Fermi National Accelerator Laboratory

Beams-Doc-2491
Version 1.0

The Understanding and Analysis of the Booster Magnet Survey Data

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AD Database Keywords: Alignment, Booster, Geodesy, Magnet, Proton Plan, Survey

Abstract

Employing the latest Booster magnet survey data taken in the year, 2005 by the Survey Alignment and Geodesy group at Fermilab, the analysis was performed to take a close look at them. The complete calculation methods for all types of alignment errors with raw survey data are presented from ground zero. It is analyzed that what types of alignment errors are currently present and what their distributions are like around the Booster ring. Also, the misaligned magnets are identified with their error types and magnitude. This document can be cross-referenced to a sequel to this document on the Modeling of Magnet Alignments in the Booster.

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1. Introduction

This document was prepared in hoping that the following objectives can be achieved.

- To help us better understand the most up-to-date alignment issues in the Booster synchrotron.
- To provide accurate guidelines for the subsequent efforts of magnet survey and realignment under consideration in forthcoming years.

In February 2005, magnet survey measurements had been performed and the survey data were archived in a worksheet format by the SAG group.

The following acronyms are frequently used throughout this document:

- **SAG**: Survey and Alignment Group
- **FSCS**: Fermilab Site Coordinate System
- **CF**: combined-function magnet
- **LSS**: Long Straight Section
- **SSS**: Short Straight Section
- **MSS**: Mini Straight Section
- **US**: Up Stream
- **DS**: Down Stream
- **L**: longitudinal length of a main gradient magnet
- **len**: transverse length of a main gradient magnet

2. Fermilab Coordinate Systems

In the early 1990s, a DUSAF coordinate system was established at Fermilab. The DUSAF coordinate system is a right-handed coordinate system with the following definitions:

- Origin: A0
- Y-axis: NORTH axis. The positive direction is along the extraction line towards the *Neutrino area* from the origin.
- X-axis: EAST axis. The positive direction is to the right and perpendicular to the y-axis.
- Z-axis: ELEVATION axis. The positive direction is upward from the origin and orthogonal to both X-axis and Y-axis.

The coordinates defining the origin of the DUSAF coordinate system are as follows[1]:

- X = 100000.000 ft (= 30480.06096 m)
- Y = 100000.000 ft (= 30480.06096 m)
- Z = 720.000 ft (= 219.45644 m)

Z = 720.000 ft at A0 indicates that the elevation of A0 is 720 ft above the DUSAF Datum, which is an *arbitrary* datum. These arbitrary coordinates at origin are selected in order to make all survey data points *positive* around accelerators for surveyor's convenience.
Hence, one can notice that the Z coordinate at A0 does NOT imply that it is 720 ft above the sea level.

The Fermilab Site Coordinate System (FSCS), which is an *assimilated* DUSAF coordinate system, is defined for the Booster magnet survey[2‡]. Its origin and rotation axes are located at A0, preserving the DUSAF coordinate system as nearly as possible.
As far as the unit conversion is concerned, the following conversion factor is used consistently.

1 meter = 39.37 US survey inches exactly.

3. The Structure of the Booster Magnet Cell

The Booster synchrotron with a circumference of 474.2-m contains 96 combined-function magnets. The magnet lattice is divided into 24 periods. Each period, or cell, contains 6-meter long straight section and 1.2-meter short straight section, and 0.5-m mini straight section. Each magnet cell comprises two focusing magnets and two defocusing magnets. (cf. Fig. 3.1)

The configuration of the 4 gradient magnets in each cell is according to the surveyor's scheme. (Fig. 3.2) There are 4 survey fiducials (A, B, C, and D) mounted on the top side of each magnet. (cf. Fig. 3.3)

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[1] Note that the Fermilab Site Coordinate System used in magnet survey is different from the Frenet-Serrar Coordinates, which are commonly used in Accelerator Physics.
[2] For the Main Injector, the Local Tunnel Coordinate System (LTCS) is defined.

4. The Magnet Survey and Alignment

1) The Purpose of Survey

The Purpose of the Booster Survey is to establish a precision control network for positioning beamline components in the Fermilab Site Coordinate System.

2) Network Measurements

In 1993 the Booster Horizontal Network (BooNet) was upgraded utilizing the modern survey technology with the laser tracker. The Horizontal Network is densified.
The Vertical Network is for deformation and is measured every year during a shutdown period.

3) Additional Measurements

In addition to the network measurements,

a) Measure "as-found" all magnet fiducials, BPMs and RF Cavities.
b) Measure "as-found" all magnet and quadrupole fiducials in the Linac and in the 400-MeV transfer line.
c) Determine the Upstream and Downstream coordinates (X, Y, Z) of each beamline component.
d) Generate a "Beamsheet" to document and archive beamline component coordinates in FSCS.

4) Booster Survey Data

Tabulated are the longitudinal lengths of lattice components that were used for the calculations of both transverse offsets and rotational angles.

[Table 4.1] The Longitudinal Length of Lattice Components

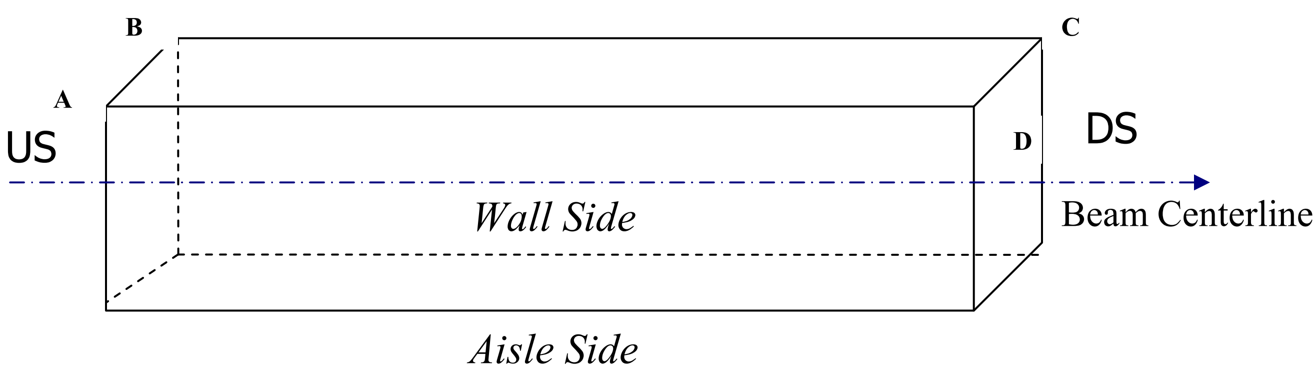
Circumference	474.2163 m
Long Straight Section (LSS)	5.9784 m
Short Straight Section (SSS)	1.1753 m
Mini Straight Section (MSS)	0.4726 m
Longitudinal CF Magnet Length	2.9145 m

5) **<u>The Types of Magnet Misalignments</u>**

By analyzing the survey data, the following types of alignment errors are found in the Booster:

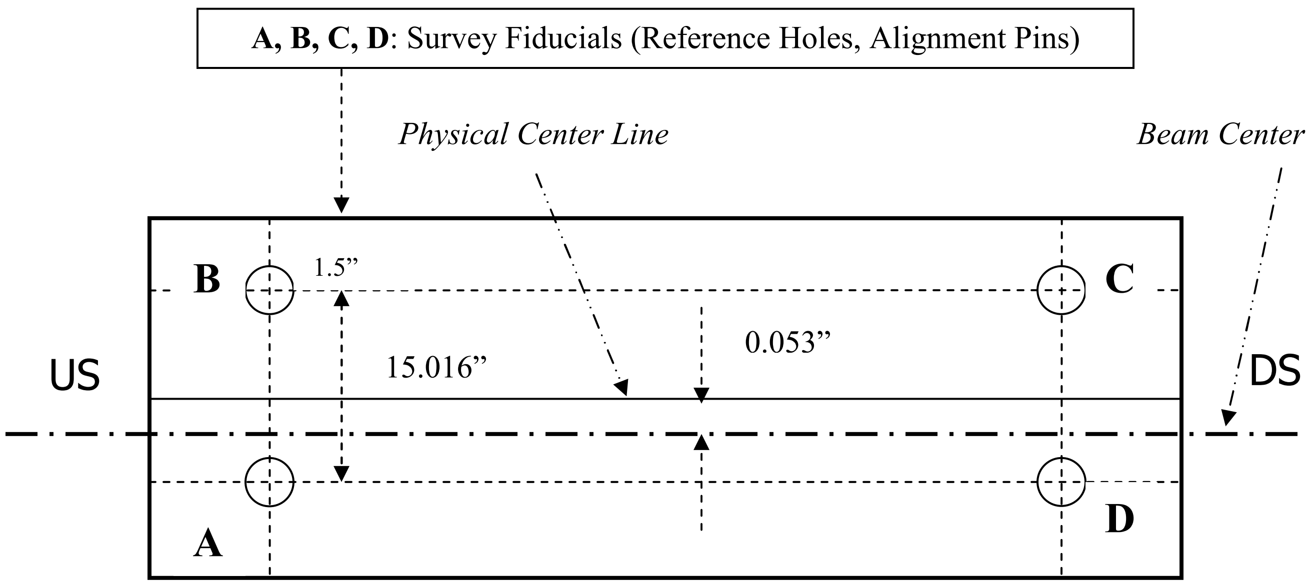
a) Radial Offset
b) Vertical Offset
c) Station Offset (mini straight section, long straight section)
d) Pitch (X-Rotation)
e) Yaw (Y-Rotation)
f) Roll (S-Rotation)
g) Twist (a Roll with a large tilt angle)

