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SURVEY AND ALIGNMENT OF THE FERMILAB MUCOOL TEST AREA BEAM LINE

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ABSTRACT

The Fermilab MuCool Test Area (MTA) is designed to develop and test muon ionization cooling components using the intense Fermilab Linac beam. The MTA beam line is designed to transport negative hydrogen (H^-) or proton beam from the end of the Fermilab 400 MeV Linac to the MTA. The installation of the MTA beam line was completed in fall of 2007. This paper discusses the installation, survey and alignment of the MTA beam line.

INTRODUCTION

MuCool Test Area (MTA) is a building complex used for the development and testing of muon ionization cooling components using the intense Fermilab Linac beam [1]. MTA facility is part of the Muon Collider and Neutrino Factory R&D program that is used to test the RF cavities and liquid-hydrogen absorbers needed for a muon cooling channel. The 25-liter liquid hydrogen (LH2) absorber is embedded in a 5 Tesla superconducting solenoid magnet. The MTA solenoid magnet is used with RF cavities exposed to a high intensity beam. To cool muon beams in the transverse direction, an alternating series of liquid-hydrogen absorbers and RF cavities are used. The absorbers reduce the momenta of beam particles in both transverse and longitudinal directions, while the cavities re-accelerate the muons in the longitudinal direction.

The MTA facility is located southwest of the Fermilab Linac. It consists of an experimental hall and a service building (Figure 1). The MTA experimental hall and Linac tunnel are separated by a 50 m (164 ft) long connecting (Linac-to-MTA) enclosure (Figure 2). The Linac-to-MTA tunnel enclosure houses the MTA beam line. The MTA experimental hall is shielded and separated from the Linac by a 3.66 m (12 ft) long concrete block. The beam line penetrates through the shielding block to the hall. The penetration has an inside diameter of 22.23 cm (8.75 in). Figure 3 shows the aerial view of the Linac, MTA experimental hall and the Linac-to-MTA proton beam line.

The Fermilab Alignment and Metrology Group (AMG) supported the installation and alignment of the MTA beam line. The installation of all components of the MTA beam line started in August of 2007. The installation along with the survey and alignment of the system were completed in October 2007.

(a)

(b)

Figure 1. (a) View of the MTA at the south end of the Fermilab Linac (b) View of the MTA from Wilson Hall

