined for the FMI [4]. 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 5). 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.

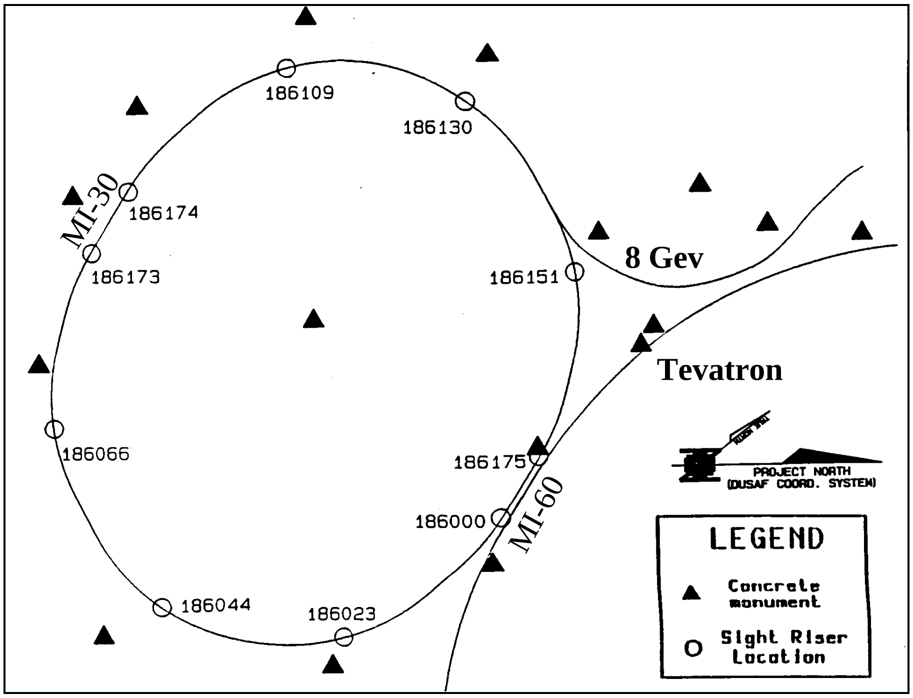

Figure 4. Geodetic Control Network

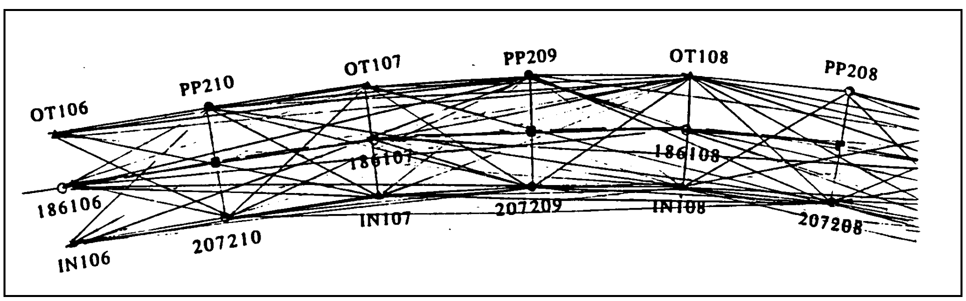

Figure 5. Tunnel Control Network

6. MAGNET FIDUCIALIZATION AND ALIGNMENT

6.1 Methodology

The method of magnet fiducialization and alignment procedures adopted for the FMI project was chosen for its ability to apply the latest most accurate measurement instrumentation and computer technology, while still maintaining optical tooling alignment capabilities for quick magnet change-outs to minimize down time. Three major factors led to the acceptance of a method termed the One Fixed - Four Random (1F4R) system [2]. First, the physical centerline of the steel laminations define the magnetic centerline of each magnet. Second, the magnets are constructed to published tolerances, the mean values being ±0.002in. radially and ±0.003in. vertically. Third, since the 1F4R system references each magnet as it is being aligned into its slot in real time, the costs associated with hardware, labor for installation and referencing are not necessary, representing a major cost reduction.

6.2 Theory

The success of the 1F4R system will be dependent upon a computer database containing the entire FMI spatial parameters, ideal magnet models and the beam lattice. This database will interact in real time with application software containing the necessary algorithms to actually align each magnet into its proper slot. The one fixed point that is required for this system to

