

Survey and Alignment of the Fermilab Electron Cooling System

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The goal of achieving the Tevatron luminosity of $3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ requires Electron Cooling in the Recycler Ring to provide an increased flux of antiprotons. The Fermilab Electron Cooling system has been designed to assist accumulation of antiprotons for the Tevatron collider operations. The installation along with the survey and alignment of the Electron Cooling system in the Recycler Ring were completed in November 2004. The Electron Cooling system was fully commissioned in May 2005 and the first cooling of antiprotons was achieved in July 2005. This paper discusses the alignment methodology employed to survey and align the Electron Cooling system.

1. INTRODUCTION

The goal of Electron Cooling in the Recycler Ring is to effectively cool 8.9-GeV/c antiprotons by mixing them in a 20-m long cooling section with a cold beam of 4.3-MeV electrons. The implementation of Electron Cooling should significantly increase the number of antiprotons stored in the Recycler and improve the antiproton production rate in the Accumulator. In turn, it will increase the luminosity of the Tevatron collider (Figure 1).

The Fermilab Alignment and Metrology Group supported the installation and alignment of the Electron Cooling project. From January 2000 to June 2004, a full-scale prototype of the Electron Cooling system was built and tested at the Wide Band Lab. The system was moved to the current location during the scheduled shutdown of 2004. The new location is inside the MI-31 service building and the Recycler beamline, located in the 300-sector (MI-30) of the Main Injector (MI) tunnel (Figures 1 and 2). The MI-31 service building and MI-30 tunnel are separated by an 18.66 m (61.2 ft) long connecting enclosure (Figure 2). The end of the connecting tunnel is filled with steel shielding 3.35 m (11 ft) long, 2.13 m (7 ft) wide, and 2.44 m (8 ft) high. The survey and alignment of the Recycler Ring, a 3319.4 m (10,900 ft) circumference 8 GeV kinetic energy storage ring, was done in 1999 [1]. The installation of all components of the Electron Cooling system started in June of 2004. The installation along with the survey and alignment of the system were completed in November 2004.

2. ELECTRON COOLING SYSTEM (E-COOL)

The Electron Cooling system involves interacting a 4.3 MeV electron beam with 8.9 GeV/c antiprotons. This interaction takes place through a 20-m (65.6-ft) long cooling section, which consists of ten 2-m long solenoid modules. The DC electron beam is generated by a thermionic-cathode gun, located in the high-voltage terminal of an electrostatic Pelletron accelerator. The electron beam is then transported to the cooling section using conventional focusing elements and returned back to the high voltage terminal [2]. The schematic layout of the Electron Cooling system is shown in Figure 3.

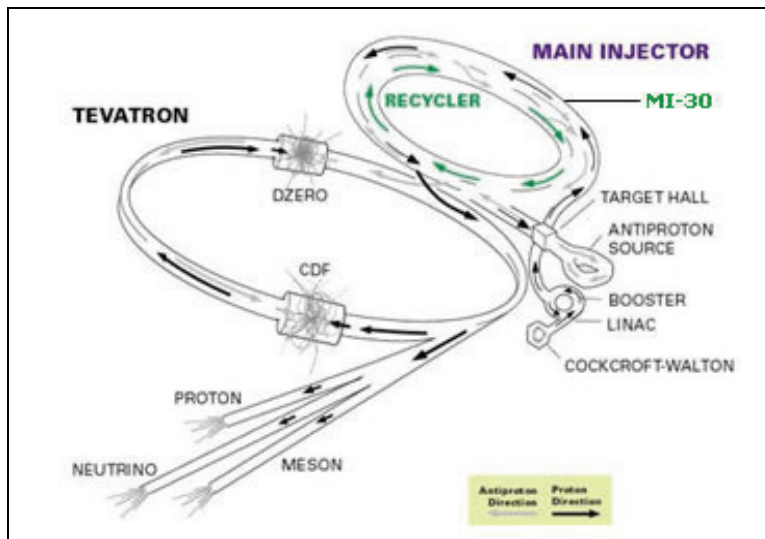


Figure 1. Fermilab's Accelerator Chain

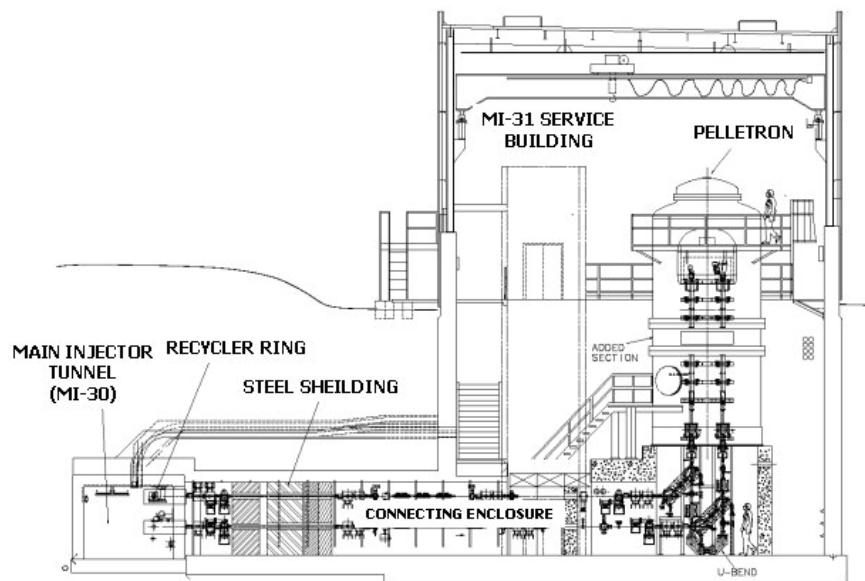


Figure 2. MI-31 and MI-30 Enclosures with Connecting Enclosure

2.1 What is Electron Cooling?

Cold electrons flow through a hot antiproton beam and cool it, so it is natural to call it Electron Cooling [3]. This is analogous to water cooling, when water flows around an engine and removes the heat. Antiproton beam is hot when the initial temperature of the antiproton gas, in the beam rest frame, is much higher than the corresponding electron temperature. Why is the antiproton hot? Antiprotons are produced at the target fly in a wide angle. The number of antiprotons ready to each be shot to the Tevatron depends, in part, on the effectiveness of their capture after the target. From that point of view, they are as hot as they still can be transported. Each machine in the antiproton production chain

- Debuncher, Accumulator, and the Recycler - cools antiprotons but then adds more and more of them into the same available volume, effectively heating them to the level still tolerable to transport to the next machine.