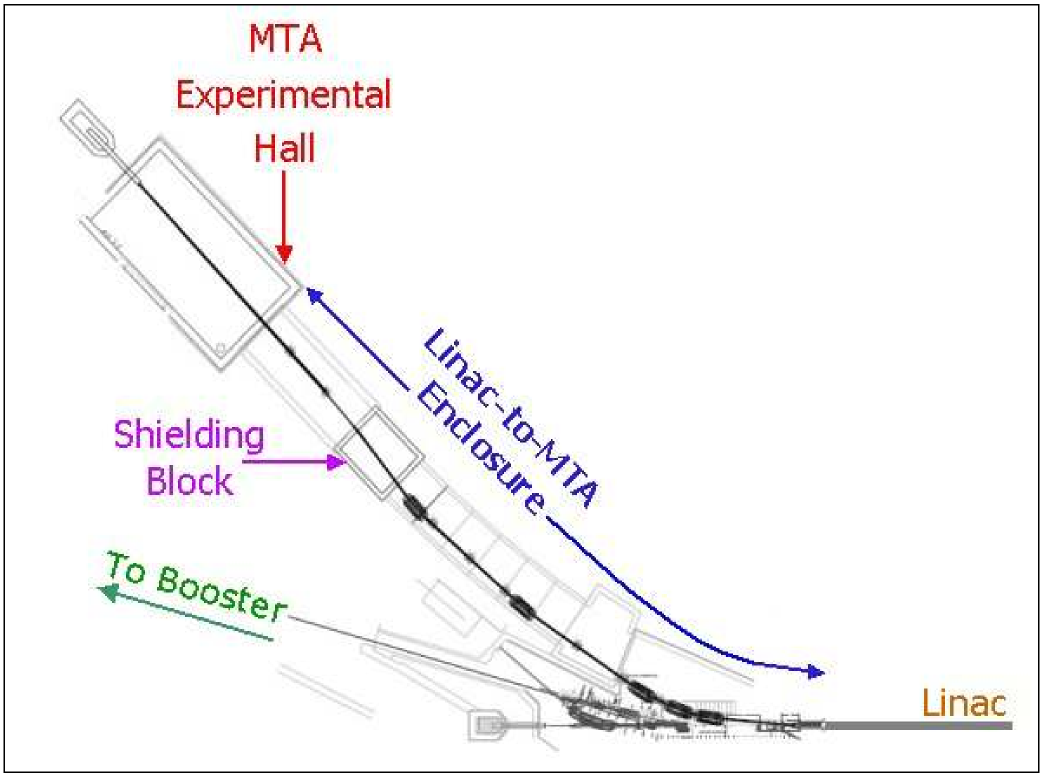

Figure 2. Linac-to-MTA enclosure

Figure 3. Aerial view of MTA and Linac

MUCOOL TEST AREA BEAM LINE

The MTA beam line is a simple beam line to transport negative hydrogen (H^-) or proton beam from the end of the Fermilab Linac to the MTA [2]. Fermilab Linac is a H^- ion, 400 MeV accelerator which currently provides beam for the Booster operation. The Linac accelerates hydrogen ions to 400 MeV protons (+charge) with two electrons (-charge) attached. The two electrons in the H^- ion are stripped off with a thin carbon foil and the remaining protons are injected into the Booster and eventually the MTA beam line. Until the thin carbon foil is installed in the MTA beam line, only H^- beam will be transported.

The new MTA beam line consists of a 15 Hz pulsed-magnetic extraction system, which diverts an entire Linac macropulse into the new beam line [3]. The beam is directed toward the MTA using two pulsed dipole magnets (C-magnets) with the first located after the last Linac accelerating module and just after Q74 quadrupole, and the second just downstream of the Chopper. At 400 MeV, this pair of magnets will produce a horizontal bend of 10.5 degrees (Figure 4).

The MTA beam line design is based on using existing dipoles, quadrupoles and other equipment available at Fermilab from previous projects. There are a total of 62 beam line components in the MTA beam lattice. The MTA beam line consists of the starting quadrupole Linac Q74, 2 C-magnets, 5 cooling ring dipoles, 4 SQA quadrupoles, 8 TQTB quadrupoles, 4 trim magnets, and 4 Booster correctors. The beam line instrumentation consists of 10 dual plane beam position monitors (BPM), 7 multiwires (beam profile monitors), 3 beam current monitors and 12 beam loss monitors [4]. There are also 2 beam stops upstream and downstream of the shielding blocks. Figure 5 shows the layout of the MTA beam line identifying the main components.

