Fermilab

Survey and Alignment of the Fermilab MiniBooNE Experiment

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ABSTRACT

MiniBooNE is the first phase of the BooNE (Booster Neutrino Experiment) program at Fermilab. One of the primary goals is to test for neutrino mass via a search for neutrino oscillations. The MiniBooNE consists of a Neutrino Beam and a 40-foot (12.2-meter) diameter Detector. The detector is located 500 m from the neutrino beam line fed by the 8 GeV protons Booster. The construction of the MiniBooNE project, which began in 1997, has been completed and Fermilab began collecting neutrino event data in August 2002. This paper discusses the alignment methodology employed to survey and align the detector and the components in the neutrino beam.

1. INTRODUCTION

The first phase of the **Boo**ster **N**eutrino **E**xperiment (**BooNE**) at the Fermi National Accelerator Laboratory is called "**MiniBooNE**." The major goal of the MiniBooNE experiment is to confirm or refute the LSND evidence for neutrino oscillations. LSND is the Liquid Scintillator Neutrino Detector experiment at the Los Alamos National Laboratory. In 1995, the LSND collaboration presented evidence for the oscillation of muon anti-neutrinos to electron anti-neutrinos. MiniBooNE is set out to confirm or refute the LSND evidence. It began its two-year data collection run in August 2002.

2. THE MINIBOONE EXPERIMENT

The MiniBooNE experiment consists of two geographically separated parts: the Neutrino Beam and the Detector [1]. The experiment is located in the southwest region of the Fermilab site (Figure 1). The BooNE neutrino beam originates at the MI-10 and points almost due north. The distance from the neutrino source to the detector is 500 m.

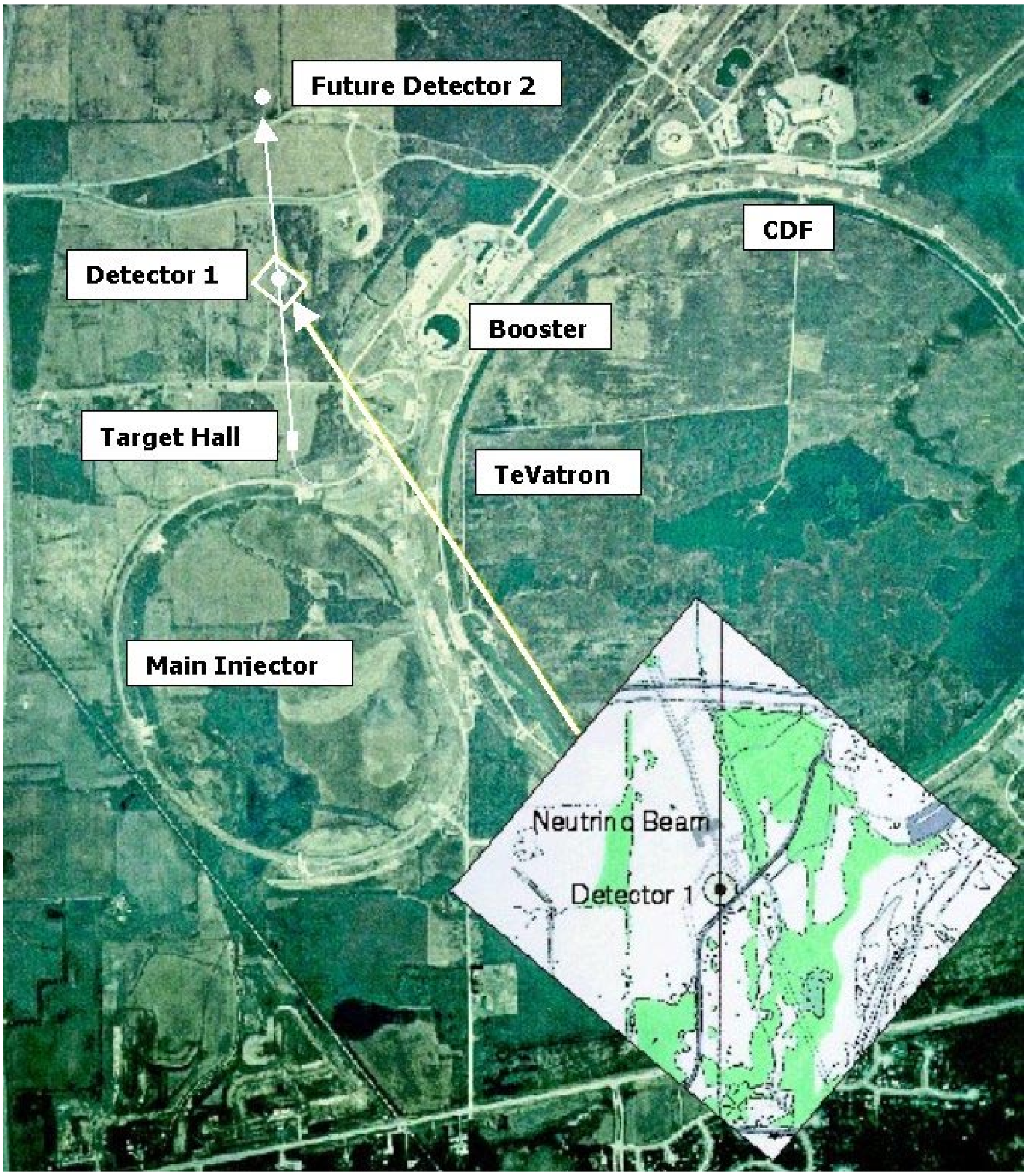

Figure 1. The MiniBooNE site location.

2.1 The Neutrino Beam

The Neutrino Beam consists of four sections: the target, the focusing system, the decay region, and the beam absorber (Figure 2) [1]. These devices are enclosed in the Target Hall (MI-12), the Target Service Building, and the Decay Pipe, and consist of all the technical elements required to form a neutrino beam (Figure 3). These include the horn (focusing system) and power supply, the target and the target shielding, and the beam absorbers.

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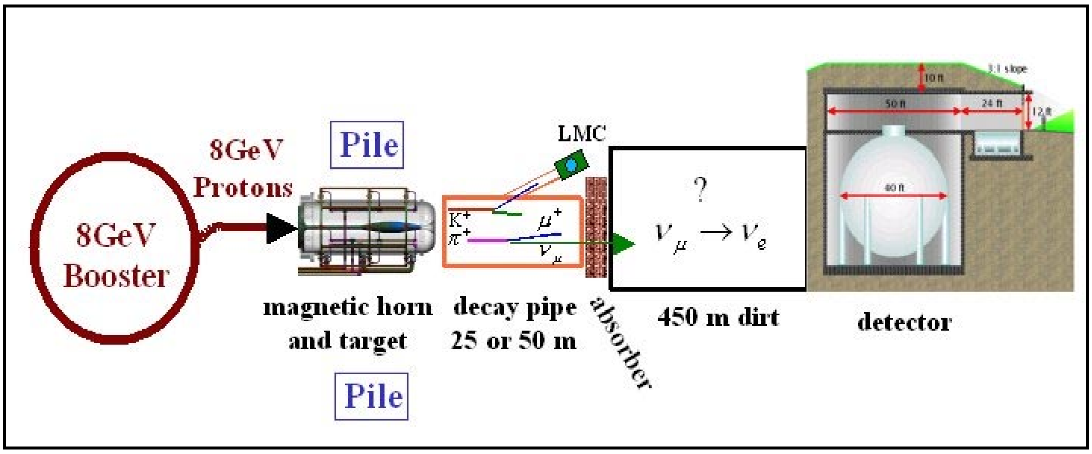

Figure 2. An overview of the MiniBooNE Experiment.