Antiproton beam needs to be cooled [3]:

To increase the life time;

To put more and more particles into the given accelerator;

To deliver more intense and denser beams to the Tevatron, which presently is the main source for increasing the luminosity.

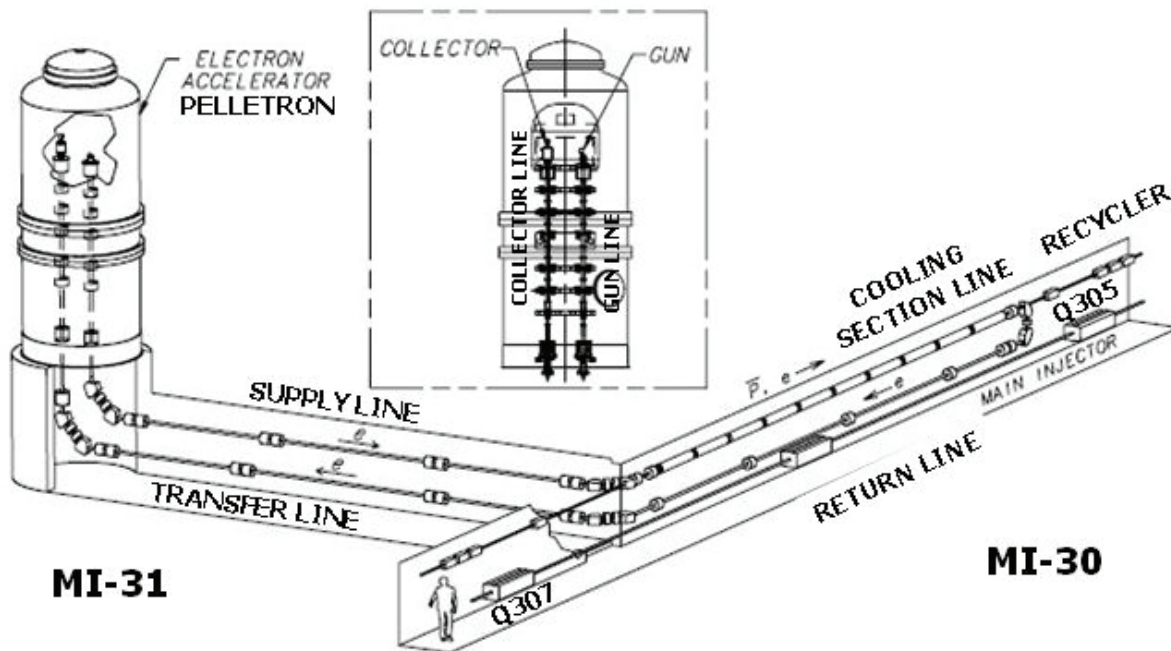


Figure 3. Schematic Layout of Fermilab Electron Cooling System and Pelletron Accelerator Cross-Section (inset)

2.2 Beam Lines

The Electron Cooling beamline consists of four connecting beamlines – the Supply Line, Cooling Section Line, Return Line, and Transfer Line (Figures 3 and 4). In addition, the Gun Line and Collector Line are located inside the Pelletron tank (Figure 3). The Pelletron weighs 45.4 metric tonne (50 ton). The beamline starts from the Gun in the Pelletron and comes down through the Gun Line into the Supply Line, which connects to the Cooling Section Line. The beam then travels through the Return Line to the Transfer Line and back through the Collector Line in the Pelletron to the Collector. The Supply Line and Transfer Line are located in the connecting enclosure that separates MI-31 and MI-30 (Figure 2). The Cooling Section Line is located between quadrupoles Q305 and Q307 of the MI-30 section of the Recycler beamline (Figures 3 and 4). The Return Line is also located in the MI-30 enclosure below the Recycler beamline (Figure 4). The Supply Line and the Cooling Section Line have the same elevation as the Recycler, which is

1.02 m (40 in) above the Return Line and Transfer Line. The Pelletron is located in the MI-31 service building (Figure 5a).

2.3 Beam Transport Line Components

The important transport line components are the Cooling Section solenoids, vacuum chamber, bends, and the various types of diagnostics [2]. There are 10 identical 2.0-m cooling solenoid modules. The bends are 90° bend magnets. Each 90° bend magnet is formed by two 45° dipoles and 5 quadrupoles. The vacuum chamber houses several components such as the OTR detector, YAG crystal, etc. There are several types of diagnostics installed such as wire scanners, beam scrapers, beam position monitors (BPMs), and flying wires.