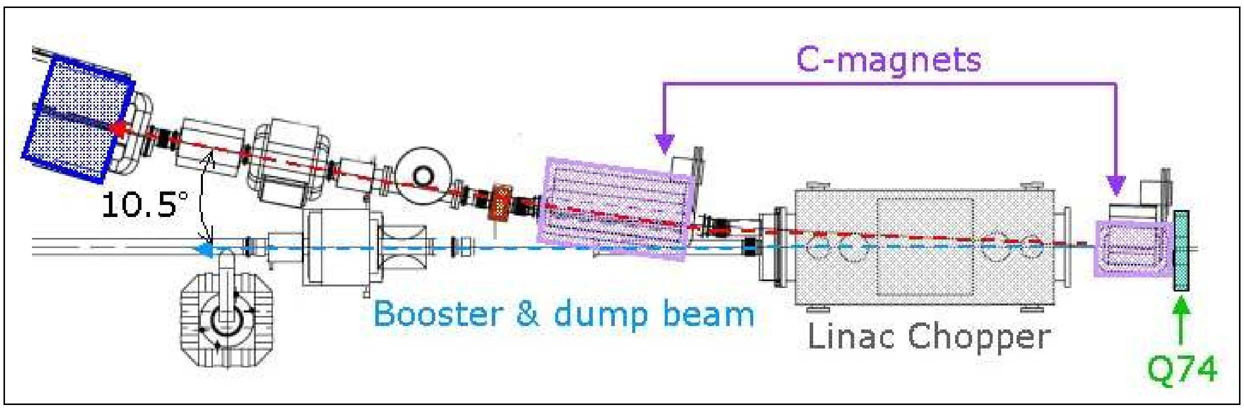

Figure 4. Extraction point to MTA Beam Line

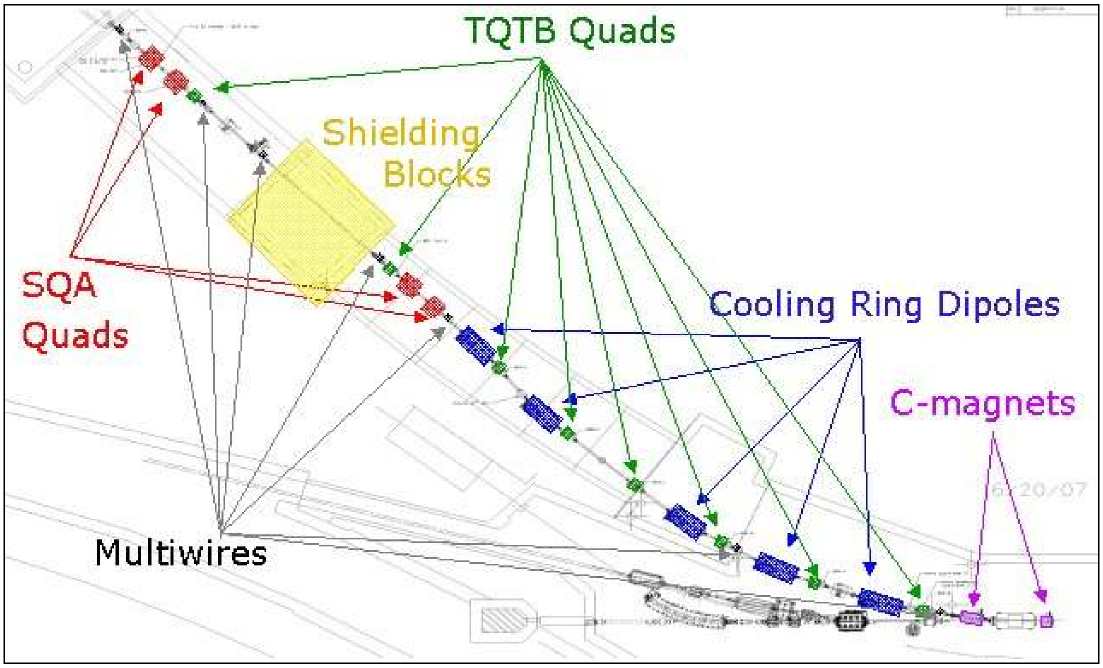

Figure 5. Layout of the MTA Beam Line

SURVEY AND ALIGNMENT OF THE MTA BEAM LINE

Survey and Alignment Methodology

The MTA beam line network was constructed starting from the existing Linac accelerator. The Linac accelerator network of 1993 was based on the Fermilab Site Coordinate System (FTCS:XYZ) [5]. In order to precisely align the MTA beam line components in the FSCS system, a secondary tunnel constraint network was established in August 2007 and tied to the existing 1993 Linac accelerator network. All components were aligned and surveyed to these control points. The survey instrumentation used for the entire MTA beam line was as follows:

i) An electronic total station Geodimeter 600 device that makes three-dimensional measurements was used to stake-out component locations for stand installation. A DMT Gyromat Gyrotheodolite was used to measure normal section azimuths. An electronic level (Leica NA3003) was used for elevations.

ii) An API Laser Tracker and Spatial Analyzer™ software were used for establishing control points in the tunnel and for component alignment.