5. <u>Magnet Fiducilization</u>

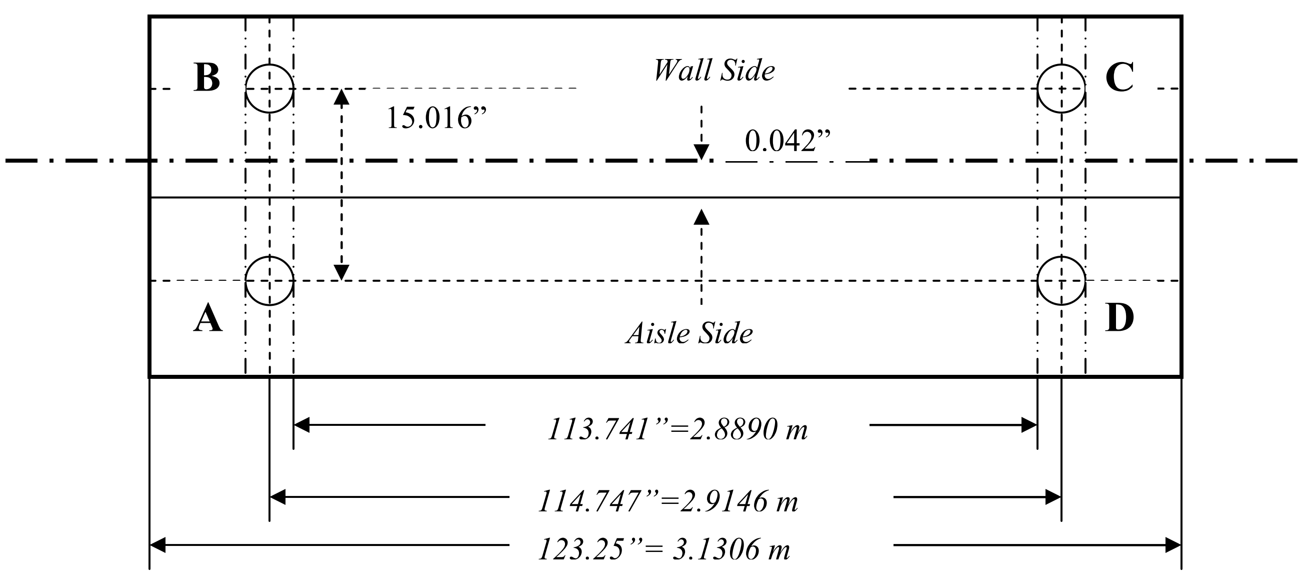


[Figure 5.1] The Side view of a Booster CF Magnet

The main gradient magnet of the Booster is depicted as a rectilinear object as above. A proton beam travels through a Booster magnet from US to DS. The side facing radially inward is labeled *wall side*, and the other side facing radially outward *aisle side*.



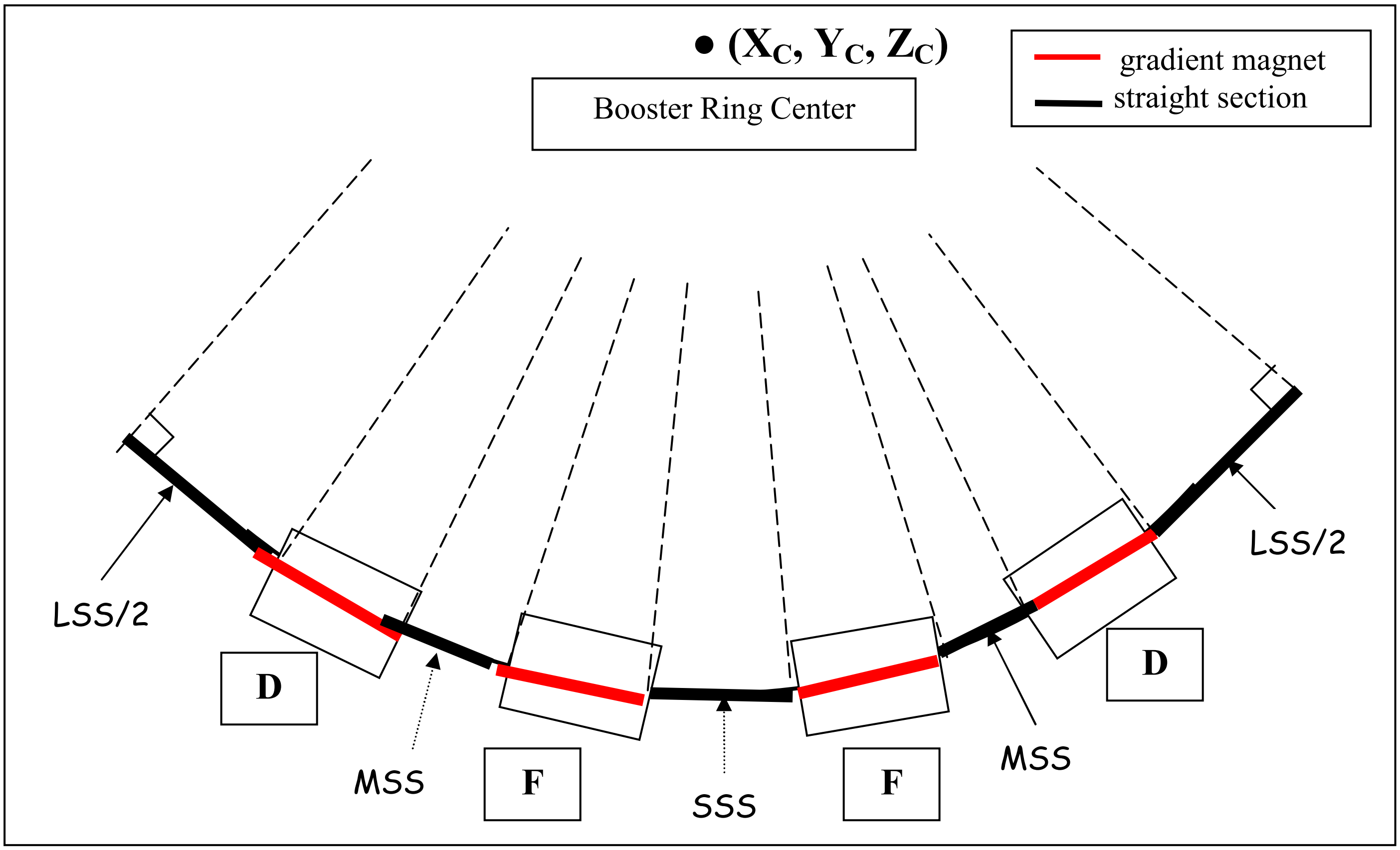
[Figure 5.2] The Top-Bottom View of a Defocusing Magnet



[Figure 5.3] The Top-Bottom View of a Focusing Magnet

6. The Methodology of The Booster Lattice Modeling

Based on the drawings of Figures 5.1, 5.2, and 5.3, the magnet coordinates and offsets at upstream and downstream of each magnet can be calculated. The following describes how offsets of all types are calculated:



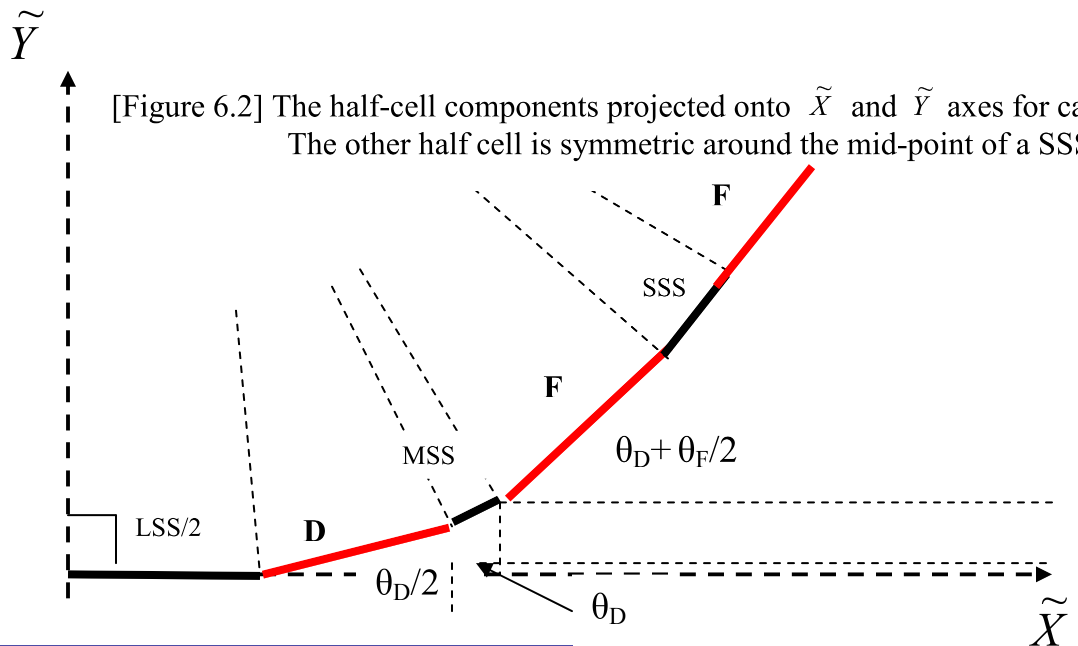
[Figure 6.1] one cell out of a 216-sided polygon of the Booster ring