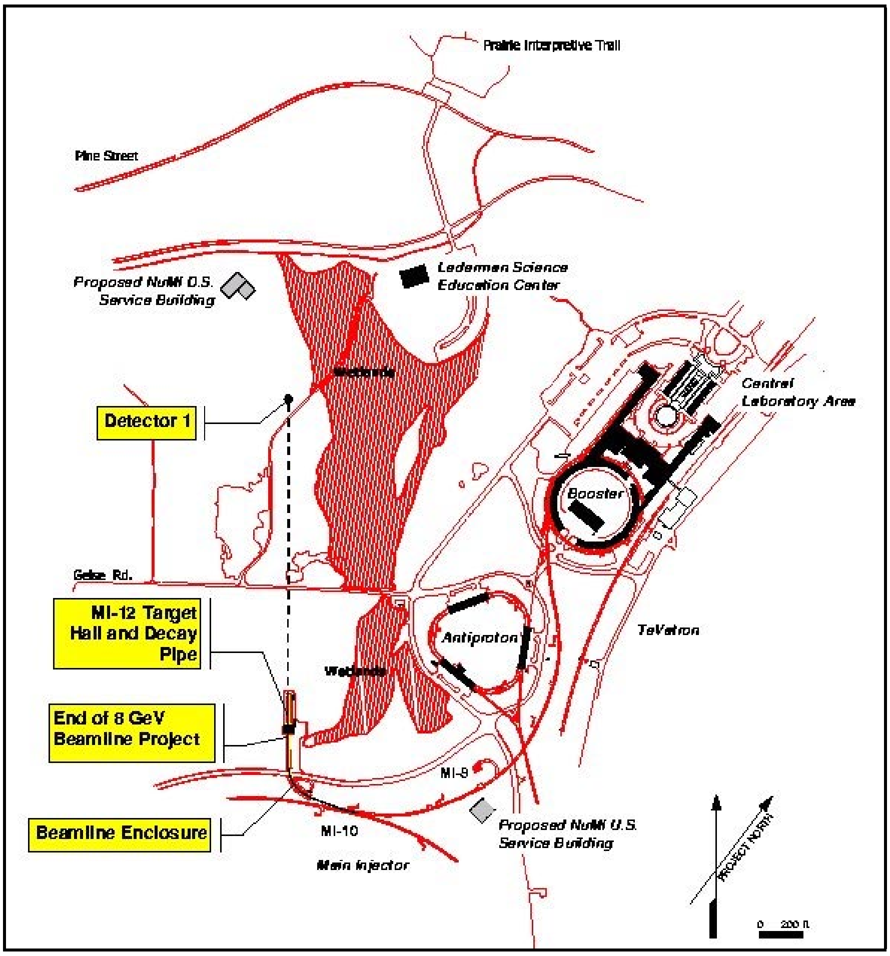

Figure 3. Schematic view of the 8 GeV Fixed Target Facility, the neutrino beam and the MiniBooNE detector.

The MiniBooNE neutrino beam is initiated by a primary beam of 8 GeV protons from the Fermilab Booster. A secondary beam is produced when the 8 GeV protons strikes a 71-cm beryllium target positioned inside a magnetic horn. Protons from the Booster are extracted near MI-10 and transported through a long string of components to the Target Hall which contains the beryllium target within a focusing system, followed by an approximately 50 m long pion decay volume. The resulting neutrino beam points to the MiniBooNE detector. Figure 2 gives an overview of MiniBooNE experiment.

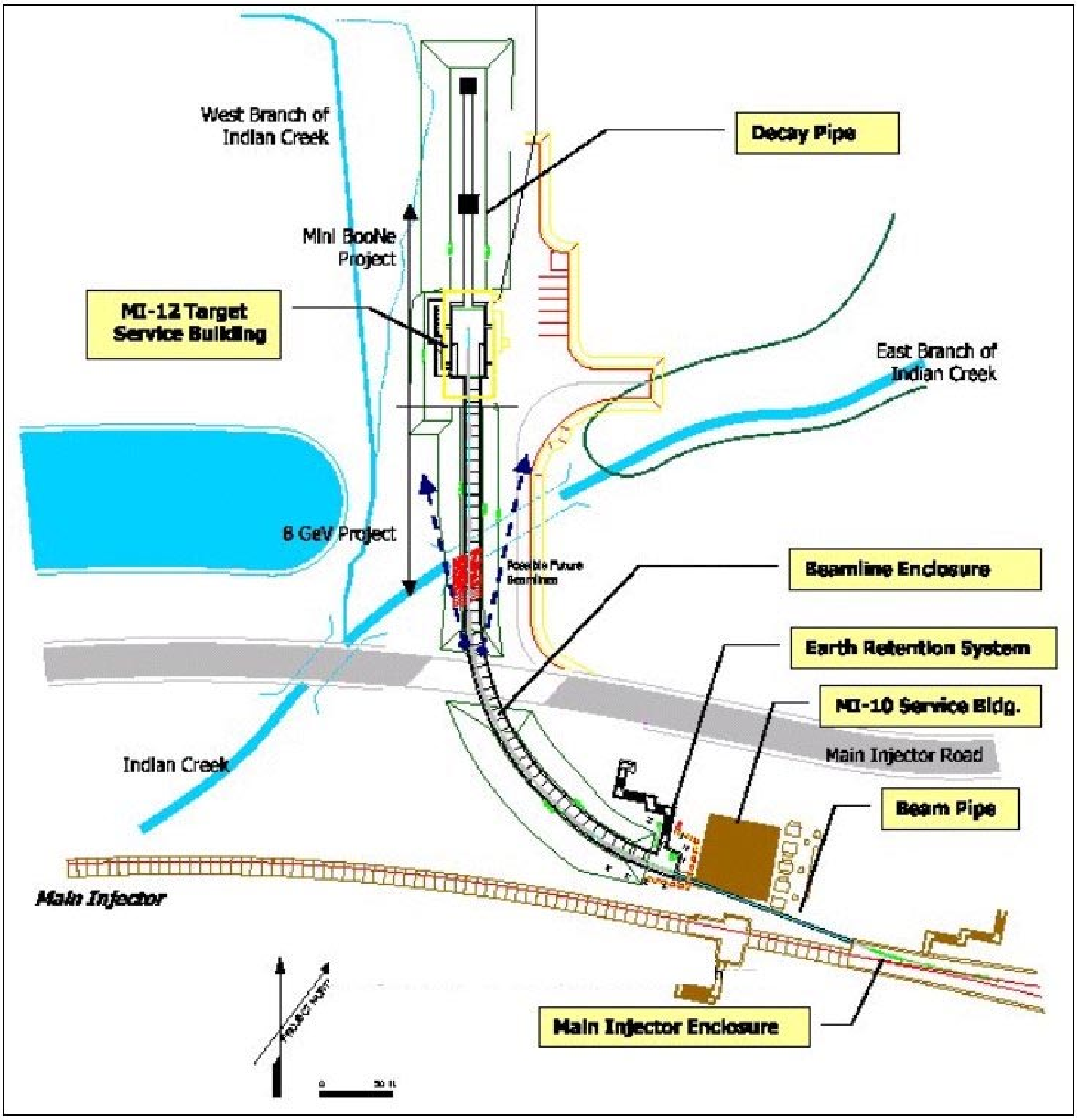

Figure 4. 8 GeV Beam enclosures and MiniBooNE Target Hall and Decay Pipe.

2.1.1 8 GeV Beamline

The 8 GeV beamline consists of a tunnel that curves into roughly a quarter circle. The tunnel is tied to the Main Injector (MI) by a 24-in (61 cm) pipe that is pushed beneath the MI-10 service building (Figure 4). The beam tunnel ties into the Target Hall at the north end. Further downstream, the Target Hall leads to the decay pipe and the beam absorbers. The MI-12 service building resides above the Target Hall.

The beamline components consist of a total of twenty 6-3-120 dipole magnets, and one 4-4-30 trim dipole. There are eleven 20-in permanent quadrupole magnets, five 3Q60 quadrupoles, four LEP quadrupoles and two other types of quadrupoles used in the beamline. Also contained in the beamline are eighteen horizontal and vertical BPMs (Beam Position Monitors), four target BPMs, six multi-wire chambers, fourteen horizontal and vertical LEP trims, two toroids, and one target. Figure 5 shows the installed dipole string in the beamline enclosure and Figure 6 shows the schematic overview of the location of the beamline components.