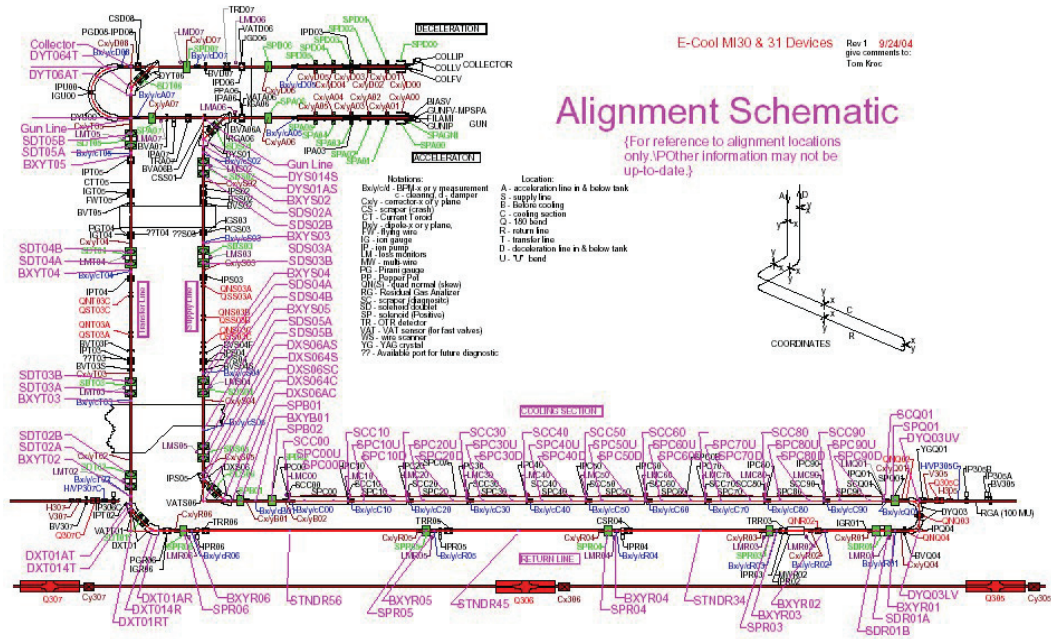


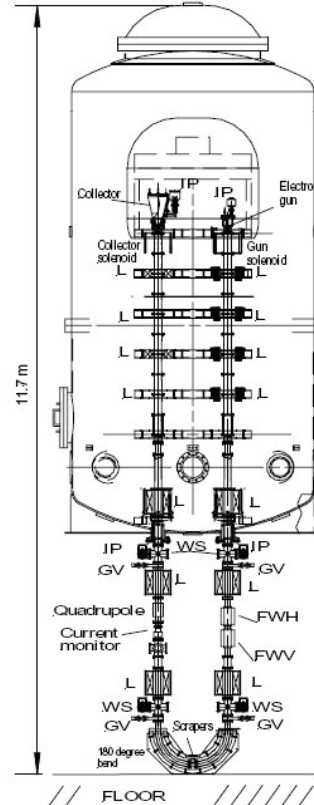
Figure 4. Alignment Schematic of the Electron Cooling System (From Tom Kroc, Fermilab)

There are a total of 105 components in the Electron Cooling beam lattice. Figure 4 shows the alignment schematic of the Electron Cooling system. The Cooling Section Line consists of 10 cooling solenoids, 11 beam scraper cans, 3 focusing solenoids, and 12 BPMs. The Return Line consists of 6 focusing solenoids and 6 BPMs. Figure 6 shows the components in the Cooling Section Line and the Return Line in MI-30. The Supply Line consists of 8 focusing solenoids and 4 BPMs. The Transfer Line consists of 8 focusing solenoids, 4 BPMs, and a Flying Wire assembly. Figure 7 shows focusing solenoids in the Transfer Line and the Supply Line in the MI-31 connecting enclosure. There are a total of four 90° bend magnet assemblies and two 180° bend magnet assemblies used in the Electron Cooling beamline. Two 90° bend magnets connect the Supply Line to the Gun Line and Cooling Section Line. The other two 90° bend magnets connect the Transfer Line to the Collector Line and Return Line. Figure 8 shows the upper and lower 90° bend magnets under the Pelletron. One 180° bend magnet is at the end of the Cooling Line connecting it to the Return Line and the

other 180° bend magnet is located beneath the Pelletron connecting the Gun Line to the Collector Line (Figure 5b). There are other components and instrumentation devices installed that are not listed in the beam lattice.



(a)



(b)

Figure 5. (a) View Inside MI-31 Showing the Fully Assembled Pelletron Accelerator
 (b) Accelerator Cross-Section: IP- ion pump, L- lens, GV- gate valve, FWH and FWV- flying wires

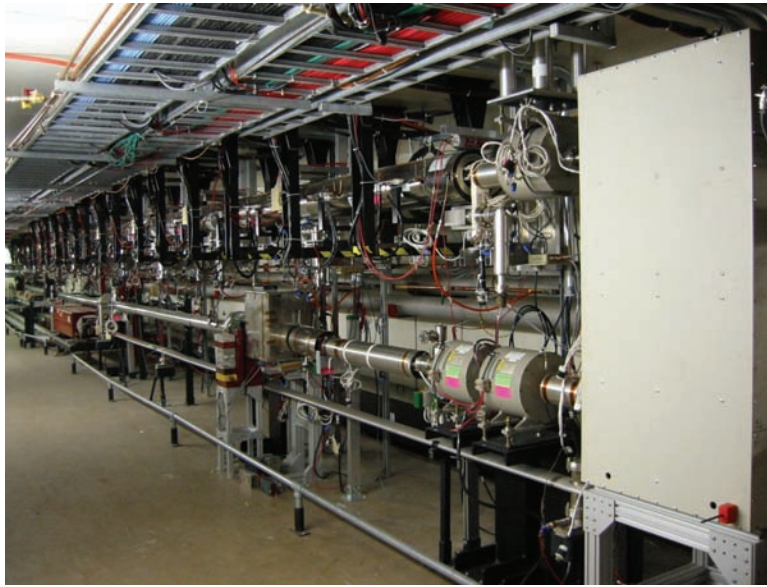


Figure 6. Components in the Cooling Section Line (Top) and Return Line (Bottom) in the Main Injector Tunnel (MI-30)



Figure 7. Focusing Solenoids in the Supply Line (Top) and the Transfer Line (Bottom) of the Electron Cooling System in the MI-31 Connecting Enclosure

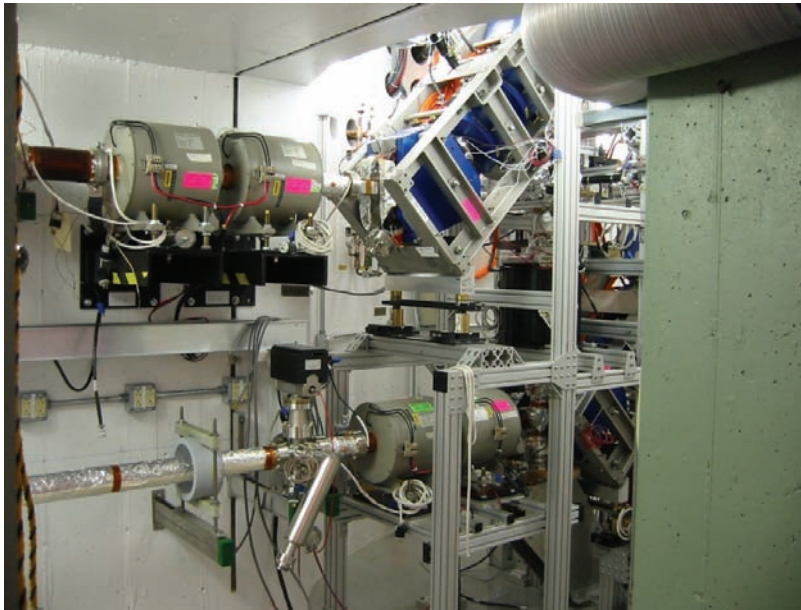


Figure 8. Upper and Lower Bend Magnets (in blue)
and Focusing Solenoids under the Pelletron