- $X_{US} = (X_A + X_B) / 2 + \Delta_{OFFSET}$
- $X_{DS} = (X_C + X_D) / 2 + \Delta_{OFFSET}$
- $Y_{US} = (Y_A + Y_B) / 2 + \Delta_{OFFSET}$
- $Y_{DS} = (Y_C + Y_D) / 2 + \Delta_{OFFSET}$
- $Z_{US} = (Z_A + Z_B) / 2$
- $Z_{DS} = (Z_C + Z_D) / 2$

- $\Delta X = X_{DS} - X_{US}$
- $\Delta Y = Y_{DS} - Y_{US}$
- $\Delta Z = Z_{DS} - Z_{US}$

- Δ_{OFFSET}: The distance between the center line and the beamline of a CF magnet.
  0.053" (= 1.346 mm) for a D-Magnet
  0.042" (= 1.067 mm) for a F-Magnet

- θ_D: bending radius for D-magnet
- θ_F: bending radius for F-magnet



[Figure 6.2] The half-cell components projected onto $\tilde{X}$ and $\tilde{Y}$ axes for calculations. The other half cell is symmetric around the mid-point of a SSS.

- $X_{LSS/2} = LSS/2$
- $Y_{LSS/2} = 0$

- $X_D = X_{LSS/2} + L*\cos(\theta_D/2)$
- $Y_D = L*\sin(\theta_D/2)$

- $X_{MSS/2} = X_D + MSS/2*\cos(\theta_D)$
- $Y_{MSS/2} = Y_D + MSS/2*\sin(\theta_D)$

- $X_F = X_{MSS/2} + L*\cos(\theta_D + \theta_F/2)$
- $Y_F = Y_{MSS/2} + L*\sin(\theta_D + \theta_F/2)$

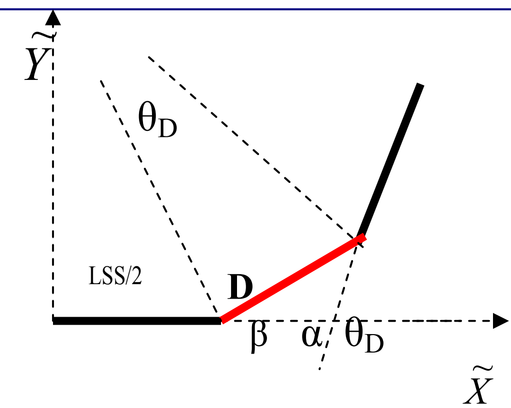
- $X_{SSS/2} = X_F + SSS*\cos(\theta_D + \theta_F)$
- $Y_{SSS/2} = Y_F + SSS*\sin(\theta_D + \theta_F)$

- $X_F = X_{SSS/2} + L*\cos(\theta_D + 3\ \theta_F/2)$
- $Y_F = Y_{SSS/2} + L*\sin(\theta_D + 3\ \theta_F/2)$

- $X_{MSS} = X_F + MSS*\cos(\theta_D + 2\theta_F)$
- $Y_{MSS} = X_F + MSS*\sin(\theta_D + 2\theta_F)$

- $X_D = X_{MSS} + L*\ \cos(3\theta_D/2 + 2\theta_F)$
- $Y_D = Y_{MSS} + L*\ \sin(3\theta_D/2 + 2\theta_F)$

- $X_{LSS/2} = X_D + (LSS/2)*\cos(2\theta_D + 2\theta_F)$
- $Y_{LSS/2} = Y_D + (LSS/2)*\sin(2\theta_D + 2\theta_F)$



$\alpha = \pi - \theta_D$

$\beta = (\pi - \alpha)/2 = \theta_D/2$

[Figure 6.3] Projection angle

$$R_L = \frac{1}{\sin\left(2\pi/24\right)} \cdot \left(\sum_{i=1}^{9} x_i \right) \approx \frac{1}{\left(2\pi/24\right)} \cdot \left(\sum_{i=1}^{9} x_i \right)$$

$$R_{Dus} = \sqrt{X_{LSS/2}^{2} + (R_L - Y_{Dus})^2}$$

$$R_{Dds} = \sqrt{X_{D}^{2} + (R_L - Y_{Dds})^2}$$

$$R_{MSS} = \sqrt{X_{MSS}^{2} + (R_L - Y_{MSS})^2}$$

continues in this way ...

The equations on the left show how the radius of each segment (LSS/2, D-magnet, MSS, F-magnet, etc.) in a cell is computed from the Booster centroid.

$$\Delta r = \sqrt{(X_i - X_c)^2 + (Y_i - Y_c)^2} - R_{i\_segment}$$

First, the distance of each component from the Booster center is calculated. Then, the radial offsets (Δr) are computed from the radius from each segment ($R_{i\_segment}$).

7. The Magnet Survey Data Analysis

The calculations of the vertical offsets for the Booster magnets are straightforward. First, an average elevation (<Z(i)>) at 4 fiducials of each magnet is computed.

$$Z(i\_mag) = \frac{1}{4}\left(\sum_{j=A,B,C,D} Z(i\_mag, j) \right)$$

$$< Z >_{Booster} = \frac{1}{96}\left(\sum_{i=1}^{96} Z(i) \right)$$

As a result, the X-Y plane of the Booster ring, $< Z >_{Booster}$, is found.

The $< Z >_{Booster}$ is computed as 221.43197 (m). Since the elevation at the origin, Z_0, is set at 720.000 (ft) (= 219.45644 m), the average elevation for 96 gradient magnets is 1.97553 (m) above the Z_0 at A0.

1) Radial Offsets (Displacements)[2]

For the calculations of radial offsets, each module, or magnet cell is divided into 9 straight segments (LSS/2, D-magnet, MSS, F-magnet, SSS, F-magnet, MSS, D-magnet, and LSS/2, proceeding from US to DS).

As one module can be considered a portion of a 9-sided polygon, due to the 24-fold periodicity, the whole Booster ring is regarded as a 216-sided polygon for calculation purpose. (cf. Fig. 5.1)

The calculation scheme is described as follows:

a) Calculate averages of East (X) and North (Y) and Elevation (Z) coordinates. These are the coordinates of the Booster ring center: (X_c, Y_c, Z_c)

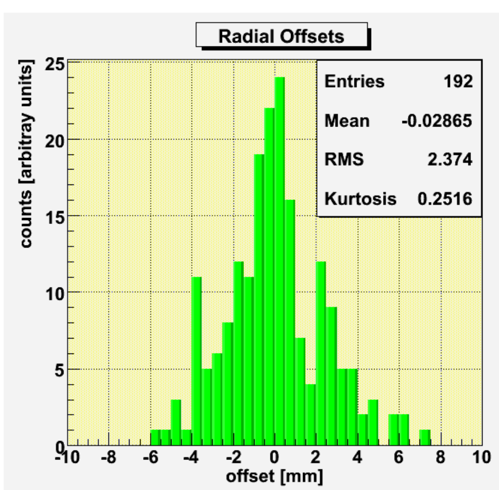
b) Calculate transverse distances (RDu, RDd, RFu, RFd) from the ring center at both US and DS of each type of magnet (F- and D-magnet).

c) Find the ideal orbit radii at both US and DS of each magnet. Now the layout of gradient magnets in each cell is D-F--F-D, the symmetry around the SSS needs to be preserved. The only input for calculation is the ratio of bending angles ($R_\theta = \theta_D/\theta_F$) obtained from Fermilab-TM-405.

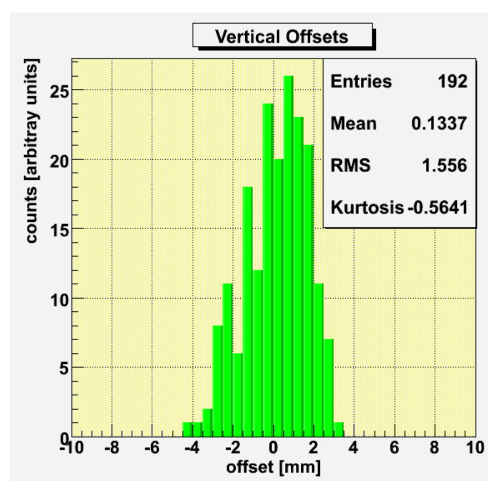
d) Calculate the radial offsets from the ideal orbit radii at both US and DS of each magnet.