Figure 5. Installed dipole string along the tunnel

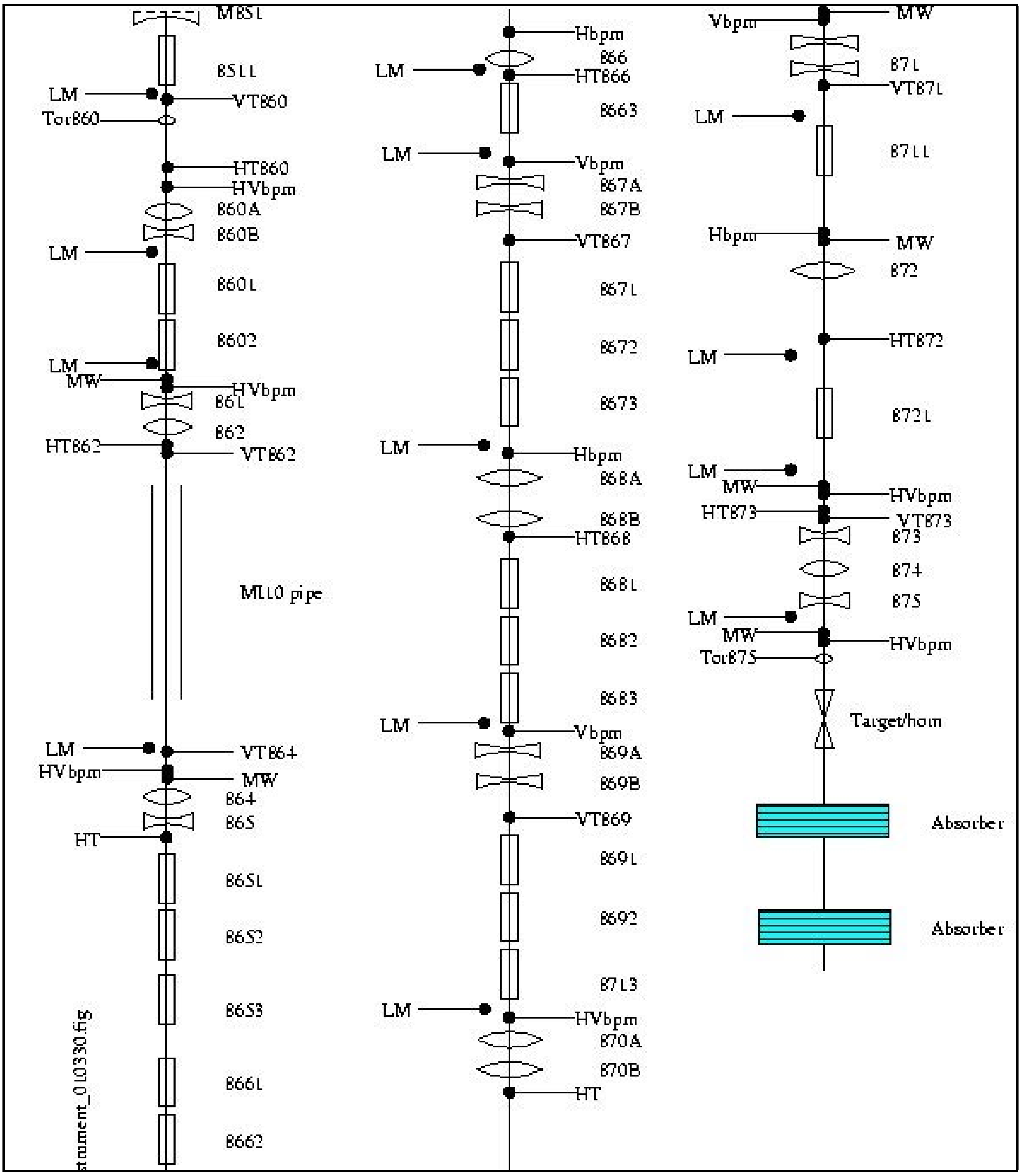

Figure 6. Schematic overview of the location of the beamline components.
LM - Loss Monitor, VT - Vertical Trim, HT - Horizontal Trim, MW - Multi-Wire
Tor - Toroid, bpm - beam position monitor.

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2.1.2 Target Hall

Located at the end of the Target Hall is the Target Pile (Figure 7). The Target Pile consists of approximately 160 steel “blue block” (1600 tons), 60 concrete shielding blocks (300 tons) and special custom sized steel (40 tons) above and below the horn module. When protons from the Booster hit the 71 cm beryllium target, short-lived hadrons are produced. The hadrons are focused by the magnetic fields generated from a high-current-carrying device called a "horn" (Figure 8). The target is located within the magnetic focusing horn. The target and the horn are located within the Target Pile, and the top of the Target Pile is covered with 24-foot (7.3 m) long shielding blocks.

Figure 7. The Horn enclosure inside the Target Pile.

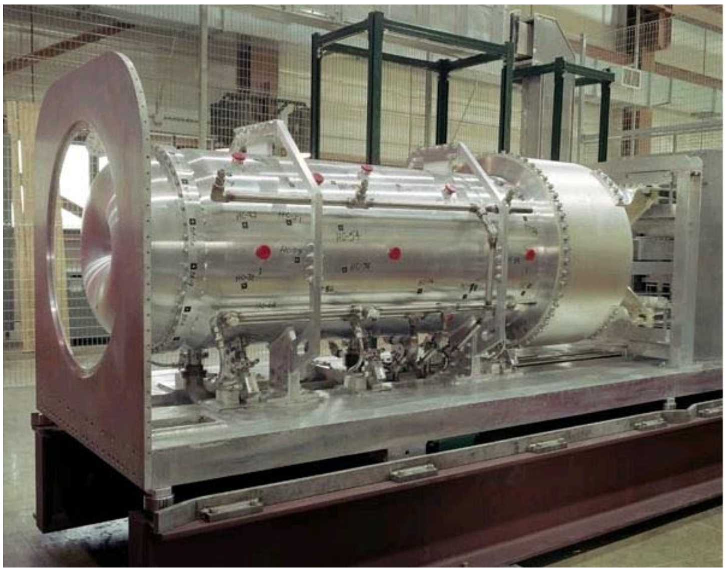

Figure 8. MiniBooNE Horn

Figure 9. The MiniBooNE Target Left: Side view. Right: Front. view

2.1.3 Decay Pipes and Absorbers

The secondary beam starts from the target (Figure 10). The beam consists of: 1) scattered and unscattered primary protons; 2) mesons produced from proton interactions in the beryllium target; 3) muons produced from decays and other interactions. These π-mesons (or pions) produced in the beam decay into neutrinos to be studied. The kaons and muons can also decay into neutrinos but these neutrinos are backgrounds and must be measured. The 25 m absorber changes these decay volume and thereby measuring a muon component. These kaons are measured with a portion of the beam at 122 milliradians (7º) and are ultimately detected in the Little Muon Counter (LMC). Knowing this angle and the location of the LMC is required to accurately measure this background. The proton beam is 100-150 mm wide at 50 m from the target. A beam absorber, which stops all the protons, mesons, and low-energy muons, is permanently located at the end of the decay pipe, 50 m from the target. An intermediate absorber, which can be lowered into the beam, is located 25 m from the target.

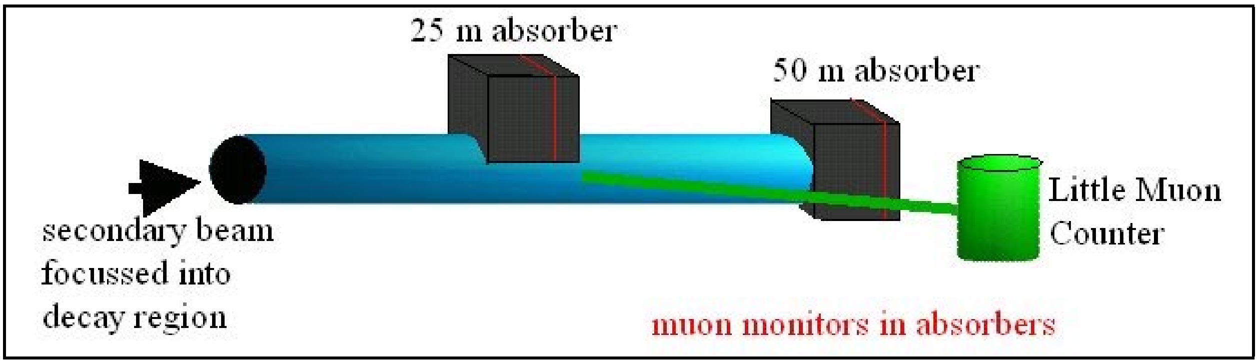

Figure 10. MiniBooNE Secondary Beam.

2.1.4 Little Muon Counters

The Little Muon Counter checks the kaon background. The LMC system consists of a muon drift pipe, which intersects the main decay pipe at a position 9 m upstream of the 50-meter absorber. The drift pipe is 8" in (20.3 cm) diameter filled with helium. The pipe is 55 ft (16.76 m) long and passes near the eastern edge of the 50 m absorber at an angle of 7º. The pipe terminates in a 14-foot (4.31 m) diameter steel vault (MI-13), which sits below the grade (Figure 10). A collimator and a range stack detector reside in this vault (Figure 11).

Figure 11. The complete collimator including the clamping bar.

2.2 The Detector

The MiniBooNE neutrino detector is a 40-ft (12.2 m) mineral oil Cherenkov detector buried so that its top is at grade level (Figure 12) [2]. The detector is a spherical tank made of carbon steel, filled with 250,000 gallons (807 tons) of ultra-pure mineral oil. A light-tight shield just inside the tank wall separates the detector into a spherical inner main region and an outer veto region. The main region is viewed by 1280 photomultiplier tubes (PMTs) and the veto region contains 240 photomultiplier tubes mounted in pairs on the tank wall. The detector is located 500 m north of the target, the neutrino source. The detector enclosure lies beneath 20 ft (6.096 m) of earth. The Detector Hall is built above the detector (Figures 12 and 13a).