MTA Tunnel Control Network

A 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. A control network was established to bring horizontal and vertical controls into the MTA experimental hall, the Linac-to-MTA enclosure, and part of the Linac enclosure. The 3.66 m (12 ft) long shielding block that separated the MTA from Linac was removed before the installation of the MTA beam line and the network measurements. The MTA network consisted of a total of 25 floor monuments, 34 wall monuments, 12 tie rods, 32 pass points and 6 brass points in the Linac enclosure.

The MTA horizontal network was tied to the existing Linac network through a series of Laser tracker networks that took place over a period of six months. As a check, gyro-azimuths were measured between the three points in the Linac and Linac-to-MTA enclosures. Figure 6 shows the resulting standardized observation residuals for the tunnel network. These results show that the network was very good. The vertical control network started by running level elevations from the surface outside monuments, then dropped down to the MTA experimental hall and ended at the Linac. Elevations were measured with the Leica NA3003 level instrument.

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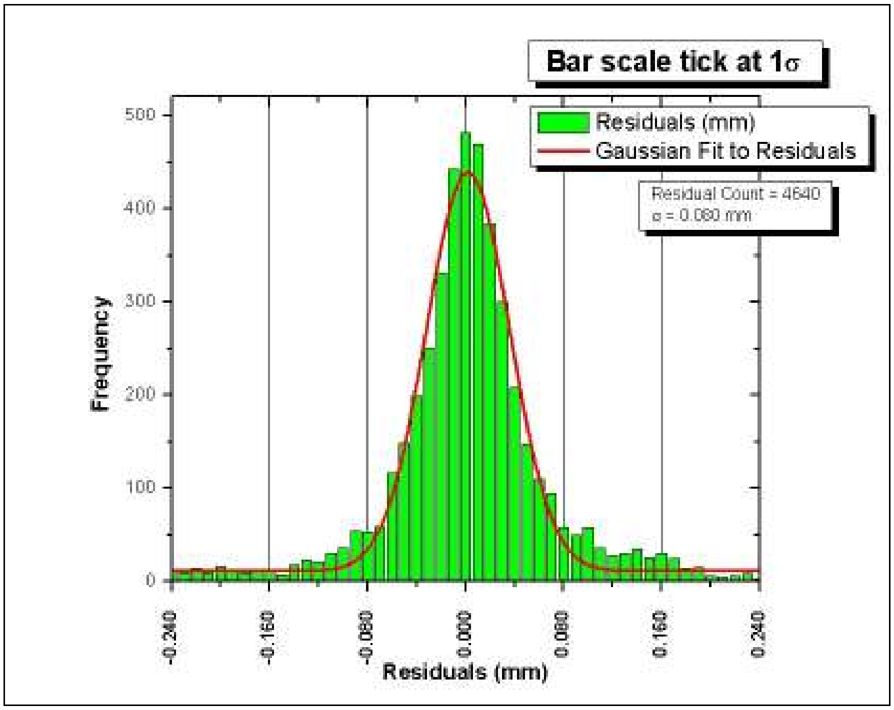

Figure 6. MTA Control Network: Histogram of Standardized Observation Residuals.

Alignment Tolerances

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

Component Fiducialization

Several survey fiducials are mounted at suitable locations on each component (Figures 7 and 8). The fiducial is 3.18 cm (1.25 in) diameter and 1.27 cm (0.5 in) thick stainless steel lug (called Shegjak lug) with a magnet in the center to hold a 3.81 cm (1.5 in) diameter Laser Tracker SMR (spherically mounted retroreflector). The location of each fiducial is defined by the center of the SMR as it precisely sits on the fiducial (Figure 7a).

Component Referencing

Each component was referenced in a local orthogonal coordinate system defined such that its origin was at the physical center, y is positive downstream, x is positive right and perpendicular to y, and z is positive up. The fiducialized cooling ring dipoles and all quadrupoles were referenced using the Laser tracker at different locations prior to installation in the beam line. Component referencing was done to better than ±0.15 mm.