3. SURVEY AND ALIGNMENT OF THE ELECTRON COOLING System

3.1 Survey and Alignment Methodology

The Electron Cooling system was constructed as part of the existing Recycler Ring, which was based on the Fermilab Local Tunnel Coordinate System (LTCS) [4]. The Recycler was based on the Main Injector (MI) network of October 1998 [1]. In order to precisely align the Electron Cooling beamline components in the MI-31 enclosure in the LTCS system, a secondary tunnel constraint network was established and tied to the existing MI network. All components were aligned and surveyed to these control points. The survey instrumentation used for the entire Electron Cooling system was as follows:

- i) An electronic total station Geodimeter 600 device that makes three-dimensional measurements was used. DMT Gyromat Gyrotheodolite was used to measure normal section azimuths. Optical (Leica N3) and electronic (Leica NA3003) levels were used for elevations. Optical Brunson tooling instruments were used for making offset measurements from the components to the control points.
- ii) The SMX 4500 Laser Tracker and its associated InsightTM software were used for establishing control points in the tunnel. The API Laser Tracker and the Spatial AnalyzerTM software were used for the component alignment. The Laser Tracker is a device that makes three-dimensional measurements. It uses a laser distance meter, two precision angle encoders and proprietary software to calculate, store and display the real-time three-dimensional position of a mirrored target positioned on the desired point or feature. The mirrored target is a spherically mounted retroreflector (SMR).

3.2 Tunnel Control Network

The Tunnel Control Network is a system of braced quadrilaterals between the floor monuments, wall monuments, and tie rods in the tunnel. The tunnel network consists of both horizontal and vertical networks.

3.2.1 MI-30 Control Network

The MI-30 and MI-31 enclosures are separated by a connecting tunnel enclosure. A portion of the MI-30 enclosure was removed for the construction of the MI-31 connecting enclosure, which lead to both horizontal and vertical deformations of the floor monuments and tie rods in MI-30. A decision was made to first upgrade the horizontal and vertical networks in the MI-30 enclosure. The MI-30 network consisted of a total of 15 floor monuments, 13 tie rods, and 31 pass points.