[Table 7.1] The Statistical Parameters of the Distribution of Each Type

	Mean	**RMS**	**Kurtosis**[3]
Radial Offsets	- 0.03 mm	2.37 mm	0.25
Vertical Offsets	0.13 mm	1.56 mm	- 0.56
Station Offsets	3.67 mm	3.04 mm	0.32
len	0.3815 m	1.0E-4 m	
L	2.9145 m	7.0E-4 m	

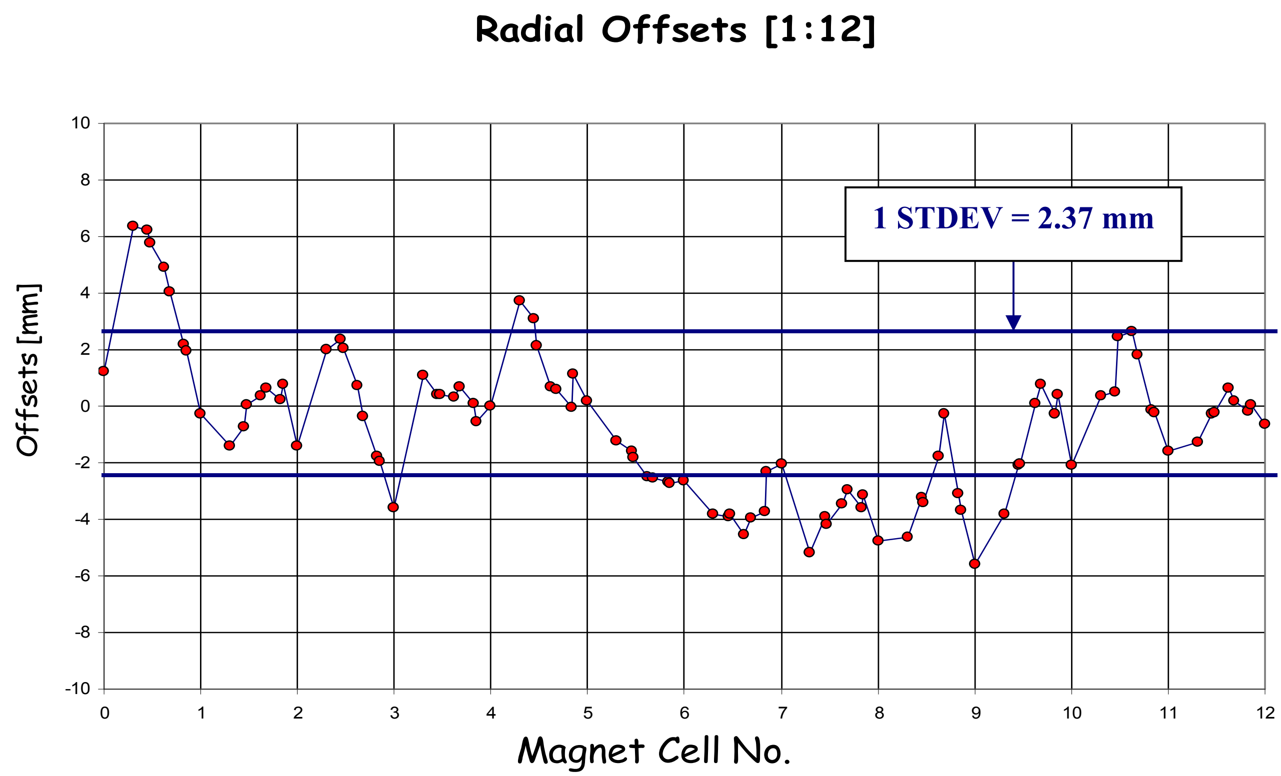


[Figure 7.1] The histogram of radial offsets

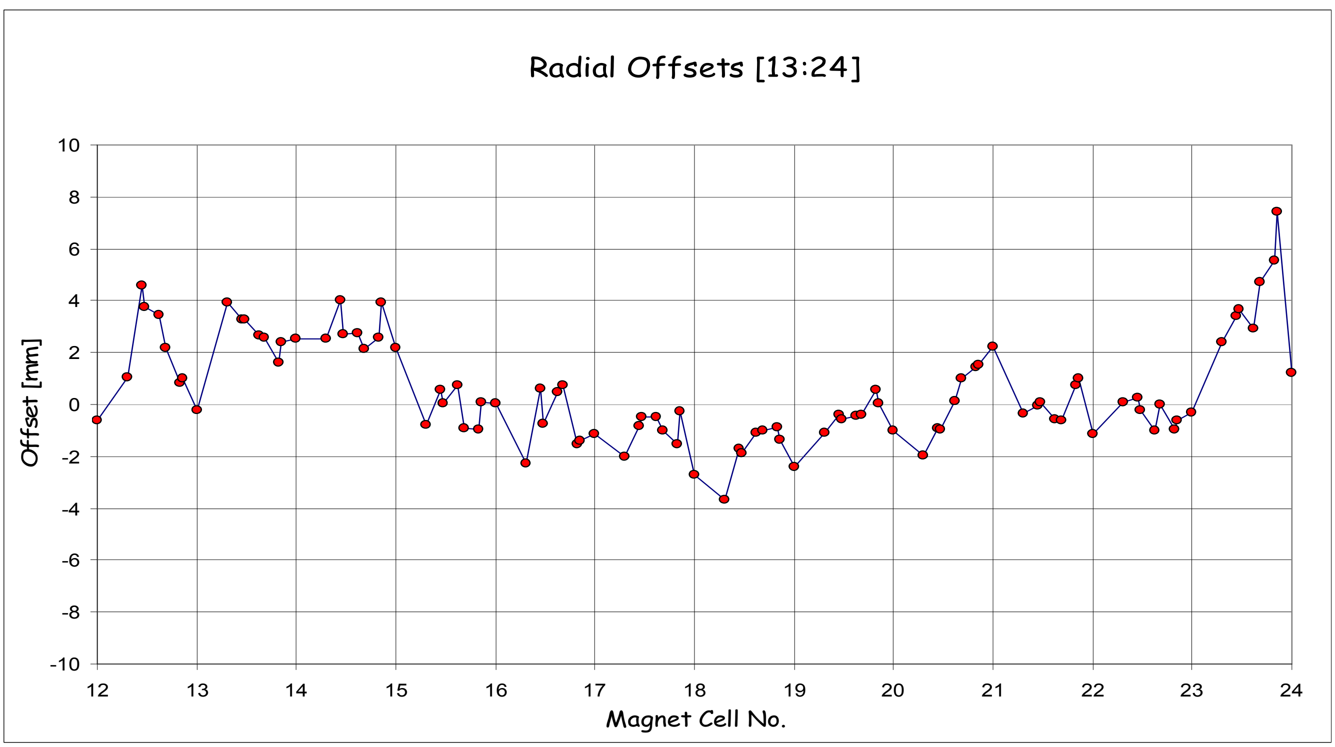


[Figure 7.2] The histogram of vertical offsets

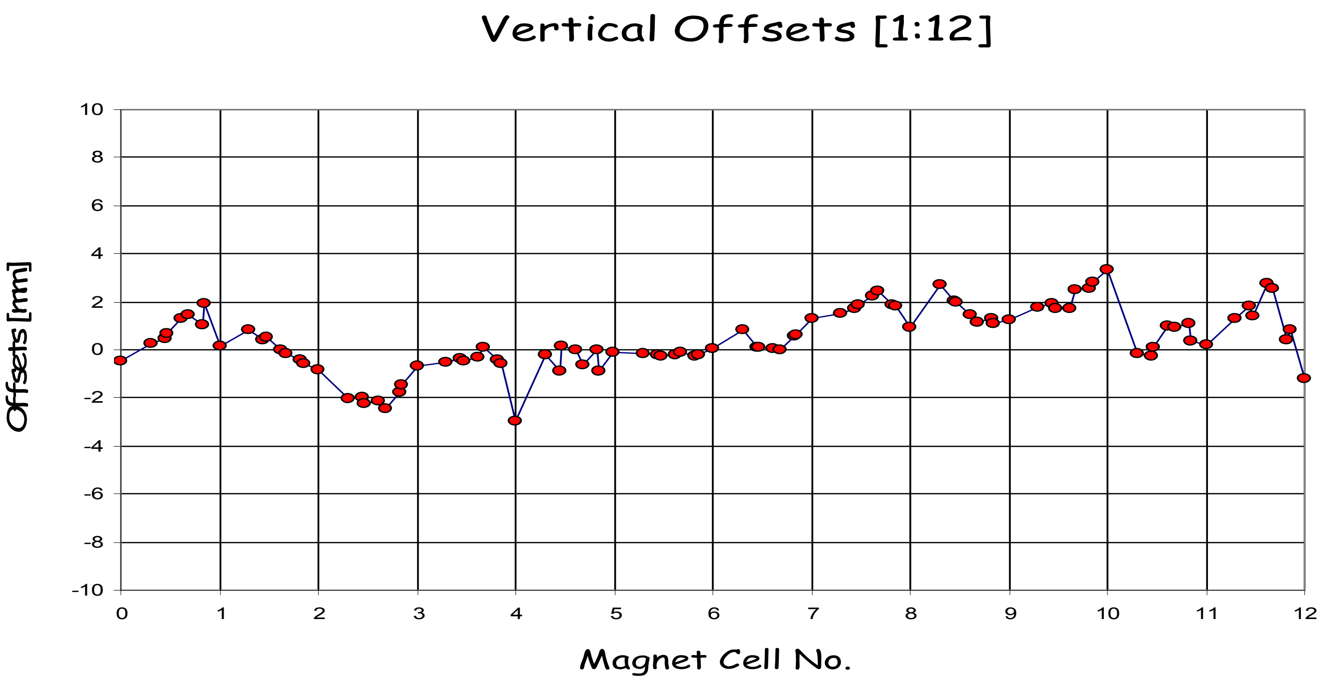
[3] The Kurtosis is a measure of how close a distribution is to the Gaussian distribution. The Gaussian distribution has a Kurtosis of zero.