Table 1. Alignment Tolerances

Magnet Type	Horizontal	Vertical	Beam Direction
Cooling Ring Dipoles	±0.25 mm	±0.25 mm	±0.50mm
C-Magnets	±0.25 mm	±0.25 mm	±0.50mm
Quadrupoles	±0.25mm	±0.25mm	±0.50mm
Trim Magnets	±0.50mm	±0.50mm	±1.00 mm
Multi-Wires	±0.50mm	±0.50mm	±1.00 mm
Instrumentation	±0.50mm	±0.50mm	±1.00 mm

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(a) (b)

Figure 7. (a) Cooling Ring Dipole with SMR sitting on Fiducial

(b) Fiducial (Shegjak Lug) on Cooling Ring Dipole

(a) (b) (c)

Figure 8. (a) C-magnet with Fiducial

(b) SQA Quadrupoles with Fiducial

(c) TQTB Quadrupoles with Fiducial

Reference Method 1: Cooling Ring Dipoles, C-Magnets and SQA Quadrupoles

Given no dimensions of component, the reference procedure is as follows: Six planes are created from Laser Tracker measurements made on six sides of the component – upstream (ABCD), downstream (JKLM), top (ADMJ), bottom (BCLK), beam left (DCML), and beam right (ABJK) planes (Figure 10). Using all possible combinations of three planes, a three-plane intersection is used to determine all corners of the rectangular component – ABCD on the upstream side and JKLM on the downstream side. The midpoints between the corner points are then computed – PQRS on the upstream side and TUVW on the downstream side. The next step is to construct a vertical plane through the midpoints SQUW at z = 0 and a horizontal plane through the midpoints RPTV at x = 0. An orthogonal frame is constructed such that the primary axis (+y) is defined by a line (Y_{USDS}) constructed from the intersection of the vertical plane SQUW and horizontal plane RPTV positive downstream. The secondary axis (+z) is defined by the normal vector from the vertical plane SQUW positive up. The +x-axis is perpendicular to the +y axis.

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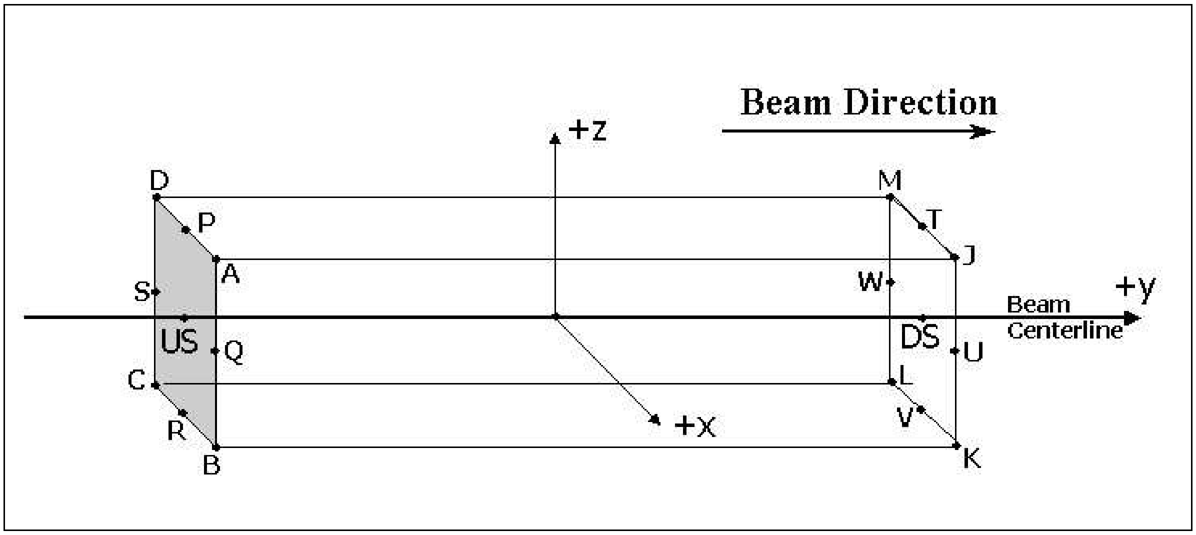