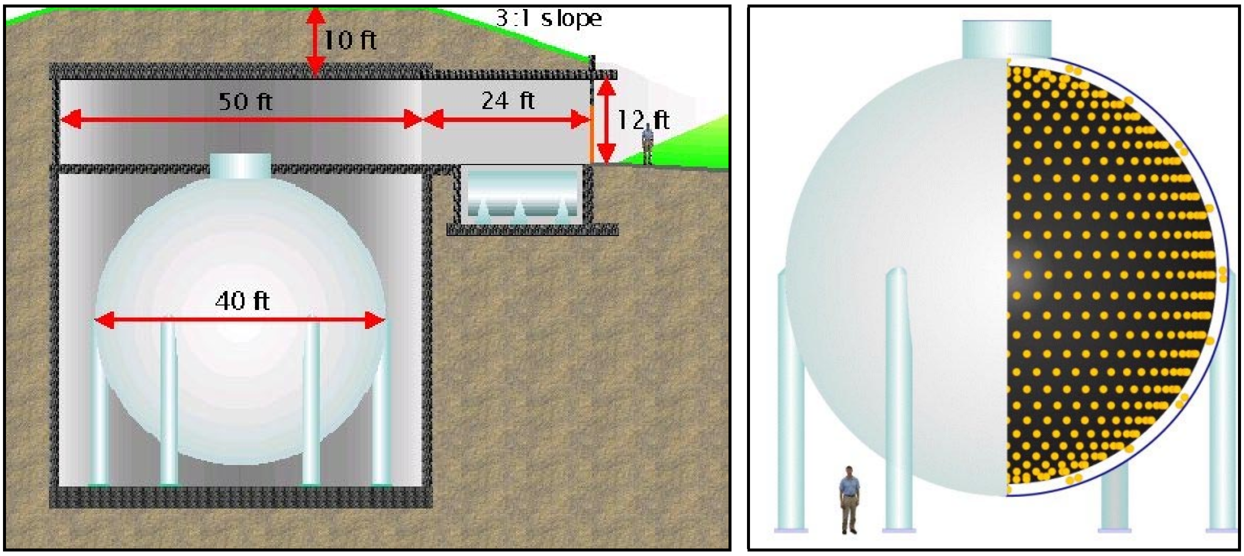

Figure 12. MiniBooNE Detector

The 1280 Photomultiplier tubes convert light into electrical signals; these signals are gathered and interpreted by MiniBooNE's data acquisition computers. The PMT sits on a 4x4x5 in attachment (Figure 13b). In addition to the PMTs, there are four Ludox-filled flasks attached to fiber optic cables [5].

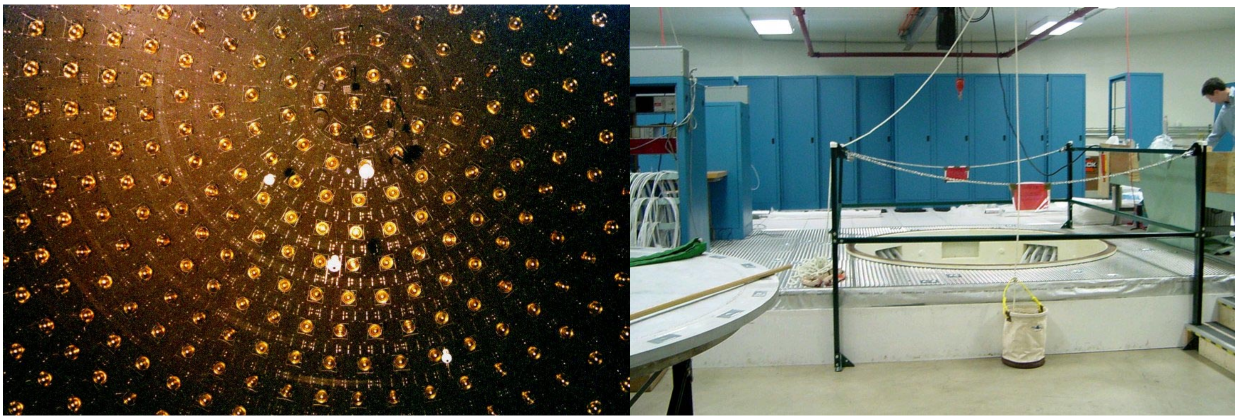

Figure 13a. Left: MiniBooNE Detector with hatch closed
Right: Detector Hall and hatch.

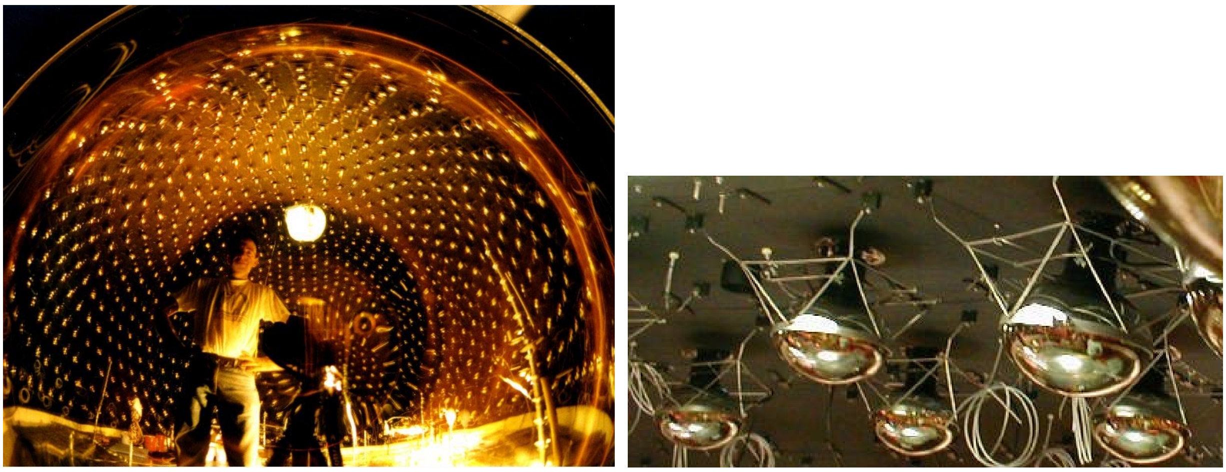

Figure 13b. Left : PMTs inside the MiniBooNE Detector with hatch opened.
Right : Close view of the PMT on the attachment.

3. SURVEY AND ALIGNMENT OF THE MINIBOONE EXPERIMENT

3.1 Survey and Alignment Methodology

In order to precisely align the MiniBooNE beamline components and survey the detector in the Fermilab site coordinate system, it was essential to first establish a geodetic surface control network. This was followed by establishing a secondary tunnel constraint network tied to the surface network. All components were then aligned or surveyed to these control points. The survey instrumentation used for the entire MiniBooNE experiment were as follows:

i) An electronic total station Geodimeter 600 device that makes three-dimensional measurements was used. Leica TCR307, an electronic total station that makes three-dimensional measurements without reflectors, was used for measuring unreachable points. Kern Mekometer ME5000 was used to measure distances and Gyromat 2000 Gyrotheodolite to measure normal section azimuths. Optical (Wild N3) and electronic (Leica NA3000) levels were used for elevations. Optical Tooling techniques were used for making offset measurements from the components to the control points.

ii) The SMX Laser Tracker and its associated software were used for establishing control points in the tunnel and for component alignments. 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).

iii) The V-Stars system was used for referencing is a portable non-contact, three-dimensional digital photogrammetric system. The system consists of one or two digital cameras and software. To measure an object, the camera(s) are used to photograph the object from various directions. The digital images are processed immediately by the software to provide three-dimensional coordinates and statistical information. The software is based on photogrammetric-bundle-triangulation methods.

3.2 Surface Control Network

The MiniBooNE experiment was constructed from the 8 GeV experiment, which is based in the Fermilab site coordinate system [3]. In order to connect the constructed coordinates to the existing system, a surface control network was establish around the MiniBooNE experiment area (Figure 14). The surface control network consisted of a geodetic control network tied to the existing control monuments. The control network consists of a total of ten survey concrete monuments on the surface and two floor points inside the Target Hall tunnel. Only the Target Hall portion of the experiment was accessible to the surface during the network survey. The ten concrete monuments include five existing monuments with known coordinates.