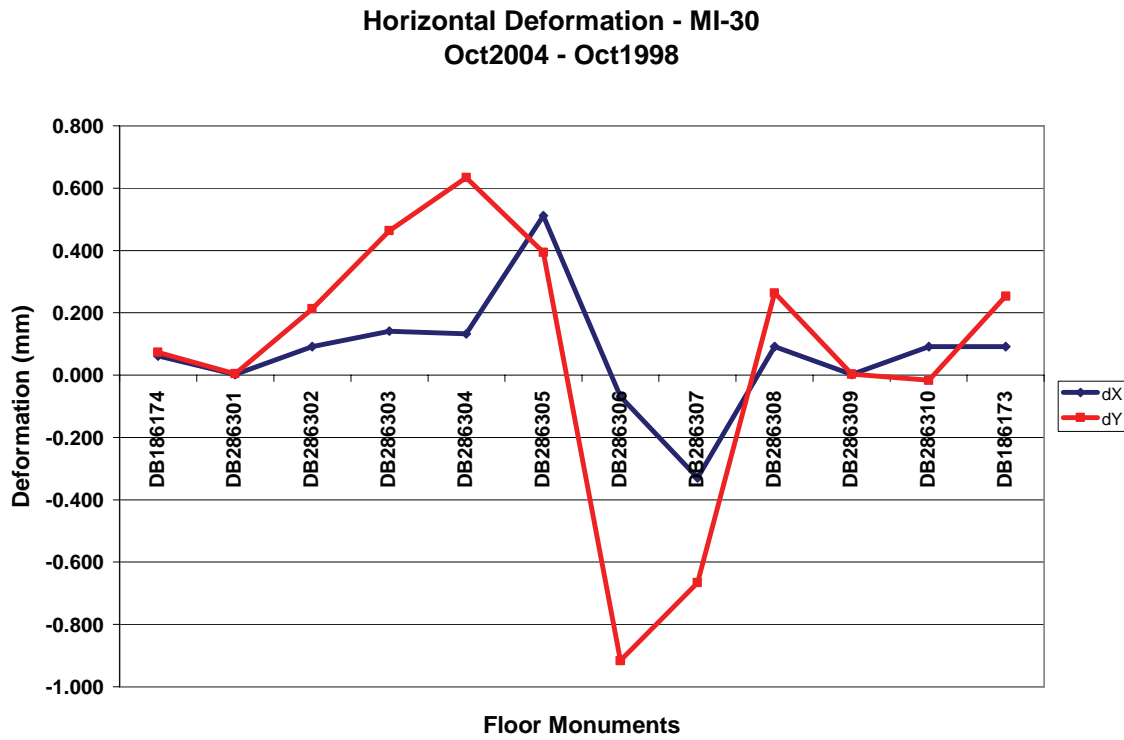


Figure 9. MI-30 Control Network: Horizontal Deformations – Floor Monuments

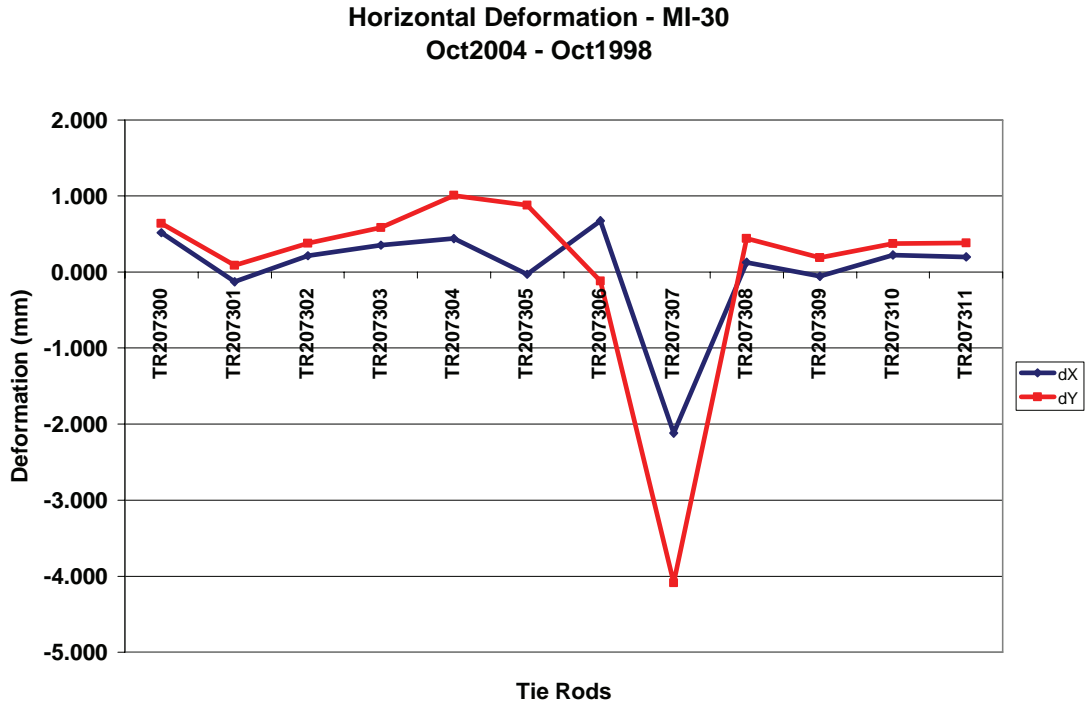


Figure 10. MI-30 Control Network: Horizontal Deformations – Tie Rods

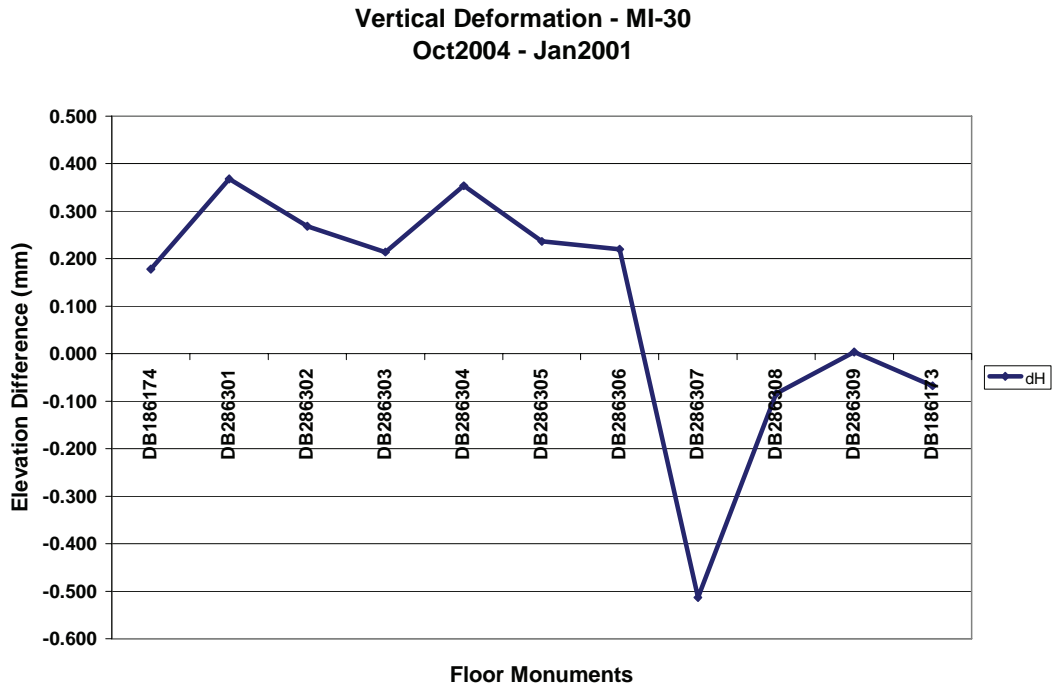


Figure 11. MI-30 Vertical Control Network: Vertical Deformations – Floor Monuments