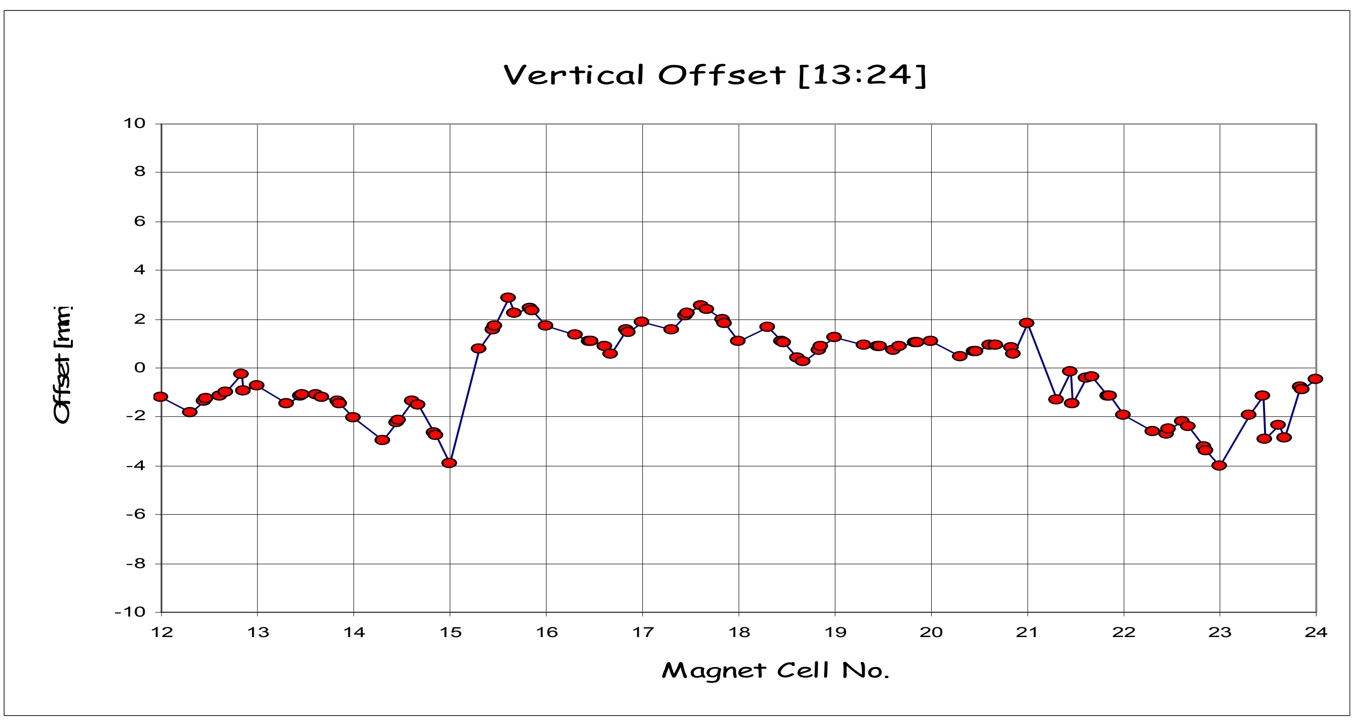
[Figure 7.3] Radial Offsets for Magnet Cell No [1:12]



[Figure 7.4] Radial Offsets for Magnet Cell No [13:24]

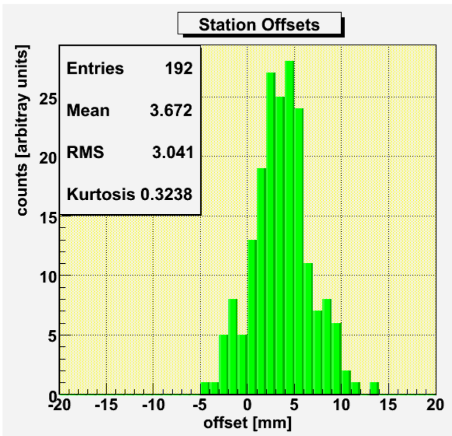


[Figure 7.5] Vertical Offsets for Magnet Cell No [1:12]



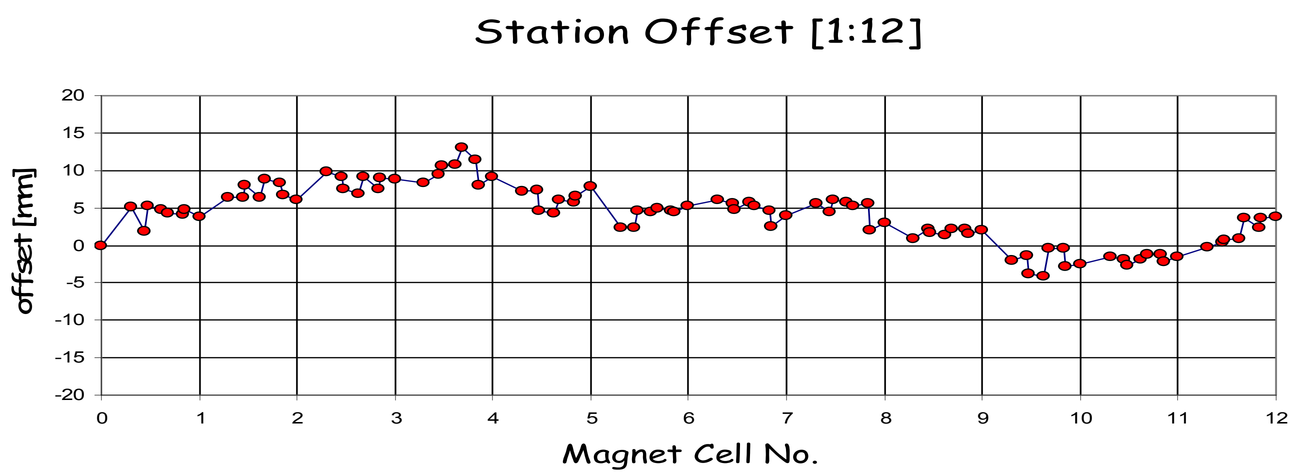
[Figure 7.6] Vertical Offsets for Magnet Cell No [13:24]

3) Station (Longitudinal) Offsets

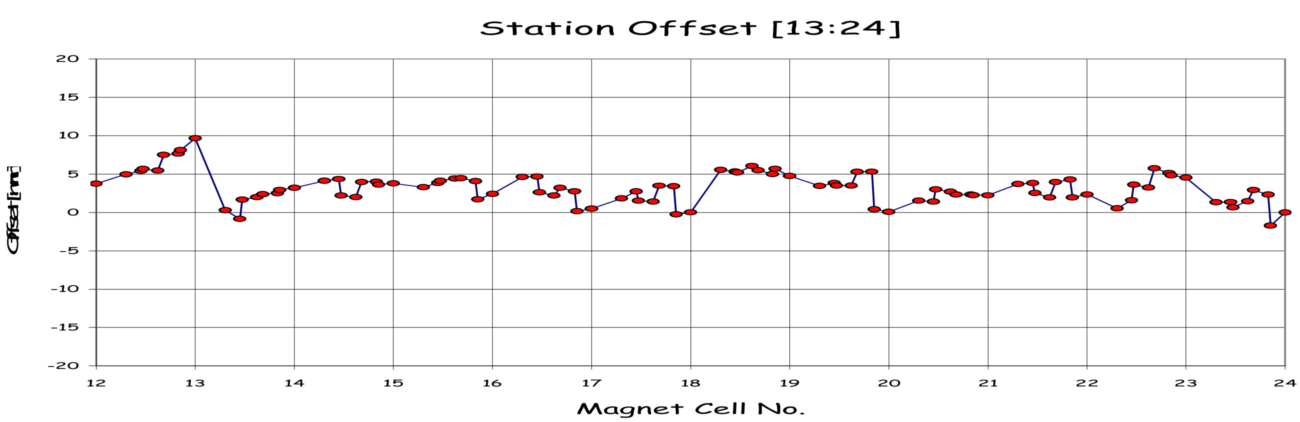


[Figure 7.7] The histogram of Station Offsets

As can be found in the statistical box in the upper left corner, the rms value of station offsets is 3.0. The rms spread is somewhat larger than those of radial offsets and vertical offsets.