Figure 10. Reference Method 1

The upstream entrance point [x_{US} , y_{US} , z_{US}] of the component is determined by the intersection of the upstream ABCD plane and the constructed line Y_{USDS}. The downstream exist point [x_{DN} , y_{DN} , z_{DN}] is determined by the intersection of the downstream JKLM plane and the constructed line Y_{USDS}. The origin of the frame is determined as follows:

$$\begin{pmatrix} x_{ORIGIN} \\ y_{ORIGIN} \\ z_{ORIGIN} \end{pmatrix} = \begin{pmatrix} x_{US} \\ y_{US} \\ z_{US} \end{pmatrix} + \begin{pmatrix} 0 \\ L/2 \\ 0 \end{pmatrix}$$

or

$$\begin{pmatrix} x_{ORIGIN} \\ y_{ORIGIN} \\ z_{ORIGIN} \end{pmatrix} = \begin{pmatrix} x_{DN} \\ y_{DN} \\ z_{DN} \end{pmatrix} + \begin{pmatrix} 0 \\ -L/2 \\ 0 \end{pmatrix}$$

where

$$L = \sqrt{(x_{DN} - x_{US})^2 + (y_{DN} - y_{US})^2 + (z_{DN} - z_{US})^2}$$

Reference Method 2: TQTB Quadrupoles

The TQTB quadrupoles have four circular pole pieces (Figure 8c). One pole is located in each of the four quadrants (Q1, Q2, Q3, Q4) of the magnet (Figure 11). The center of each pole is at 45° from the vertical and horizontal axes. Two planes are created from Laser Tracker measurements made on the upstream and downstream sides of the component. Laser Tracker measurements are made on the upstream and downstream circular pole tips in each quadrant of the component. A cylinder is constructed from the pole tip measurements in each quadrant. A line passing through the center of the cylinder and parallel to the cylindrical axis is also constructed in each quadrant. The intersections of these four lines with the upstream plane define the center points U1, U2, U3, U4. The intersections of the four lines with the downstream plane define the center points D1, D2, D3, D4. A line (X_{U2U4}) is constructed from center points U2 ,U4 and a line (Z_{U1U3}) is constructed from center points U1, U3. Similarly, a line (X_{D2D4}) constructed from center points D2, D4 and a line (Z_{D1D3}) is constructed from center points D1, D3.

The upstream entrance point (US) of the component is defined by the intersection of the line X_{U2U4} and line Z_{U1U3}. The downstream entrance point (DN) of the component is defined by the intersection of the line X_{D2D4} and line Z_{D1D3}. An orthogonal frame is defined such that the primary axis (+y') is defined by the constructed line Y_{USDS} from the upstream entrance point (US) and the downstream entrance point (DN) positive toward downstream. A secondary axis (+z') is defined by the line Z_{U1U3} positive toward center point U1. The third axis (+x') is defined by the line X_{U2U4} positive toward center point U2. The origin of the frame is defined by the upstream entrance (US) point with coordinates x'_{US}, y'_{US}, z'_{US}]. The downstream exist point (DN) is located at [x'_{DN} , y'_{DN} , z'_{DN}].