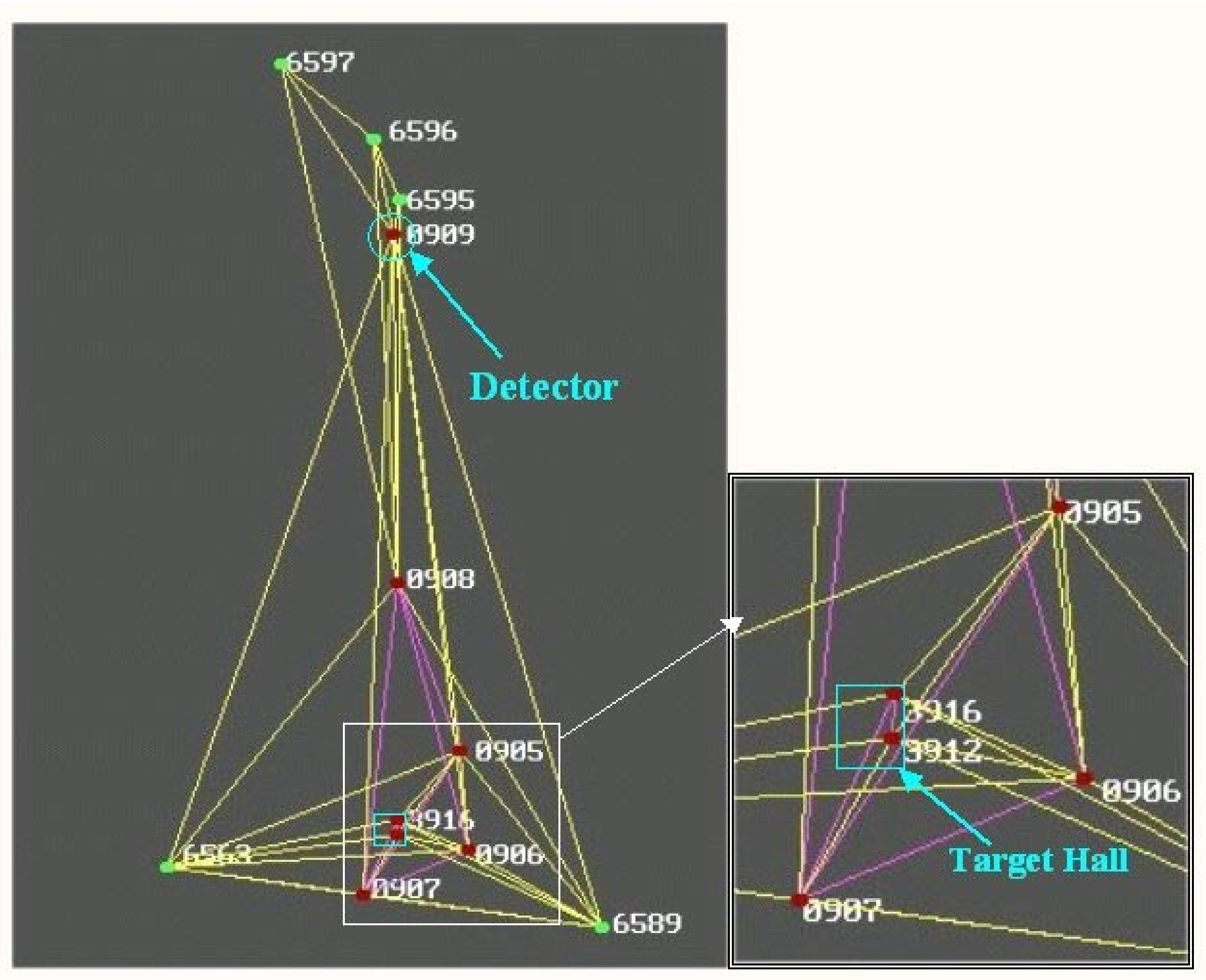

Figure 14. Surface Control Network

The surface control network consisted of both horizontal and vertical networks. The surface horizontal network was performed using the Trimble 4000 SSE GPS receivers and Kern Mekometer ME5000 to measure all distances. A combined GPS and terrestrial network adjustment was done in the performed. Figure 15 shows the graphical representation of the resulting absolute error ellipses at the 95% confidence level which, were in the ±2 mm range. The vertical control network was measured using the Leica NA3000 level instrument.

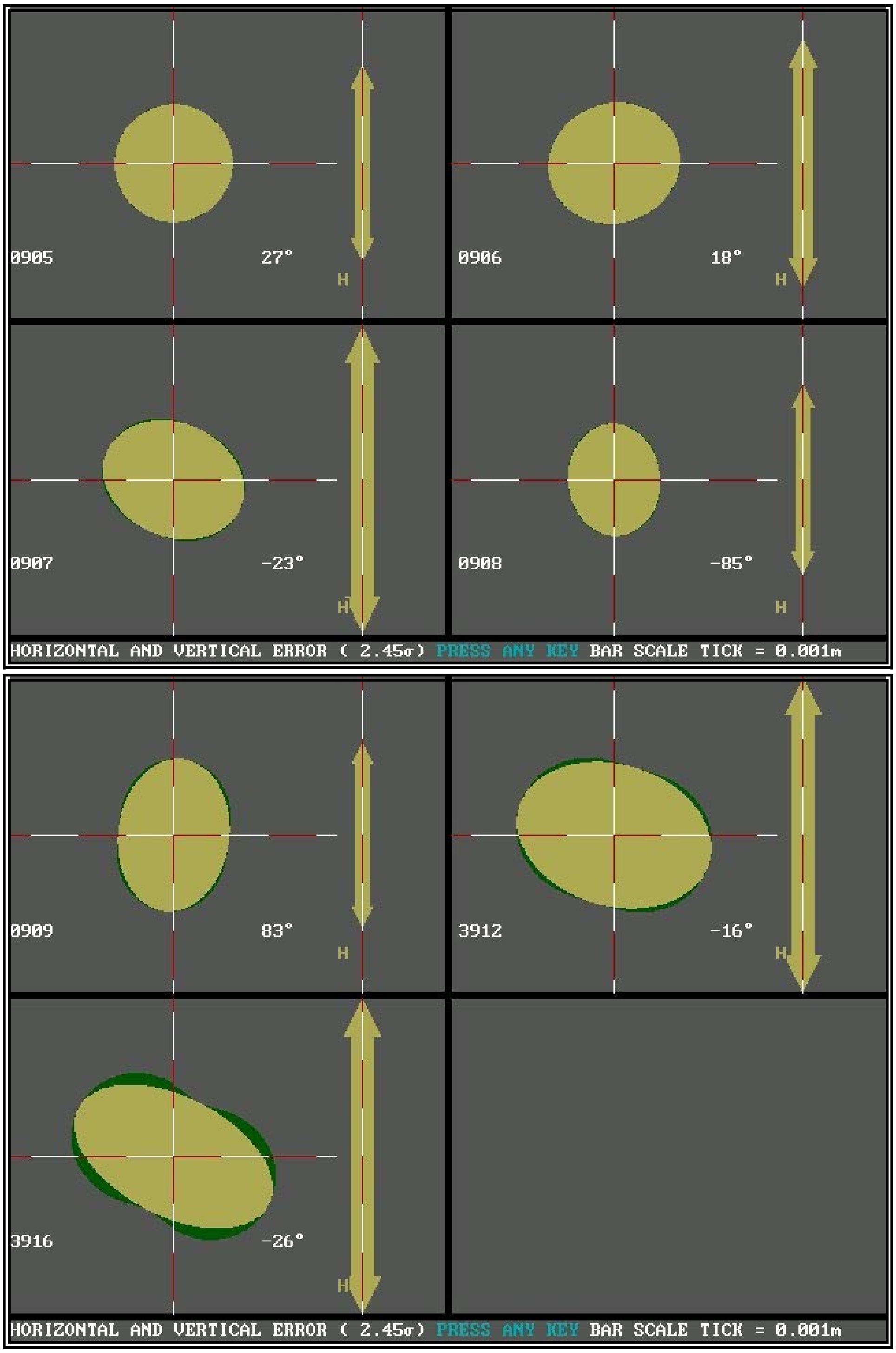

Figure 15. Surface Control Network Error Ellipses (95%)

3.3 Tunnel Control Network

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

3.3.1 Beamline Control Network

The Beamline tunnel control network consisted of a secondary tunnel constraint network, which was established to include the two points from the surface control network (Figure 16). The network contains a total of 22 floor monuments, 14 wall monuments and 22 tie rods from the 8 GeV Beam Enclosure to the Target Hall. A dead bolt with a 0.250-in (6 mm) hole was used for the floor monuments (Figure 17a). The dead bolt is a modified ¾x 10 in (1.9 x 25.4 cm) stainless steel hex head bolt, machined to provide a high accuracy, repeatable point of monumentation. It is used as a sub-surface, corrosion resistant, low cost, horizontal and vertical monument that is easily installed.