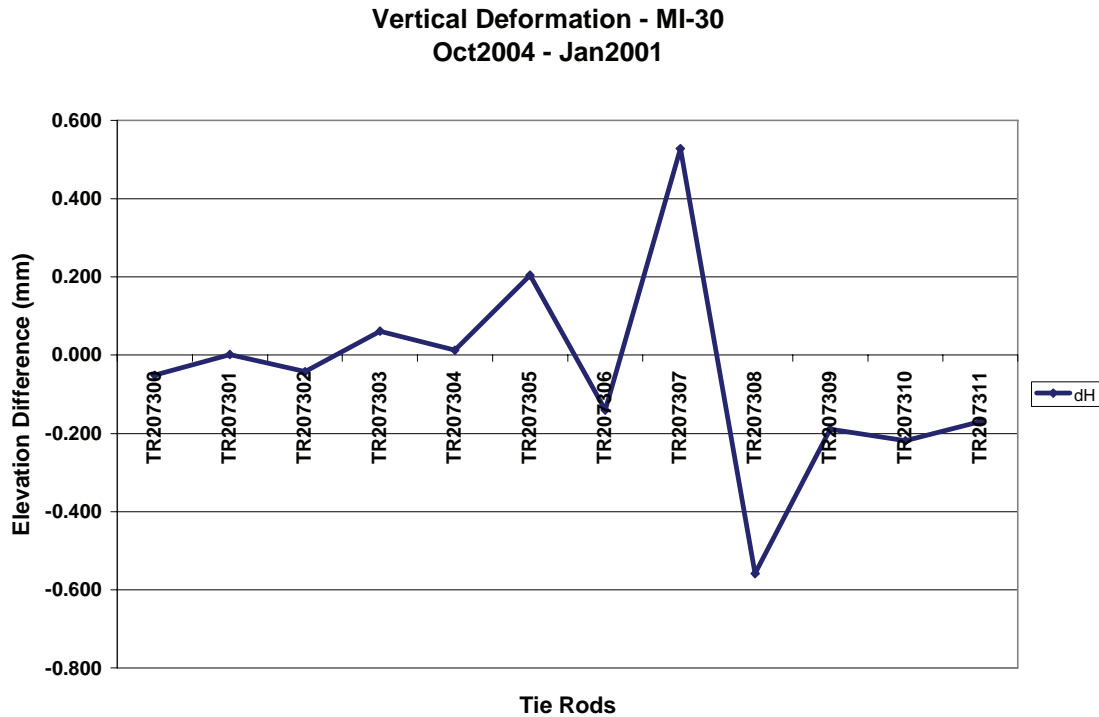


Figure 12. MI-30 Vertical Control Network: Vertical Deformations – Tie Rods

A deformation analysis was performed after the network adjustment. Results show deformations in and around the construction area between cell bodies 304 and 308. Figures 9 and 10 show the horizontal deformations between the October 2004 and the October 1998 horizontal networks. Figures 11 and 12 show the vertical deformations between the October 2004 and the January 2001 vertical networks.

3.2.2 MI-31 Control Network

A control network was established to bring horizontal and vertical controls into the MI-31 building before the Pelletron was installed. This network was tied to the existing MI-30 network through two 3.35-meter (11-foot) holes in the long steel radiation shielding at the end of the tunnel that separates MI-31 and MI-30 (Figure 13). The dimension of the hole is 20.32-cm x 20.32-cm (8-in x 8-in) wide. This was the best option available since there was no opportunity for an open tunnel connection. The steel shielding was installed as part of the initial construction phase of MI-31. The MI-31 network consisted of a total of 24 floor monuments, 27 wall monuments, 8 tie rods, 7 pass points, and 3 brass points from the tunnel to the MI-31 enclosure. The three brass points were earlier installed at the Gun, Collector and the Center locations for the Pelletron installation. The entire horizontal control network was measured with the SMX 4500 Laser Tracker. As a check, gyro-azimuths were measured between the two points in the MI-31 enclosure. Figure 14 shows the resulting standardized observation residuals for the tunnel network. Figure 15 shows the resulting absolute error ellipses

at the 95% confidence level, which were all less than 0.40 mm. These results show that the network was very good. The vertical control network was measured using the Leica NA3003 level instrument.

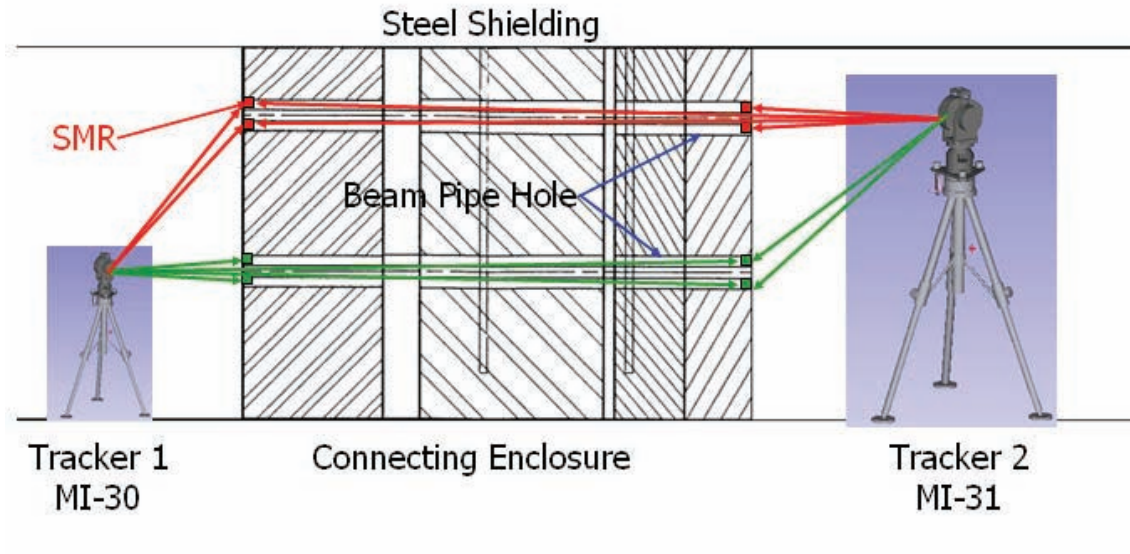


Figure 13. Tracker Setups for Connecting MI-30 and MI-31 Networks

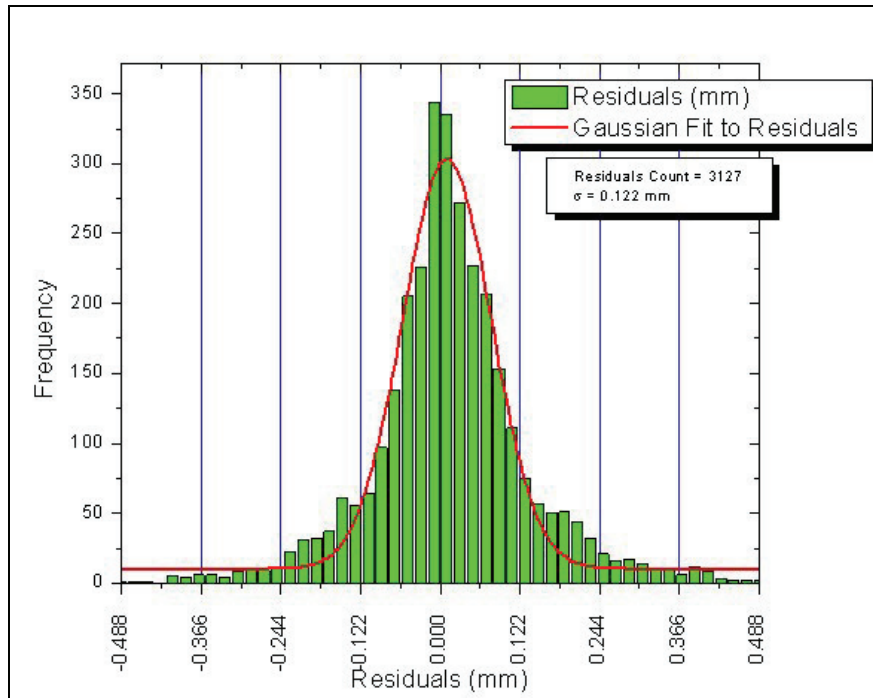


Figure 14. MI-31 Control Network: Histogram of Standardized Observation Residuals.