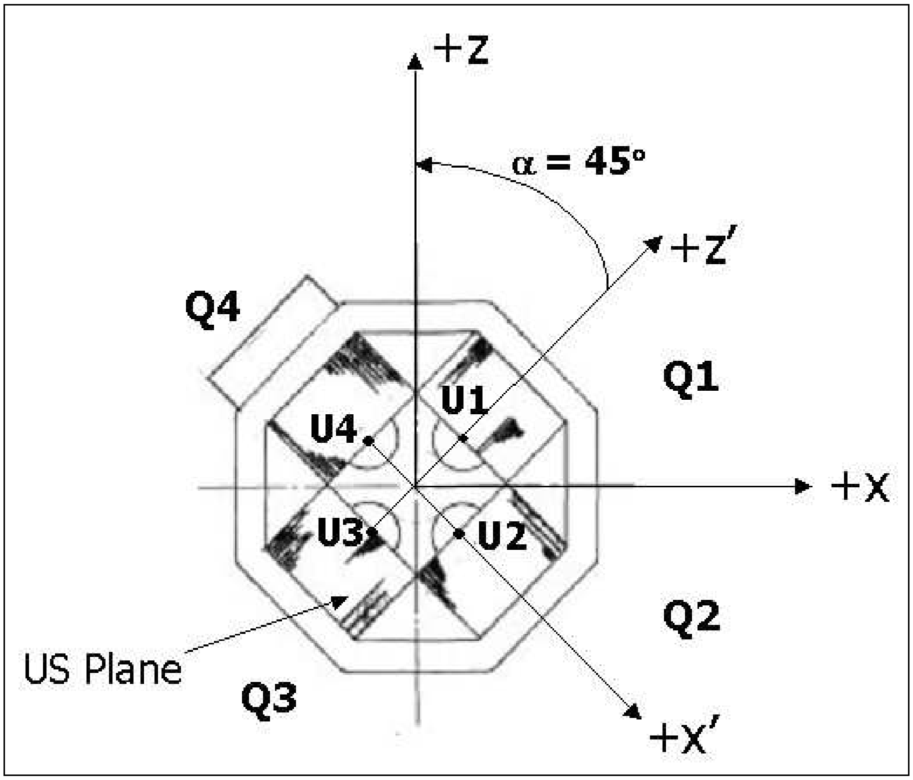

Figure 11. Reference Method 2

A new frame is defined with the +y axis the same as the +y' axis and by rotating the +x and +z axes by angle α = 45° around the +y axis as follows:

$$\begin{pmatrix} x_{US} \\ y_{US} \\ z_{US} \end{pmatrix} = \mathbf{R}(\alpha_Y) * \begin{pmatrix} x'_{US} \\ y'_{US} \\ z'_{US} \end{pmatrix}$$

$$\begin{pmatrix} x_{DN} \\ y_{DN} \\ z_{DN} \end{pmatrix} = \mathbf{R}(\alpha_Y) * \begin{pmatrix} x'_{DN} \\ y'_{DN} \\ z'_{DN} \end{pmatrix}$$

where $\mathbf{R}(\alpha_Y)$ is the rotation matrix.

The origin of the new frame is determined as follows:

$$\begin{pmatrix} x_{ORIGIN} \\ y_{ORIGIN} \\ z_{ORIGIN} \end{pmatrix} = \begin{pmatrix} x_{US} \\ y_{US} \\ z_{US} \end{pmatrix} + \begin{pmatrix} 0 \\ L/2 \\ 0 \end{pmatrix}$$

where

L=

$$\sqrt{(x_{DN} - x_{US})^2 + (y_{DN} - y_{US})^2 + (z_{DN} - z_{US})^2}$$

Beam Line Component Alignment

The API Laser Tracker and the Spatial Analyzer™ software are used for the pre-alignment and final alignment of all components. The procedure used to set a magnet is as follows:

1) Import into the Spatial Analyzer software the coordinates of all control points - floor, wall and tie rods in the FSCS (XYZ) coordinate system (world frame).

2) Import the beamsheet coordinates in the FSCS (XYZ) coordinate system.