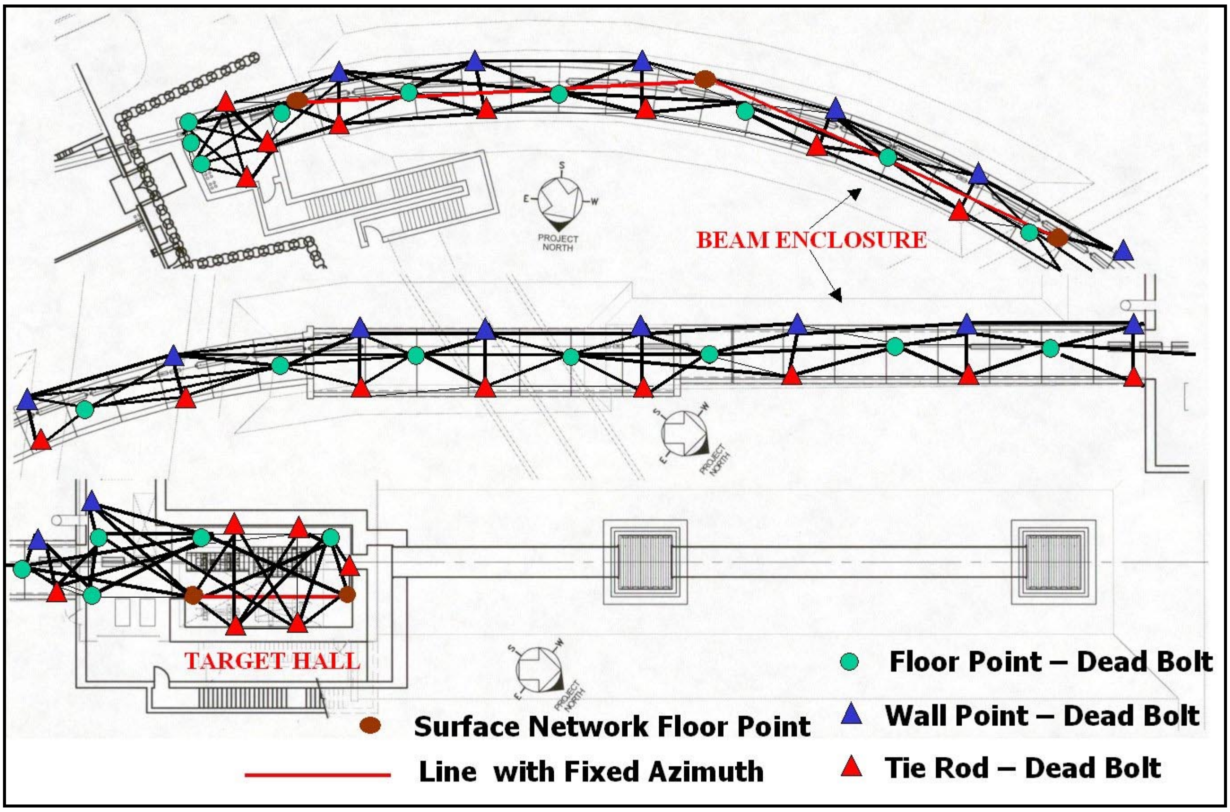

Figure 16. Beamline Tunnel Control Network

The 0.250-in hole provides a receptacle for Laser Tracker and optical tooling fixtures (Figures 17b and 18b). Figure 18a shows a tie-rod used for vertical monumentation and the fixture used on the tie-rod for measurements. Three brass points that were installed while the tunnel was under construction, were also included as part of the network. The brass point is a flat flushed brass surface with a very small punched hole in the middle (Figure 19a). A floor centering plate is used to set over a brass point (Figure 19b); a pin nest and a target fixture sit on the floor plate.

The entire horizontal tunnel control network was measured with the Laser Tracker, Kern Mekometer ME5000, Gyromat 2000 Gyrotheodolite, and Kern E2 theodolites. As a check Gyro azimuths were measured between the two points in the Target Hall that were part of the surface control network. Gyro azimuths between the three brass points in the curved section of the tunnel (Figure 16) were also measured. These azimuths were held fixed in the network adjustment. Figure 20 shows the resulting standardized observation residuals for the tunnel network. Figure 21 shows the resulting absolute error ellipses at the 95% confidence level, which were below ±0.30 mm. The vertical control network was measured four times using the Leica NA3000 level instrument. The first vertical control network measurements were made when the Target Hall and the Beam Enclosure were empty. The other three vertical network measurements were made after all the components had been installed in the Beam Enclosure and the Target Pile installed in the Target Hall. The vertical network consisted of a level run from two existing surface survey monuments through the stairs, the tunnel monuments and back to the surface monuments. Figures 22 through 24 show the elevation differences between the four vertical network measurements for the tie rods, floor points and the wall points respectively.

3.3.2 Detector Control Network

The Detector Control Network was established in the Detector Hall. The horizontal network consisted of six brass monuments on the floor and three K+E targets on the ceiling directly above the spherical tank. Inside of the tank, only the K+E targets were visible from the bottom of the tank. A Geodimeter traverse was performed to connect all the brass monuments and the K+E targets to the surface control network monuments. The vertical network consisted of a level run from two existing surface survey monuments to a tie rod inside the Detector Hall, and then through a vertical drop of about 462 in (12.5 m) to another tie rod on the cylindrical wall outside of the spherical tank. A temporary benchmark was established under the bottom hatch of the tank and elevations of all the points inside tank were tied to this benchmark through the tie rod elevation.

Figure 17a. Exposed Dead Bolt.

Figure 17b. Dead Bolt with Nest and SMR

Figure 18a. Nest, Adapter and SMR on Tie Rod

Figure 18b. Stick-Mic Adapter and Nest on Dead Bolt

Figure 19a. Brass Control Point.

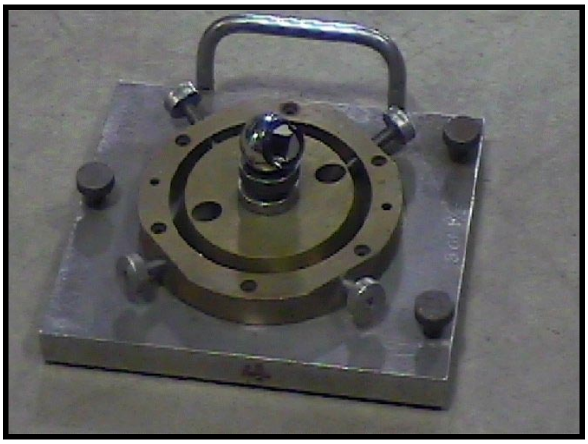

Figure 19b. Centering Plate with Nest and SMR over brass

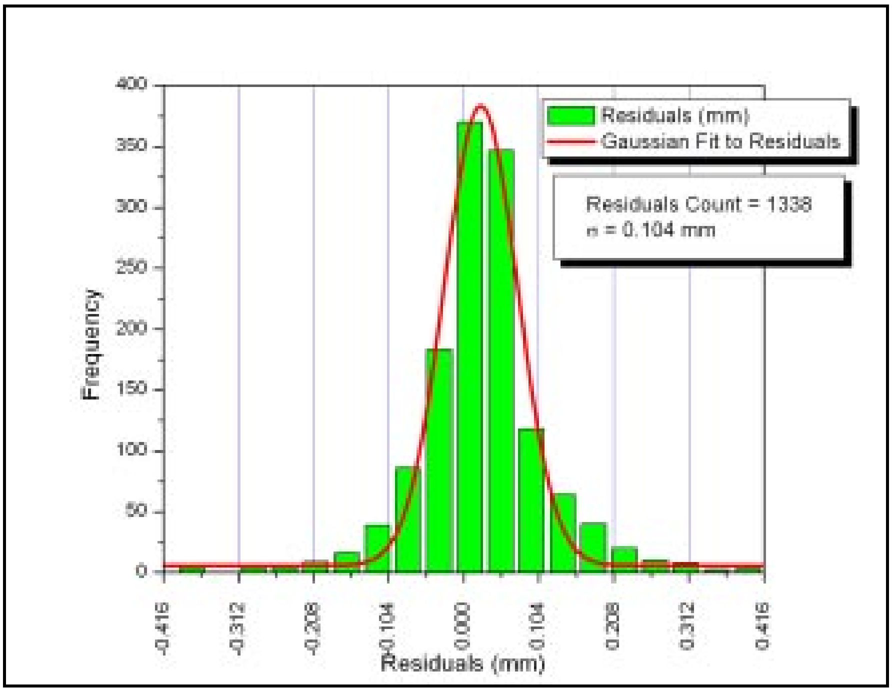

Figure 20. Tunnel Control Network. Histogram of standardized observation residuals.

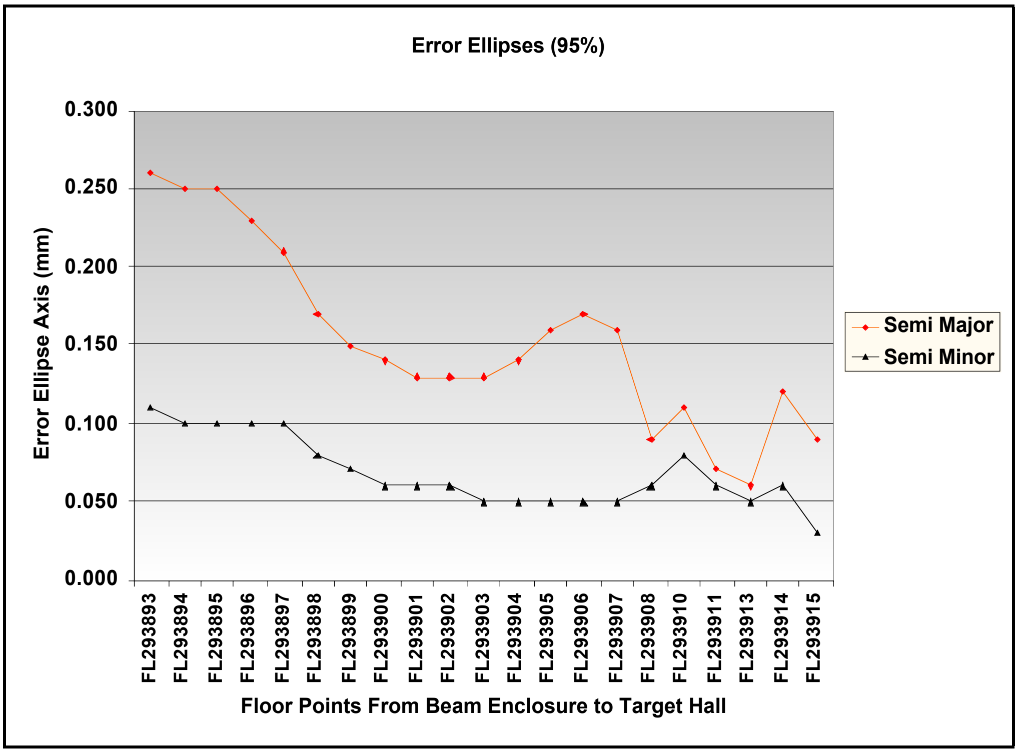

Figure 21. Tunnel Control Network: Floor Points Error Ellipses (95%).