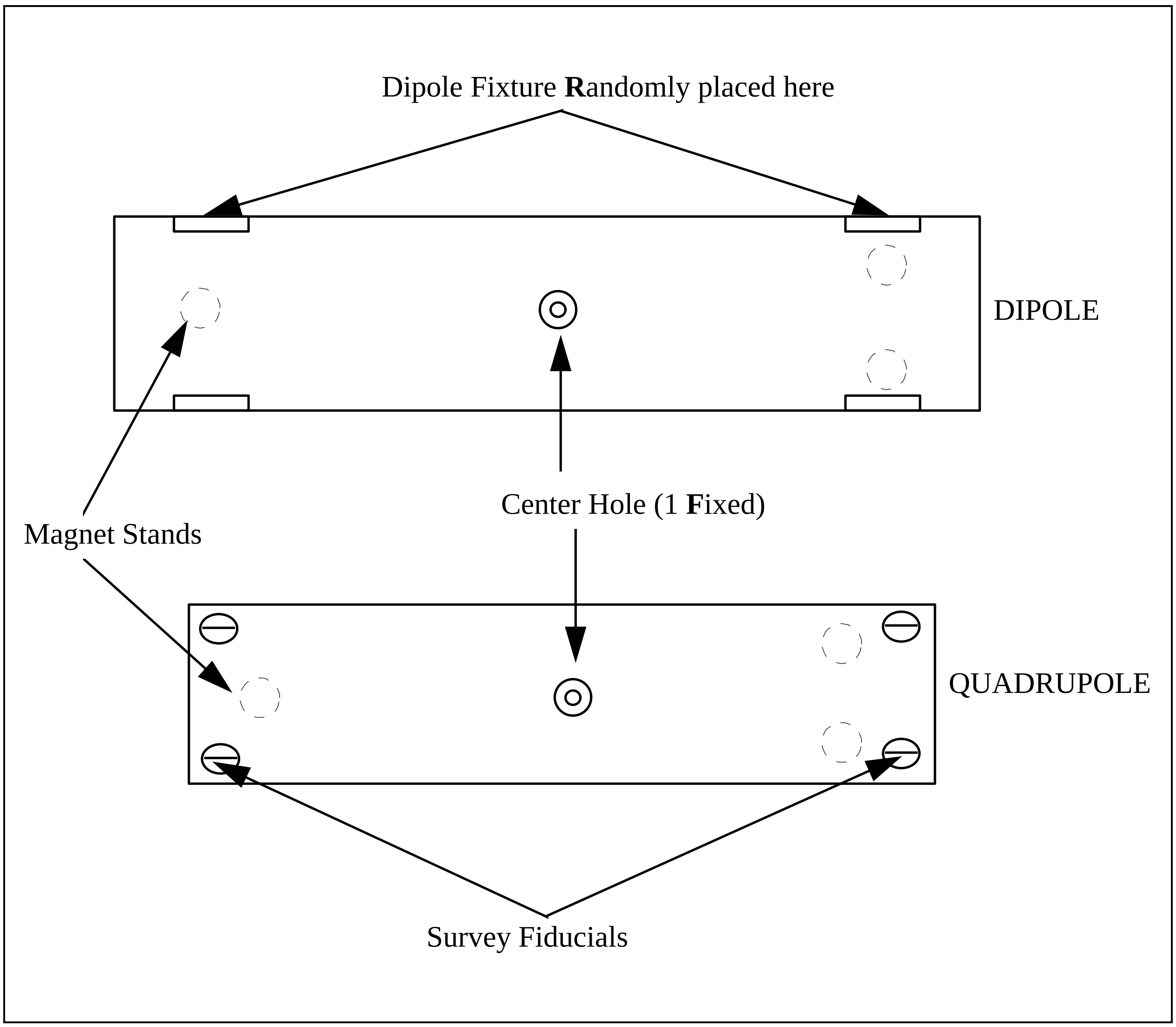

Figure 6. Dipole and Quadrupole Magnets showing Fixture locations.

work is placed at the longitudinal centerline of each magnet to an accuracy of one lamination (±1.5mm). This fixed point is not required to be located accurately in the radial direction. The four random points (mobile fixtures accepting a standard Laser Tracker nest) will determine each magnet's radial alignment (Figure 6).

6.3 Pre-Alignment

Before any alignment could be performed, the magnet stands, the dipole and quadrupoles, and the BPMs had to be installed. This was accomplished as follows:

1) Using the beam lattice, the entrance and exit y-coordinates of all dipole and quadrupole magnets, and BPMs were marked on the floor to within 3mm.

2) The positions of the magnet stands were also marked on the floor.

3) The magnet stands were installed as marked on the floor.

4) The magnets were then placed on the stand as marked on the floor.

A Geodimeter Total Station was used for these operations. Once all the magnets had been placed on the stands a pre-alignment of the magnets was performed. This was 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 were computed to the four fiducial locations at the top of all the dipole magnets and the quadrupole magnets around the ring. These offsets were used to place the magnets along the beamline around the whole ring.