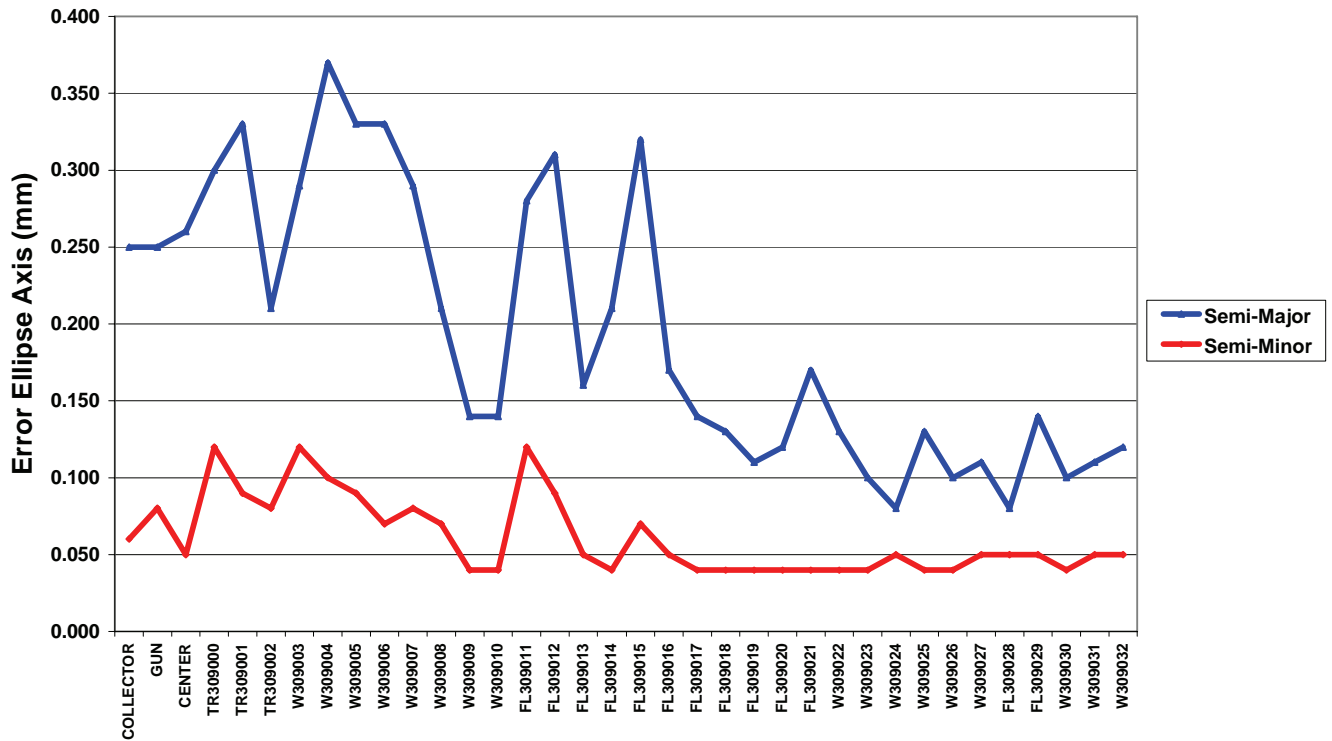
3.3 Alignment Tolerances

Table 1 defines the relative alignment tolerances of the components to adjacent components.

Table 1. Alignment Tolerances

Magnet type	Horizontal	Vertical	Beam Direction
Cooling Solenoids	±0.25 mm	±0.25 mm	±0.50mm
90° and 180° Bend Magnets	±0.25 mm	±0.25 mm	±0.50mm
Focusing Solenoids	±0.50mm	±0.50mm	±1.00 mm
Beam Position Monitors	±0.50mm	±0.50mm	±1.00 mm
Flying Wire & Multi-Wires	±0.50mm	±0.50mm	±1.00 mm
Other Components	±0.50mm	±0.50mm	±1.00 mm

Error Ellipses (95%) Confidence Level



MI-31 Control Network: Tie-Rods (TR), Floor (FL) and Wall (W) Points

Figure 15. MI-31 Control Network: Error Ellipses (95% Confidence Level)

Other tolerances specified are as follows:

The deviation of the measured distance from the design distance from the Pelletron to the Recycler (length of the Transfer Line) should be ± 25.4 cm (± 1.00 in).

The location where the Transfer Line breaks into the Recycler should be ± 25.4 cm (± 1.00 in).

The level of accuracy that the Transfer Line needs to be perpendicular to the Return Line should be $\pm 1.0^\circ$.

3.4 Beamline Component Alignment

3.4.1 Component Fiducialization and Referencing

The goal of the component fiducialization is to relate its physical or magnetic center to the survey fiducials mounted on the component. Several survey fiducial points are mounted at suitable locations on each component. At the center of each fiducial is a 0.250-inch (6.0-mm) hole that precisely fits a Laser Tracker SMR pin nest. The center of this hole defines the location of the fiducial point. Each component is referenced in a local component coordinate system, defined such that its origin is at the physical center. Software was written to transform the local fiducial coordinates to the beam lattice coordinate system. The fiducialized cooling solenoids, 90° magnets, and 180° bend magnets were referenced using the Laser tracker at different locations prior to installation in the beamline.