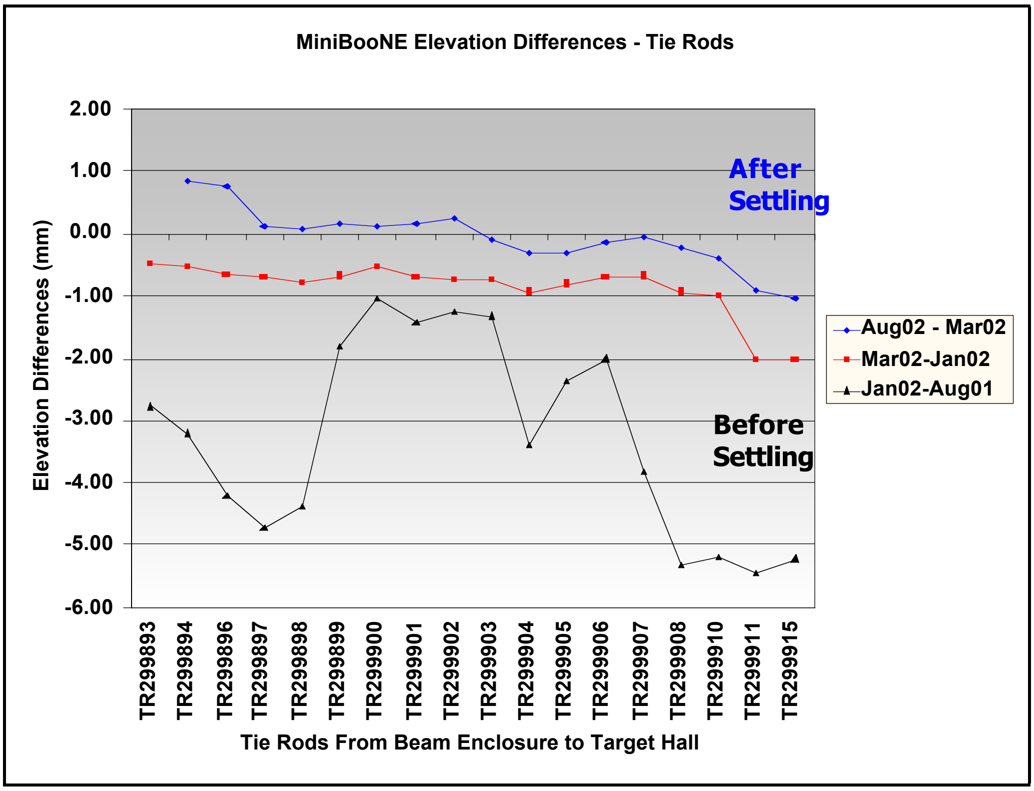

Figure 22. Tunnel Control Network Tie Rods Elevation Differences

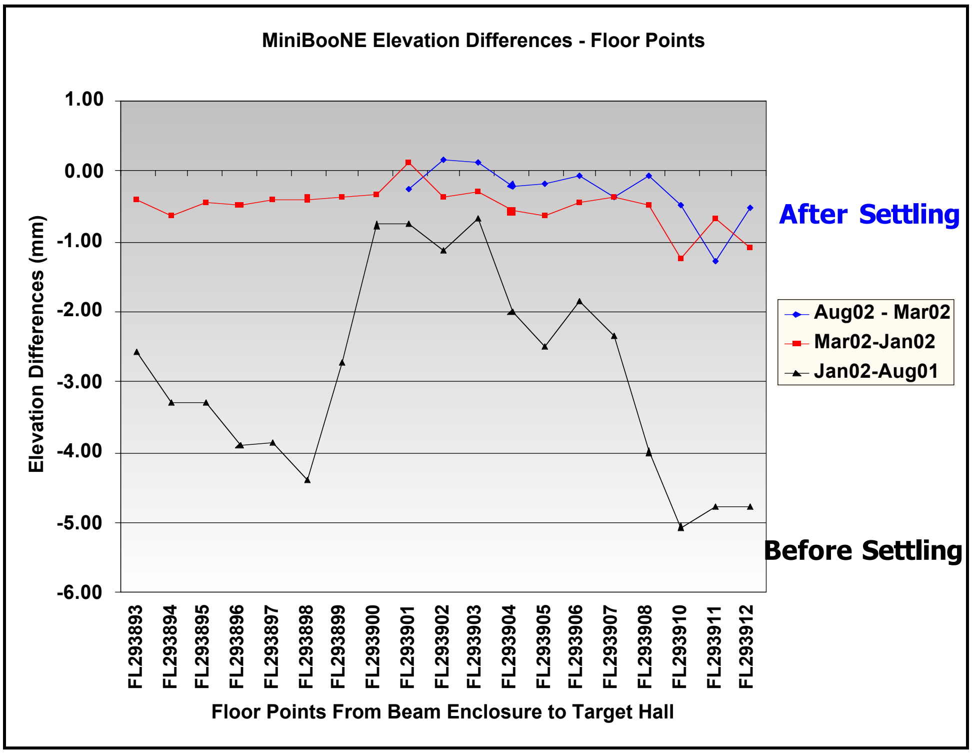

Figure 23. Tunnel Control Network Floor Points Elevation Differences

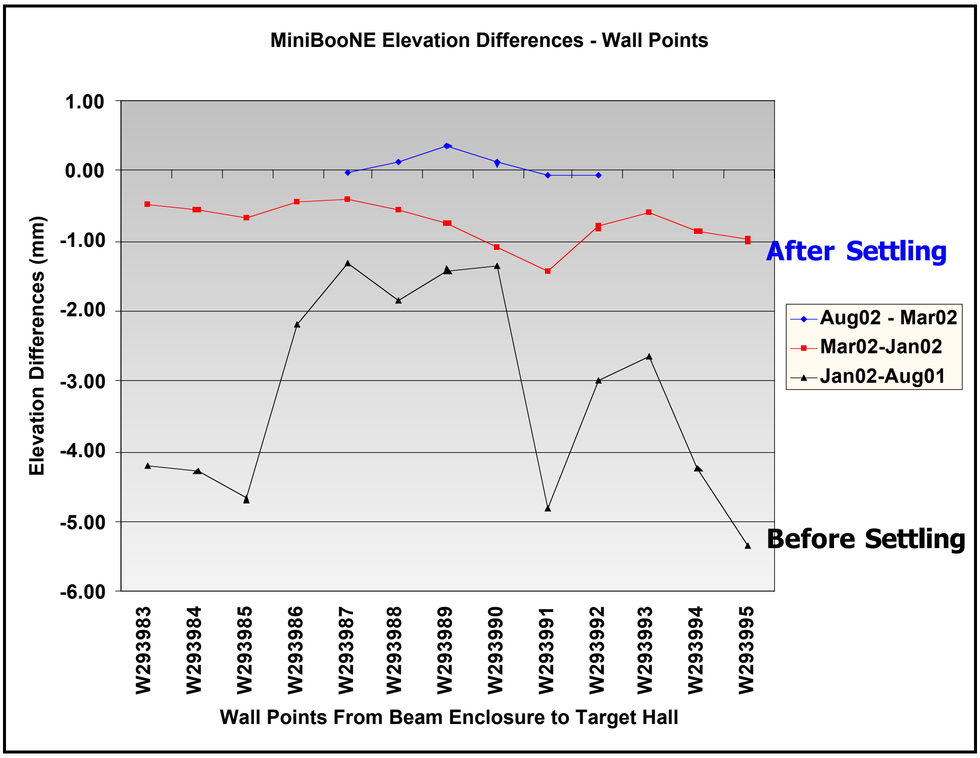

Figure 24. Tunnel Control Network Wall Points Elevation Differences

3.4 Beamline Alignment

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

Table 1. Alignment Tolerances

Magnet type	Horizontal	Vertical	Beam Direction
Quadrupoles	±0.25 mm	±0.25 mm	±1.00 mm
Dipoles	±1.00 mm	±0.25 mm	±1.00 mm
Beam Position Monitors	±1.00mm	±1.00 mm	±1.00 mm
Multi-Wires	±0.25 mm	±0.25 mm	±1.00 mm
LEP Trims	±5.00 mm	±1.00 mm	±5.00 mm
Other Instrumentations	±1.00 mm	±1.00 mm	±1.00 mm

3.4.1 Component Fiducialization and Referencing

The goal of the component fiducialization is to relate all its physical or magnetic measurements and the physical or magnetic center to the survey fiducials mounted on the component. Several survey fiducial points are mounted at the corners of each component. At the center of each fiducial is a 0.250 in. 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, y is positive downstream, x is positive right and perpendicular to y, and z is positive up. The components 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, H coordinates for entrance and exit points for all components were supplied to the Alignment and Metrology group in the beam lattice coordinate system. A software was written to compute the fiducial coordinates in the beam lattice coordinate system.

3.4.2 Beamline Component Alignment

The beamline component alignments started in the MI-10 stub with the quadrupole Q851 on the 8 GeV beam line.