[Figure 7.8] Station Offsets for the Magnet Cell No. [1:12]



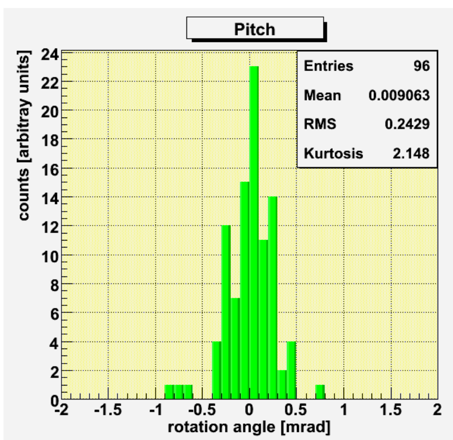
[Figure 7.9] Station Offsets for the Magnet Cell No. [13:24]

2) Rotational Alignment Errors

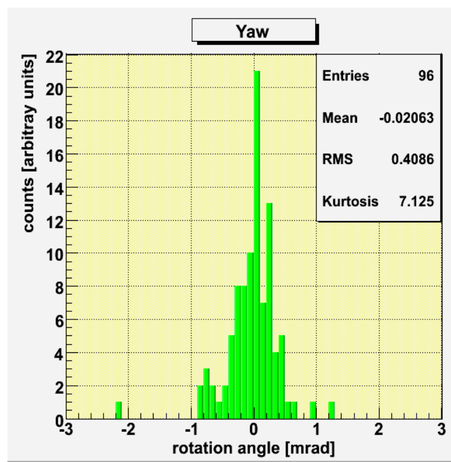
- **L**: longitudinal length of a magnet
- **len**: transverse length of a magnet
- $\boldsymbol{\Theta}_x$: x-rotation angle (pitch)
- $\boldsymbol{\Theta}_y$: y-rotation angle (yaw)
- $\boldsymbol{\Theta}_s$: s-rotation angle (roll)

- $< \mathbf{L} > = \sqrt{\{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2\}}$
- $\mathbf{len} = (L_{AB} + L_{CD})/2$
- $\boldsymbol{\Theta}_x = \arctan(\Delta Z / < L >)$
- $\boldsymbol{\Theta}_y = \arctan (\Delta R / < L >)$
- $\boldsymbol{\Theta}_{s,US} = \arctan((Z_B - Z_A) / <len>)$
- $\boldsymbol{\Theta}_{s,DS} = \arctan((Z_C - Z_D) / <len>)$