6.4 Final Alignment procedure

Algorithms have been developed for the 1F4R system. An application software - MAGSET - containing these necessary algorithms to actually align each magnet into its proper position have also been developed and is now being tested. The application software accepts inputs from the Laser Tracker software. 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

Fixtures are placed on each of the two dipoles and one quadrupole that make up one observation session for a Laser Tracker setup. One fixture on each magnet is placed on the fixed (1F) point and four fixtures are placed on each magnet at four random (4R) points at a position in

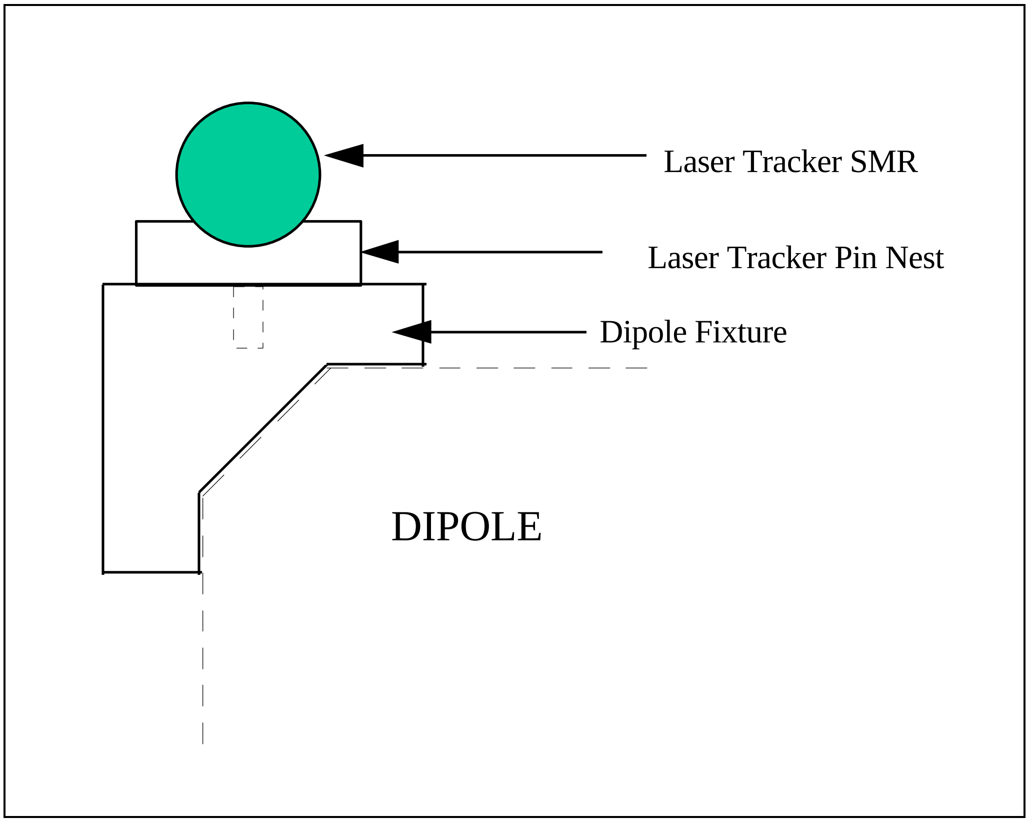

Figure 7. Dipole Fixture with Nest on Top.

a designated area directly above the magnet support stands (Figure 6) [2]. At the center of each fixture is a 0.25in. hole that fits precisely a Laser Tracker SMR (Spherically Mounted Retroreflector) nest (Figure 7). The center of this hole defines the location of the fiducial point.

The Laser Tracker will be positioned and oriented into the Tunnel Control System (TCS) at a point nearly perpendicular to a quadrupole magnet. This allows the strongest measurement to take place at the most critical component using optimum geometry. From this setup all 15 fiducials comprising this observation session will be measured (Figure 8). The software will compute each magnet's geometry, compare it to the ideal magnet model in the database to alert the operator of any misplaced fixtures or other spatial problems, and compute the offsets required to place each magnet into its slotted position according to the beam lattice.   The two dipoles and one quadrupole will be aligned from this setup. The center point of the last quadrupole aligned will serve as a pass point in the current setup. 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.