3.4.2 Pre-Alignment

Prior to the alignment, beam lattice coordinates of all components were marked on the floor in MI-31 and on the ceiling in MI-30 to within 3 mm. The components were then placed at the beam height on the stands as marked on the floor or the ceiling. A Geodimeter Total Station was used for these operations. After the component installation, each component was rough aligned to the beam lattice using optical Brunson tooling instruments. Using the coordinates of the established floor control points and the beam lattice coordinates of the components, offsets were computed to the center of the components. These offsets were then used to place the components along the beamline in the MI-30 and MI-31 enclosures.

3.4.3 Final Alignment

The API Laser Tracker and the Spatial Analyzer™ software were used for the final alignment of all components using the floor control points and tie rods. First, the ideal coordinates of fiducials for all the magnets were imported into the Spatial Analyzer software. Second, after the normal calibration, the Laser Tracker was positioned at a point near the component to be measured. Third, the Laser Tracker was oriented into the beamline Tunnel Control Network by best fitting to several floor control points and tie-rods. From this setup, measurements were made to the fiducials on the components – the cooling solenoids, 90° bend magnets, and the 180° bend magnets. The components 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 deviations of the as-set components from the ideal beam locations for the cooling solenoids in the Cooling Section Line. These results show that the components were set to specified tolerances.

Cooling Solenoids: Deviations from Beamline

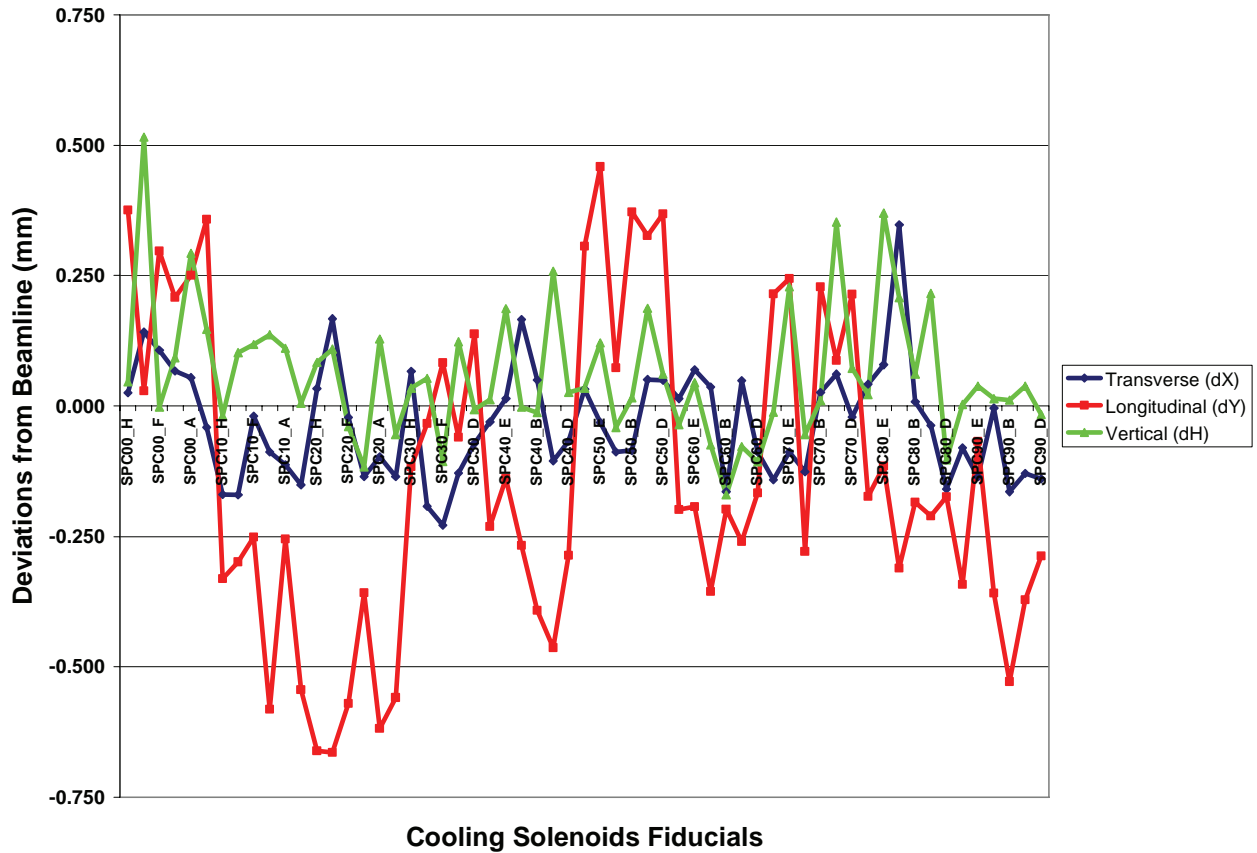


Figure 16. Cooling Solenoids: Deviations from Beamline

The focusing solenoids were measured as cylinders, with the upstream and downstream ends measured as planes. Cylindrical fits yielded the coordinates for the center of the cylinder, centered on the beamline. By constructing a line parallel to the beamline through the cylinder center and using the plane-line intersection capability in the software, coordinates of the entrance and exit points on the solenoids were computed. The BPMs, Flying Wire, Multi-Wires, and flanges on other components were measured as circles. Circle fits yielded the coordinates for the center of the circle centered on the beamline. The beam pipes were also aligned to the beam centerline with the Laser Tracker. The lens components (Figure 5b) inside the Gun Line and the Collector Line in the Pelletron were aligned using the Leica ZL Zenith and the Leica NL Nadir optical plummets. All the installation and final alignment of the beamline components were completed in November 2004.

4. CURRENT STATUS OF THE ELECTRON COOLING SYSTEM

The Electron Cooling system was fully commissioned in May 2005 and the first cooling of antiprotons was achieved in July 2005. Electron Cooling is currently operational at a beam current of 0.5 amps DC. Fermilab has a unique electron cooling system for cooling 8.9 GeV/c antiprotons in the Recycler ring [5]. The Recycler anti-proton stack size has been

increased to over 200×10^{10} pbars [6]. Fermilab now has a world record Electron Cooling system, which is a major contributor to record luminosity for the Tevatron [7].

5. Conclusion

The Electron Cooling system has been surveyed and aligned and the results have been presented. The alignment methodology used has also been presented.

Acknowledgment

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