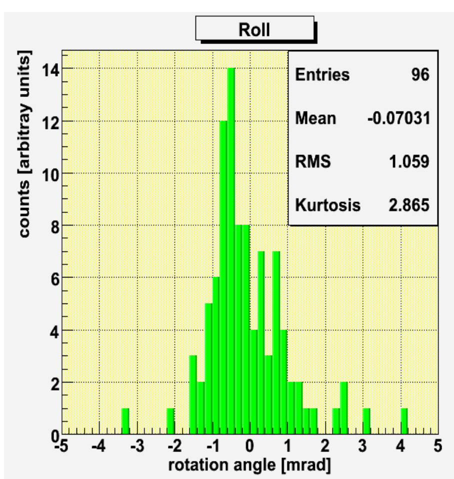
a) Pitch, Yaw, and Roll



[Figure 7.10] Histogram of Pitch angles

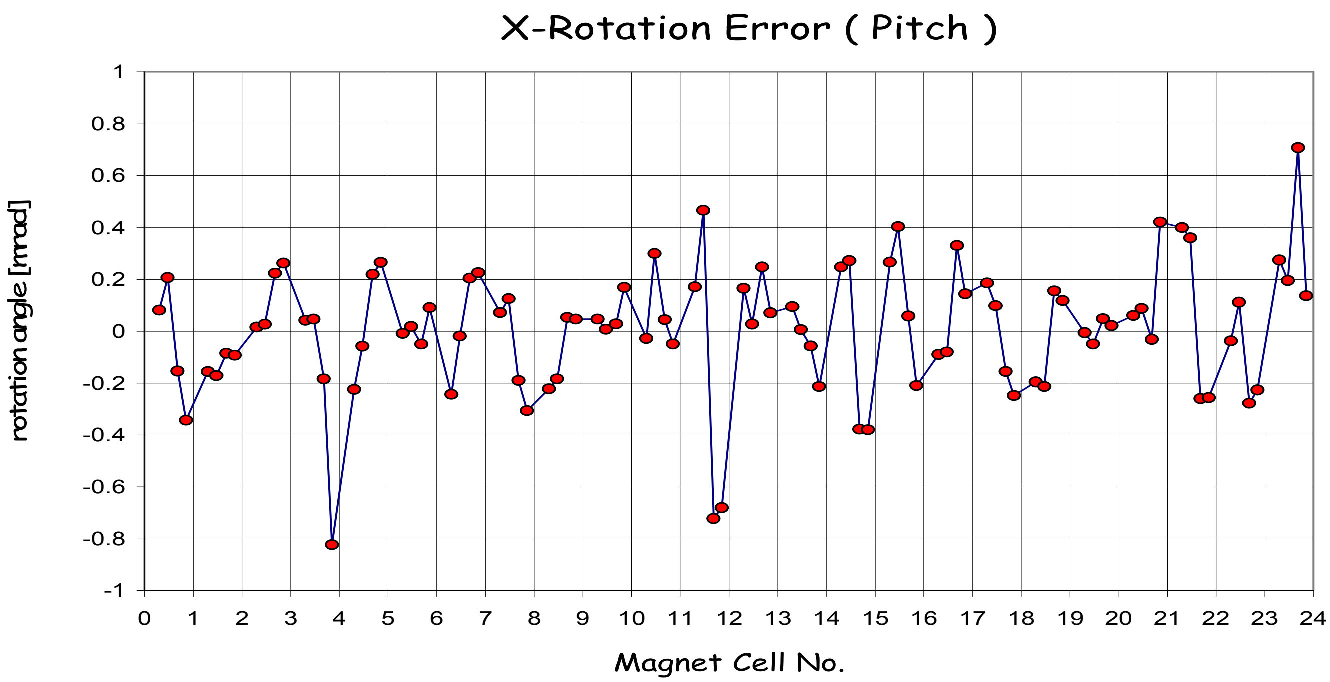


[Figure 7.11] Histogram of Yaw angles

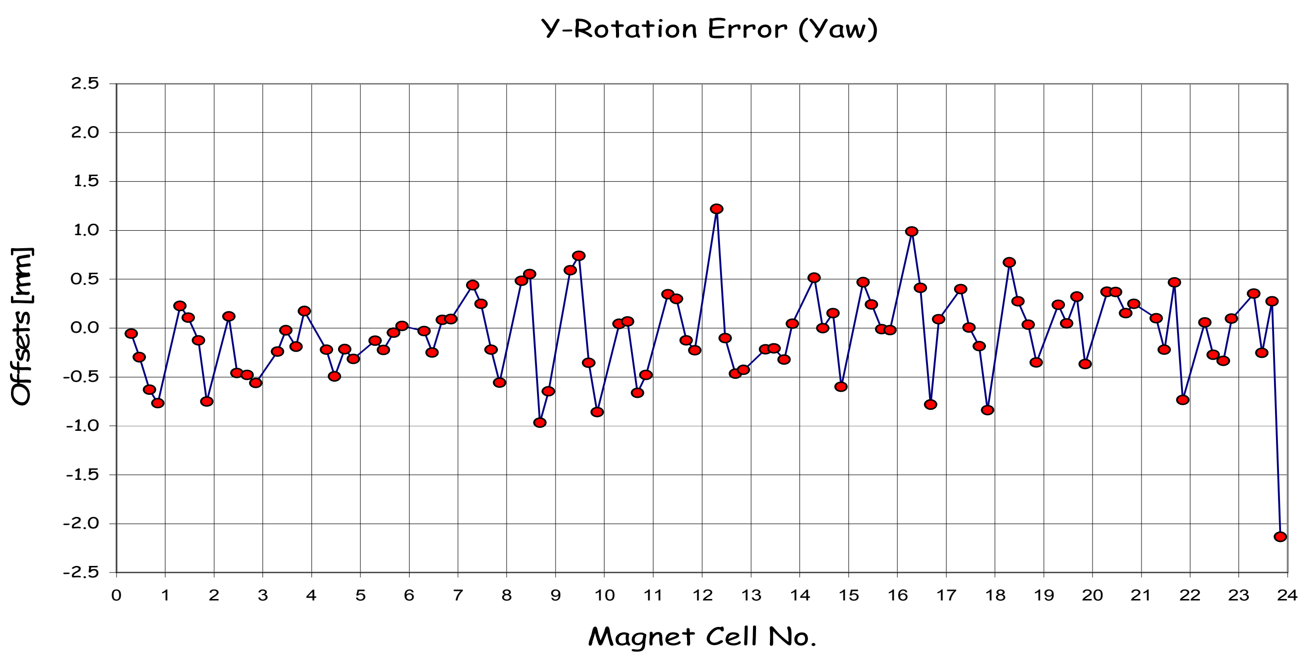


[Figure 7.12] Histogram of Roll angles

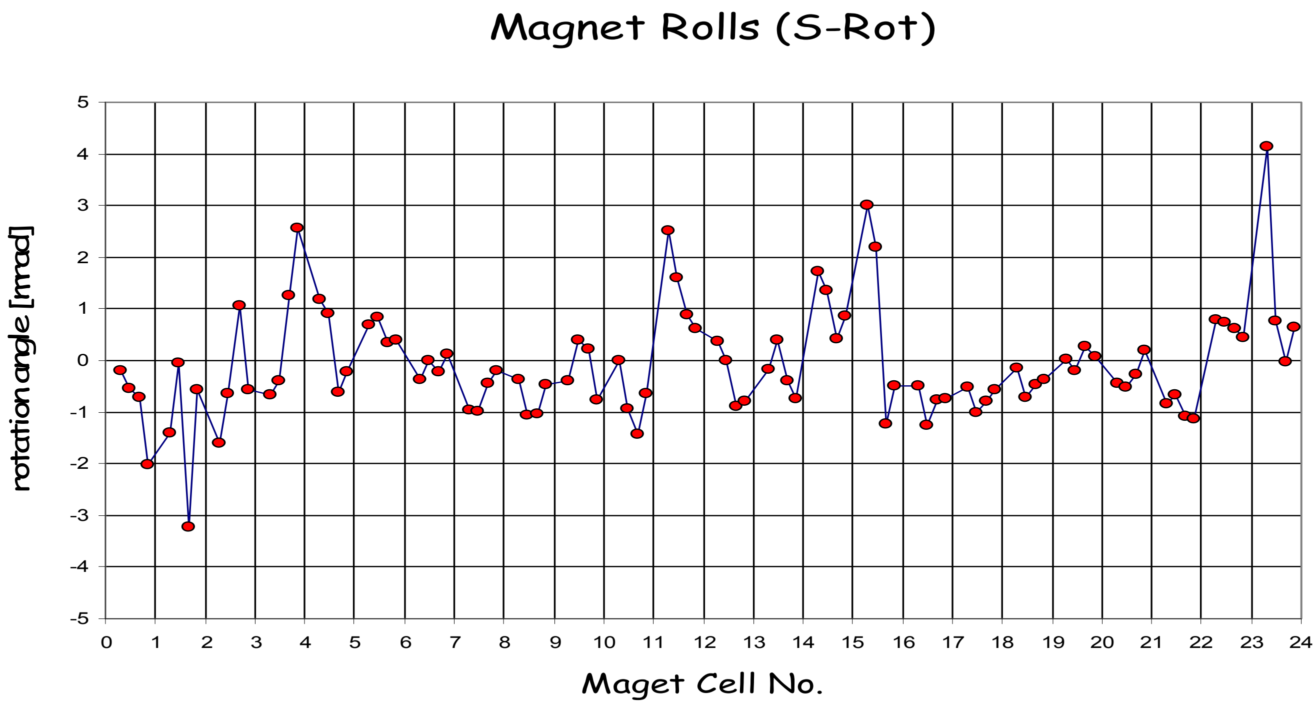
The Figure 5.13 is a histogram plot of roll angles distributed around the ring. As shown in the statistics box on the upper right corner, the rms value is about 1 mrad.
The roll angle is calculated as an average angle at US and DS of each magnet.



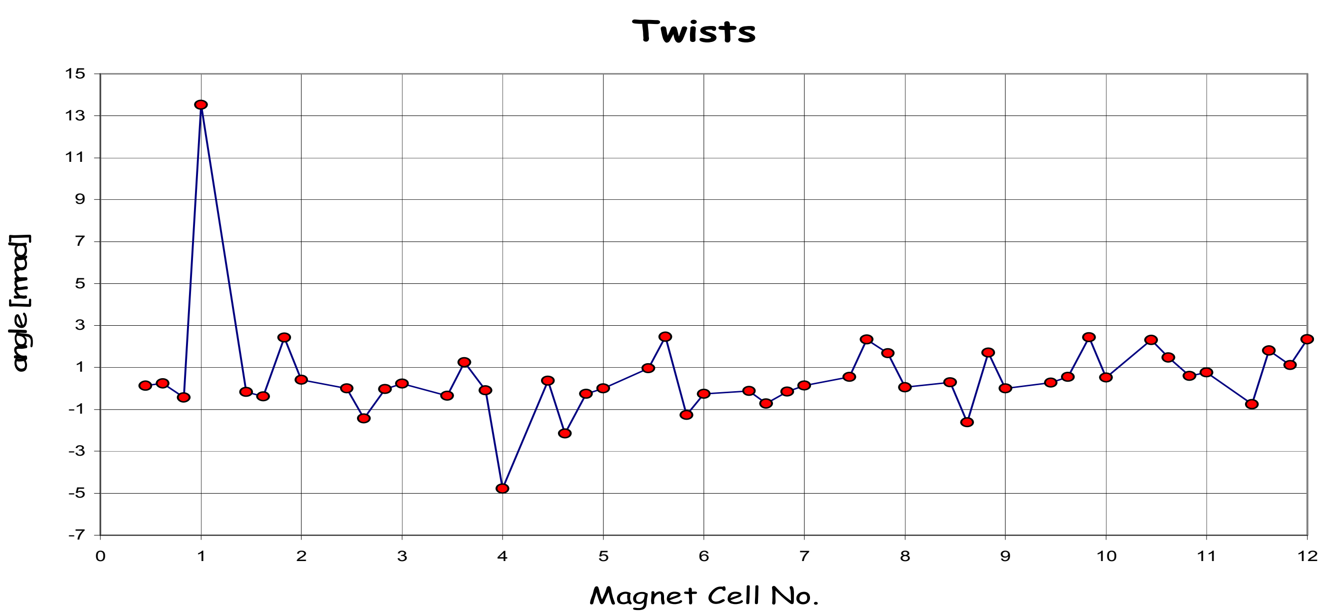
[Figure 7.13] Pitch angles around the Booster ring



[Figure 7.14] Yaw angles around the Booster ring



[Figure 7.15] Roll angles around the Booster ring



[Figure 7.16] The angle difference ($\Delta\theta$) between an upstream roll and a downstream roll for each magnet
$\Delta\theta = \Delta\theta_{s,DS} - \Delta\theta_{s,US}$

5) The List of Magnets Survey Data to Re-measure

In accordance with the surveyor's notation, the fiducial points that need re-measurements are denoted as [*cell no.*]_[*magnet no.*][*fiducial id*].

[Table 7.2] the list of magnets that need to be re-surveyed

1_4D	2_4D	4_4D
8_1A	8_1B	8_1C
8_1D		

4) The List of Misaligned Magnets

According to the histogram of rotation angles, it is speculated that any magnets with rotation angles larger than the rms value of ±1 mrad can be considered *twisted* magnets. The roll angles of those magnets fall outside of the 1 sigma region. In the plot below, two red horizontal lines of ± 1 mrad are drawn. About 25 % of total gradient magnets have large roll angles, i.e. they are twisted. At present, it is not known to us how to re-align twisted magnets. However, we can unroll the rolled magnets all around the Booster.

Following the surveyor's convention, the first number is for the cell number and the second number is for the magnet number in each cell. The magnet cell no. begins from the LSS 1 from the foil location. The cell number increments, following the direction of the proton beam.

Out of all alignment error types, pitches are the easiest of all. As far as yaws and simple rolls are concerned, it is possible to realign them. At present, however, it is not known to us how to realign twisted magnets. Station errors are worst of all because there is no way to realign them.