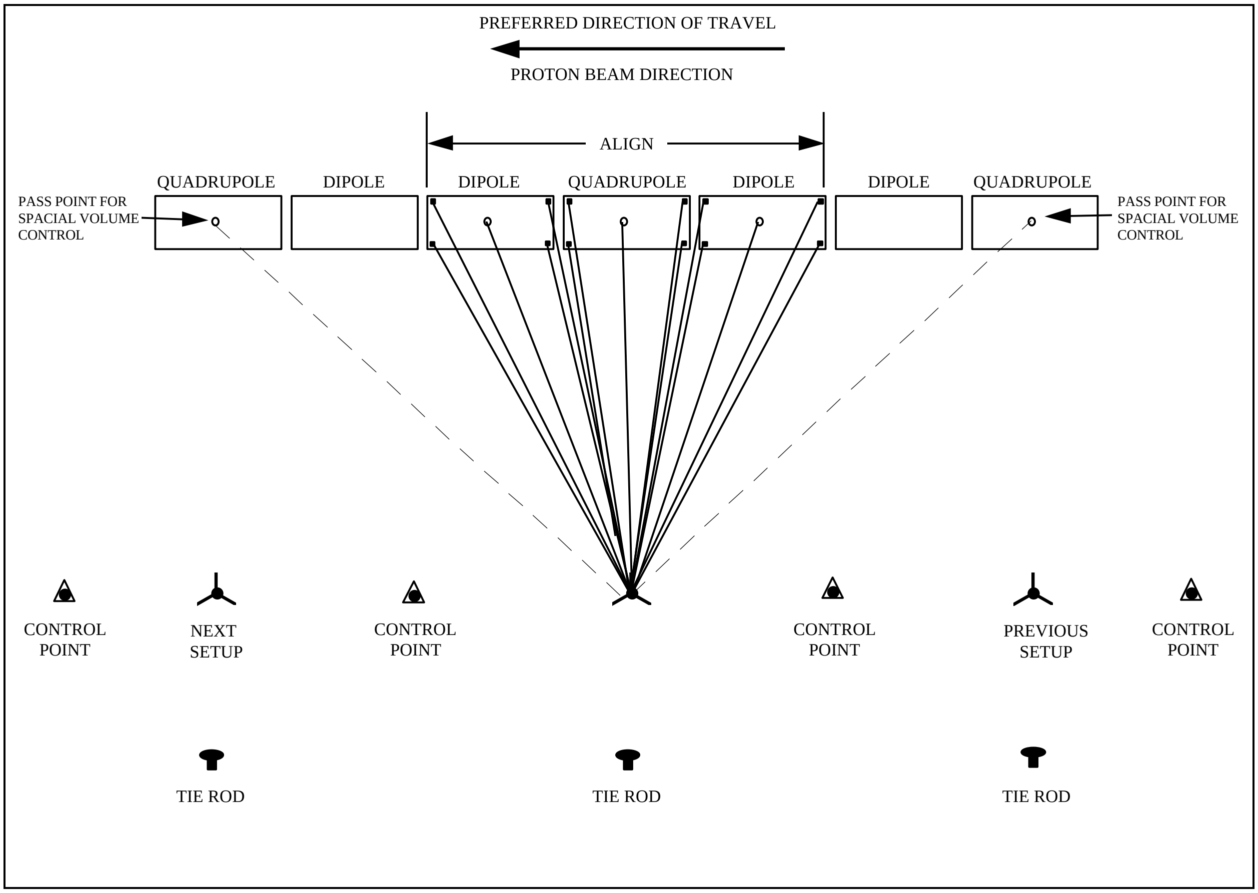

Figure 8. Magnet Alignment Procedure

7. 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 [5][6]:

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

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

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

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

σ_{nf} = standard deviation of nest to fixture 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

$= \{\sigma_{fm}^2 + \sigma_{cl}^2 + \sigma_{cd}^2\}^{1/2}$

σ_{fm} = standard deviation of the fixture to magnet (lamination) repeatability

σ_{cl} = standard deviation of the magnet center depending of the different locations of the fixture on lamination

σ_{cd} = standard deviation of the magnet center depending of the discrepancies between the designed and as built component

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:

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

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

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

$\sigma_{nf} = \pm 0.000007\text{m}$

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

$\sigma_f = \pm 0.000140\text{m}$

$\sigma_{fm} = \pm 0.000035\text{m}$

$\sigma_{cl} = \pm 0.000098\text{m}$

$\sigma_{cd} = \pm 0.000095\text{m}$

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

$$\sigma_{Mag\_Align} = \pm\{0.000158^2 + 0.000046^2 + 0.000140^2 + 0.000025^2\}^{1/2}$$

$$= \pm 0.000217\text{m}$$

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

8. CONCLUSION

An FMI ring, with a circumference of 3319.419 meters, is being constructed at Fermilab. The FMI consists of 344 dipoles magnets and 208 quadrupole magnets. These magnets are being aligned with respect to the specified accuracy by using the Laser Tracker. An algorithm and application software were developed for the final alignment procedure. The procedure and the software are currently in the testing stages. The FMI project will be fully commissioned in March of 1999.

9. ACKNOWLEDGMENT

We would like to thank Terry Sager, Chuck Wilson and other members of the group for their continuing effort for the FMI magnet alignment project.

10. REFERENCES

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