3.4.2.1 Pre-Alignment

Prior to any alignment, the magnet stands and all the components were installed. Using the beam lattice, the entrance and the exit coordinates of all dipole and quadrupole magnets, and BPMs were marked on the floor to within 3 mm. The positions of the magnet stands were also marked on the wall. The magnet stands were installed as marked on the wall. The magnets were then placed at the beam height on the stands as marked on the floor. 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 top of all the dipole and the quadrupole magnets in the Beam Enclosure. These offsets were then used to place the component along the beamline in the Beam Enclosure and the Target Hall.

3.4.2.2 Final Alignment

The Laser Tracker, SMX Tracker 4500 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 near components 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 four fiducials at the top of the dipole and the quadrupole magnets. 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. The Laser Tracker was also used to survey the BPMs. All other components were final aligned to the beam lattice using the optical tooling techniques.

3.4.3 The Horn and Target Survey

The MiniBooNE horn and target were both referenced and surveyed in MI-8 service building. The referencing for the horn and the target rail was done using the V-Stars system. Optical tooling techniques were then used to reference the 71 cm beryllium target to the target rail and the horn. This survey was repeated several times with the target outside the horn, since the target could only be inserted once. Once the referencing was completed, the target was insert into the horn. The horn and the target were boxed up in a horn coffin, which was then transferred to the Target hall where it was placed in the beamline inside the Target Pile using the optical tooling techniques.

3.4.4 Decay Pipes and Absorber Surveys

The decay pipes and the 20 m and 50 m absorbers were all surveyed before being buried and covered with dirt. The shielding blocks around the absorber were also surveyed. All the pipes were measure with the Geodimeter total station. The centers and the straightness of the pipes were computed and compared to the ideal values. The horizontal and vertical tolerances are ±3.0 mm.

3.4.5 LMC Survey

Four pedestals with 0.250-in holes were welded to the cylindrical wall of the vault in MI-13 and one pedestal on the floor. A Geodimeter traverse was run from the outside surface control network to the pedestal on the floor. Gyro azimuths were measured from a point located at about the center of the vault on the floor to all the five pedestals. Azimuth measurements were also made to the top and bottom locations of the downstream and upstream flanges attached to the ends of the 8" pipe. The average of the top and bottom locations azimuths yielded the centerline azimuth of the 9-meter pipe. Horizontal coordinates were obtained for all five pedestals and the center of the upstream and downstream flanges. The vertical information consisted of a level run from existing surface survey monuments and an elevation drop of about 250 in to the floor pedestal. The pipe had earlier been surveyed for straightness. The collimator and a range stack detector that reside in the vault would be surveyed later when the installation is completed by the winter of 2003. The horizontal and vertical tolerances are ±3.0 mm and ±1.0 mm for the collimator.

3.5 Detector Survey

The detector spherical tank was surveyed several times while being constructed. After construction of the tank, a final survey was performed using the TCR307 total station. Inside the tank were series of points called veto-bosses or main-bosses that would hold the PMTs. The instrument was set at the bottom of the tank and measurements were made to all the veto-bosses or main-bosses around the sphere. With the top hatch of the tank opened, measurements were made to the K+E targets on the ceiling of the Detector Hall. A sphere fit was performed to transform the resulting coordinates into a local spherical coordinate system with the origin at the center of the sphere. A Geodimeter total station was setup near the open hatch outside the tank in the Detector Hall and measurements were made to all visible veto-bosses inside the spherical tank and to the brass monuments and K+E targets in the Detector Hall. Through a series of seven-parameter transformations all the points inside the spherical tank were obtained in the Fermi site coordinate system. The horizontal and vertical tolerances are ±3.0 mm.

3.5.1 PMT Survey

After the PMTs were installed inside the tank, it was required to relate the center of the PMTs to the previous survey of the detector spherical tank. With the instrument set at the bottom of the tank, measurements were made to the lower left corner of each of the attachment holding the PMTs using the TCR307 total station. With the top hatch of the tank opened, observations were made to the K+E targets on the ceiling of the Detector Hall. A sphere fit was then performed to transform the resulting coordinates into a local spherical coordinate system with the origin at the center of the sphere. Radial and vertical corrections were applied to the data to go from the left corner of the attachment to the center of the PMT. Through a series of seven-parameter transformations all the coordinates of the PMTs inside the spherical tank were obtained in the LTCS coordinate system. In addition to the PMTs, four Ludox-filled flasks attached to fiber optic cables were also surveyed.

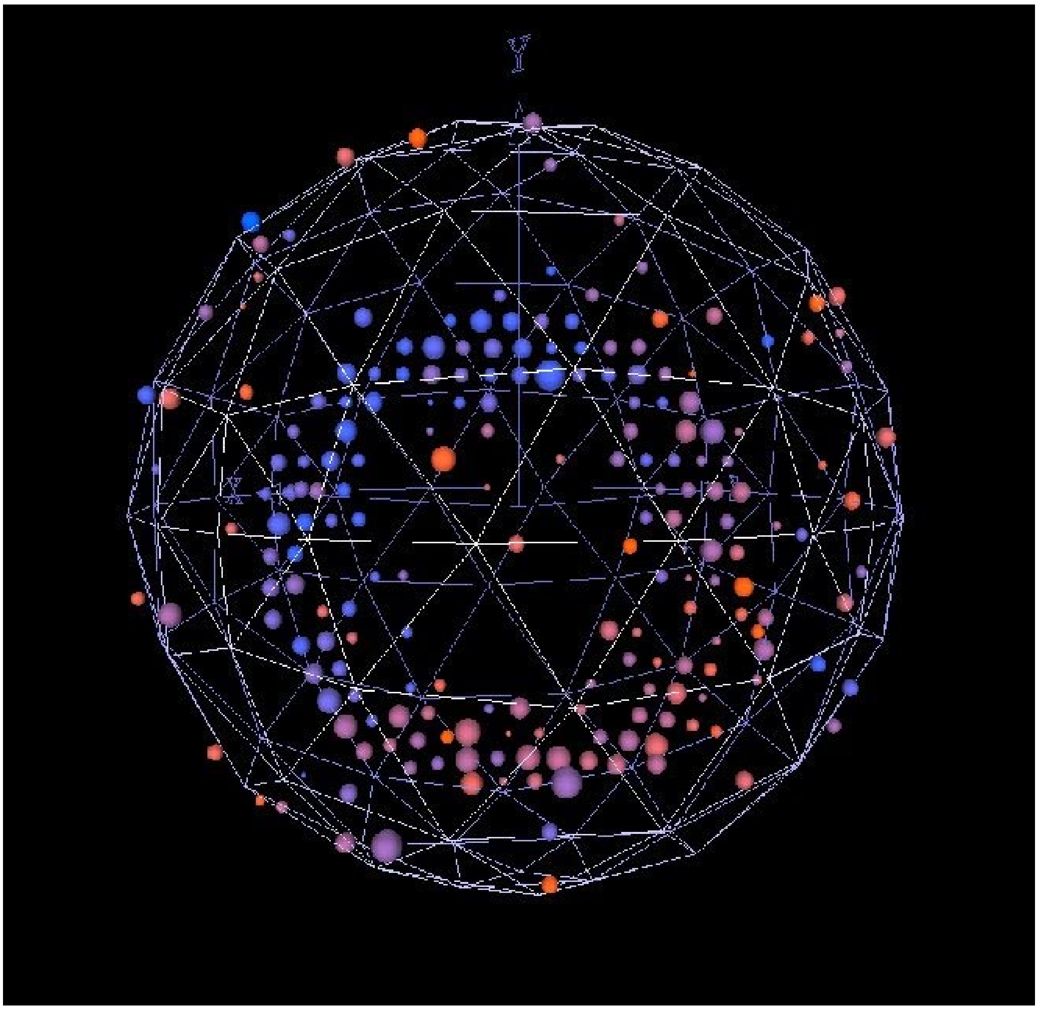

Figure 25. MiniBooNE Event.

4. CURRENT STATUS OF THE MINIBOONE EXPERIMENT

MiniBooNE is currently collecting data and is processing huge amount of beam with intensity greater than the entire Fermilab has ever produced. It is transporting huge amount of beam through the beam pipe without loss. Figure 25 shows an event display of the muon signature from a candidate muon neutrino interaction in the detector. Each dot represents a hit PMT with the size proportional to the charge collected, which is also proportional to the energy deposited. By analyzing the patterns of energy deposits, the experimenter reconstructs the original event. Knowing the location of each PMT is required to successfully reconstruct the event. With two years of running MiniBooNE should be able to completely confirm or rule out the entire LSND signal region. If a signal is confirmed, miniboone will be upgraded to the BooNE with a second detector.

5. CONCLUSION

The MiniBooNE experiment, which consists of a Neutrino Beam and a Detector, has been survey and aligned and the results have been presented. The alignment methodology used has also been presented. Fermilab began collecting neutrino event data in August 2002.

6. ACKNOWLEDGMENT

I would like to thank the Alignment and Metrology Group members, who participated in the MiniBooNE experiment. A special thanks goes to my colleagues, Dr. Virgil Bocean and Mr. Gary Coppola for their help with the experiment. Special thanks also to Dr. Robert Bernstein, the group leader, for his valuable suggestions and for proof reading this paper.

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