3) Construct a local magnet frame using the beamsheet upstream entrance and downstream exit coordinates such that the +*y* is longitudinal along the beam line positive downstream, *x* is transverse to the beam line positive beam right, and *z* is vertical positive above the beam line. The origin of the frame is at the center of magnet. This is now the working frame. This frame is

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an overlay of the local magnet reference frame on to the beam line.
4) Switch frame to the magnet frame.
5) Import the reference ideal coordinates of fiducials for all magnets in the local magnet coordinate system (x, y, z).
6) Position the Laser Tracker at a point near the component to be measured and perform normal calibration.
7) Measure control points in the area surrounding the component.
8) Orient the Laser Tracker into the beam line Tunnel Control Network by best-fitting to the measured tie-rods, floor and wall control points.
9) Make measurements to the fiducials on the component. The components are moved to their ideal nominal position to within the specified tolerance by using the "Watch Window" capability in the Laser Tracker software.
10) Record the as-set measurements to the fiducials on the component in the FSCS (XYZ) coordinate system.
11) Perform a best-fit transformation between the as-set measurements and the imported reference ideal coordinates of fiducials for all magnets in the local magnet coordinate system (x, y, z). This will result in the as-set coordinates for all the fiducials not measured and also the entrance and exit point coordinates.
12) Switch frame to the world frame.
13) Export as-set coordinates of all fiducials plus the coordinates of the magnet origin and the entrance and exit points in the FSCS (XYZ) coordinate system for input into the AMG database.

Pre-Alignment

Prior to the alignment, beam lattice coordinates of all components were marked on the floor in the Linac-to-MTA enclosure to within ±6 mm for the component stand installation. A Geodimeter Total Station was used for this operation. The components were then placed at the beam height on the stands as marked on the floor.

After the component installation, each component was rough aligned to the beam lattice using the Laser Tracker. The purpose of the rough alignment is:

i) to get the components close enough to their final location for electrical wire, vacuum and water connections.
ii) to reduce the roll (rotation around y-axis of the component) as much as possible before the components are put under vacuum. It is harder to remove the roll when the components are under vacuum.

The rough alignment was done to better than ±0.5 mm.

Final Alignment

After the rough alignment, all the components were put under vacuum and leak checked. The final alignment was performed with the Laser Tracker to set the components to their ideal beam line coordinates. For rectangular components, measurements were made to all accessible sides of the component. Planes and lines created from these measurements were used to construct a local magnetic frame on the beam line. Using a combination of plane-plane and plane-line intersections, the upstream entrance and downstream exit points of the component were constructed on the beam line. The component was placed on the beam line as described in the section above. The round shaped components 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 beam line. By constructing a line parallel to the beam line through the center of the cylinder and using the plane-line intersection capability in the software, coordinates of the entrance and exit points on the component were computed. The multi-wires, BPMs, and flanges on other components were measured as circles. Circle fits yielded the coordinates for the center of the circle centered on the beam line. The beam pipes were also aligned to the beam centerline with the Laser Tracker. The final alignment of the beam line components was not completed by the end of the shutdown in mid-October 2007 because the Linac had to resume normal operation. The final alignment would be completed in stages depending on Linac downtime in 2008.

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 that independently affect the total radial standard deviation of a magnet alignment [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

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

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:

$\sigma_n = \pm 0.158$mm
$\sigma_m = \pm 0.017$mm
$\sigma_{nm} = \pm 0.008$mm
$\sigma_{LT} = \pm$ 0.015mm
$\sigma_f = \pm 0.035$mn
$\sigma_s = \pm 0.025$mm

$$\sigma_{Mag\_Align} = \pm\{0.158 + 0.017 + 0.008 + 0.015 + 0.035 + 0.025\}^{1/2}$$
$$= \pm 0.165 \text{ mm}$$

The resulting standard deviation is within the specified accuracy of ±0.25 mm.

CURRENT STATUS OF THE MTA BEAM LINE

The project goal was to have all the main components, instrumentation and MTA beam line under vacuum by early October 2007 and the final alignment by the end of the 2007 shutdown mid-October. The final alignment was not completed by the end of the shutdown because Linac had to resume beam operations early. The current status MTA beam line is as follow:

i) The two C-magnets have to be installed during a Linac downtime sometimes in 2008.

ii) Since all the components have been put under vacuum and leak checked, a final alignment has to be completed during a Linac downtime sometimes in 2008.

iii) Full commissioning is expected to be sometimes in 2008.

CONCLUSION

The MTA beam line has been installed, surveyed and aligned. The alignment methodology used has been presented.

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