All magnets identified with radial, vertical, and rolled alignment errors are tabulated as follows:

[Table 7.3] the list of magnets with radial offsets larger than 1 STDEV:
a total of 63 fiducials for 37 main gradient magnets
The magnets are listed in order of increasing cell number

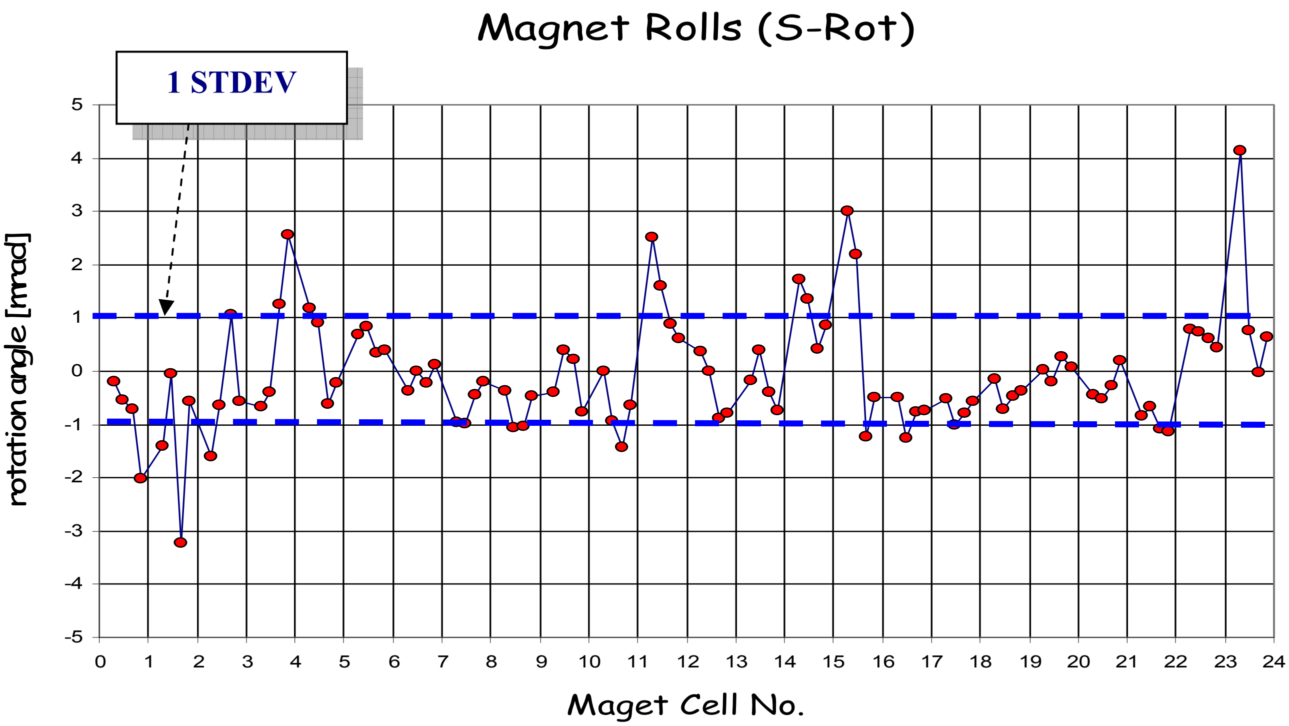
- 1-1U,1-1D, 1-2U, 1-2D, 1-3U
- 3-4D
- 5-1U, 5-1D
- 6-2D, 6-3U, 6-3D, 6-4U, 6-4D
- 7-1U, 7-1D, 7-2U, 7-2D, 7-3U, 7-3D
- 8-1U, 8-1D, 8-2U, 8-2D, 8-3U, 8-3D, 8-4U, 8-4D
- 9-1U, 9-1D, 9-2U, 9-3D, 9-4U, 9-4D
- 10-1U, 10-1D
- 11-2U, 11-2D
- 13-1D, 13-2U, 13-2D
- 14-1U, 14-1D, 14-2U, 14-2D, 14-3U, 14-4U, 14-4D
- 15-1U, 15-1D, 15-2U, 15-2D, 15-3D, 15-4U
- 18-4D
- 19-1U, 19-4D
- 24-1U, 24-1D, 24-2U, 24-2D, 24-3U, 24-3D, 24-4U

[Table 7.4] the list of magnets with vertical offsets larger than 1 STDEV:
a total of 63 fiducials for 40 for main gradient magnets.

- 1_4U
- 3_1U, 3_1D, 3_2U, 3_2D, 3_3U, 3_3D,
- 4_4D
- 8_1D, 8_2U, 8_2D, 8_3U, 8_3D, 8_4D
- 9_1U, 9_1D, 9_2U
- 10_1U, 10_1D, 10_2U, 10_2D, 10_3U, 10_3D, 10_4U, 10_4D
- 12_2D, 12_3U
- 13_1U
- 14_4D
- 15_1U, 15_1D, 15_2U, 15_3D, 15_4U, 15_4D
- 16_2U, 16_2D, 16_3U, 16_3D, 16_4U, 16_4D
- 17_4D
- 18_1U, 18_1D, 18_2U, 18_2D, 18_3U, 18_3D, 18_4U
- 19_1U
- 22_4D
- 23_1U, 23_1D, 23_2U, 23_2D, 23_3U, 23_3D, 23_4U, 23_4D
- 24_1U, 24_2U, 24_2D, 24_3U

[Table 7.5] the list of rolled magnets with large roll angles (a total of 17 main gradient magnets)

1_4	2_1	2_3	3_1	4_3
4_4	5_1	11_3	12_1	12_2
15_1	15_2	16_1	16_2	16_3
17_2	24_1			



[Figure 7.17] Roll angles all around the Booster ring

5) The Types of Rolled Magnets

> Note: **(i)** ⊗ indicates the longitudinal beam direction, +Z
> **(ii)** The percentage in parentheses implies that how many magnets with the corresponding roll type are present amongst 96 CF magnets.

The circle represents the entrance and exit faces of a magnet. The blue arrow indicates the normal direction from the top side of a magnet.

	Total	Large angle
Same Orientation	**69 %**	**14 %**
Opposite Orientation	**31 %**	**25 %**

[Table 7.16] The distribution of roll angles: The angle is an average angle of an upstream roll and a downstream roll for each magnet.

<u>Case I:</u> Both US and DS rolls are in the same orientation[4] (=69 %)

<u>Case II</u>: Both US and DS rolls are in the same orientation *with large angles* (= 14 %)

<u>Case III</u>: US roll and DS roll are in opposite orientation (= 31 %)

<u>Case IV</u>: US roll and DS roll are in opposite orientation with large angles (= 25 %)

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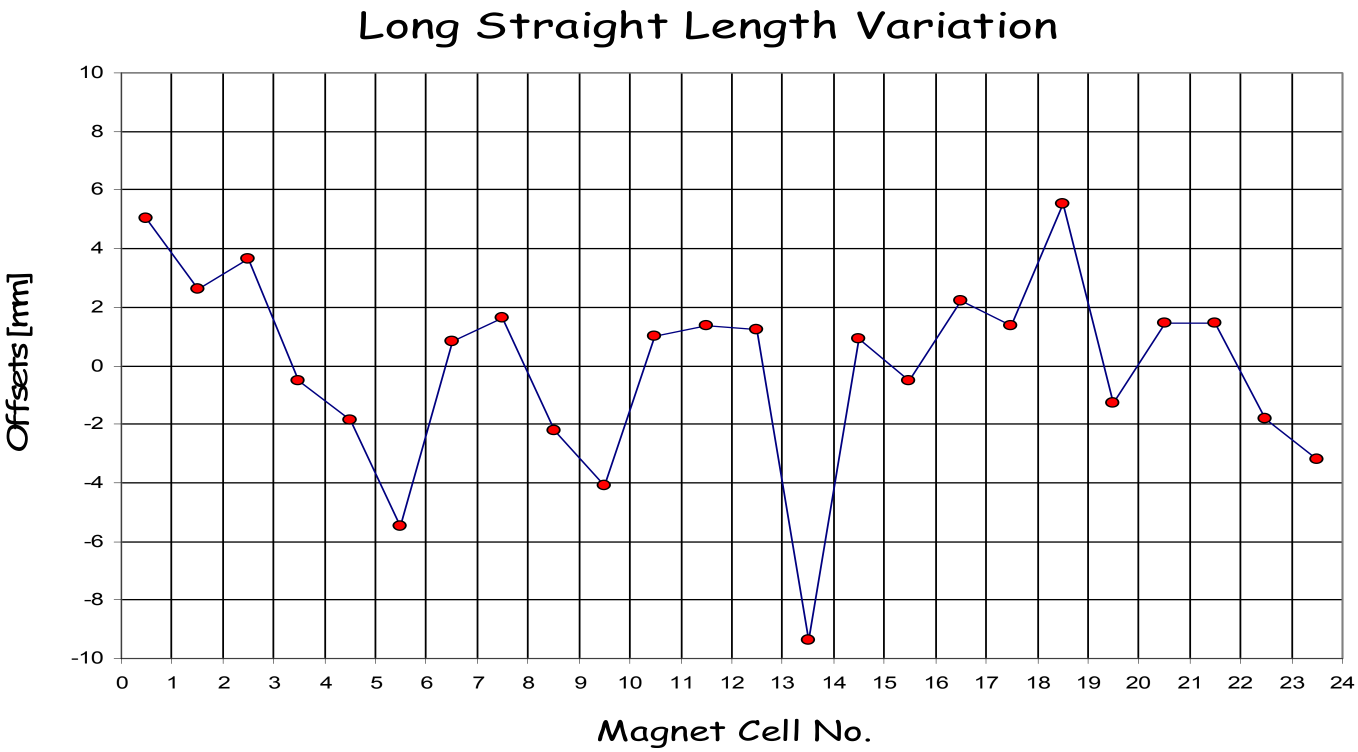
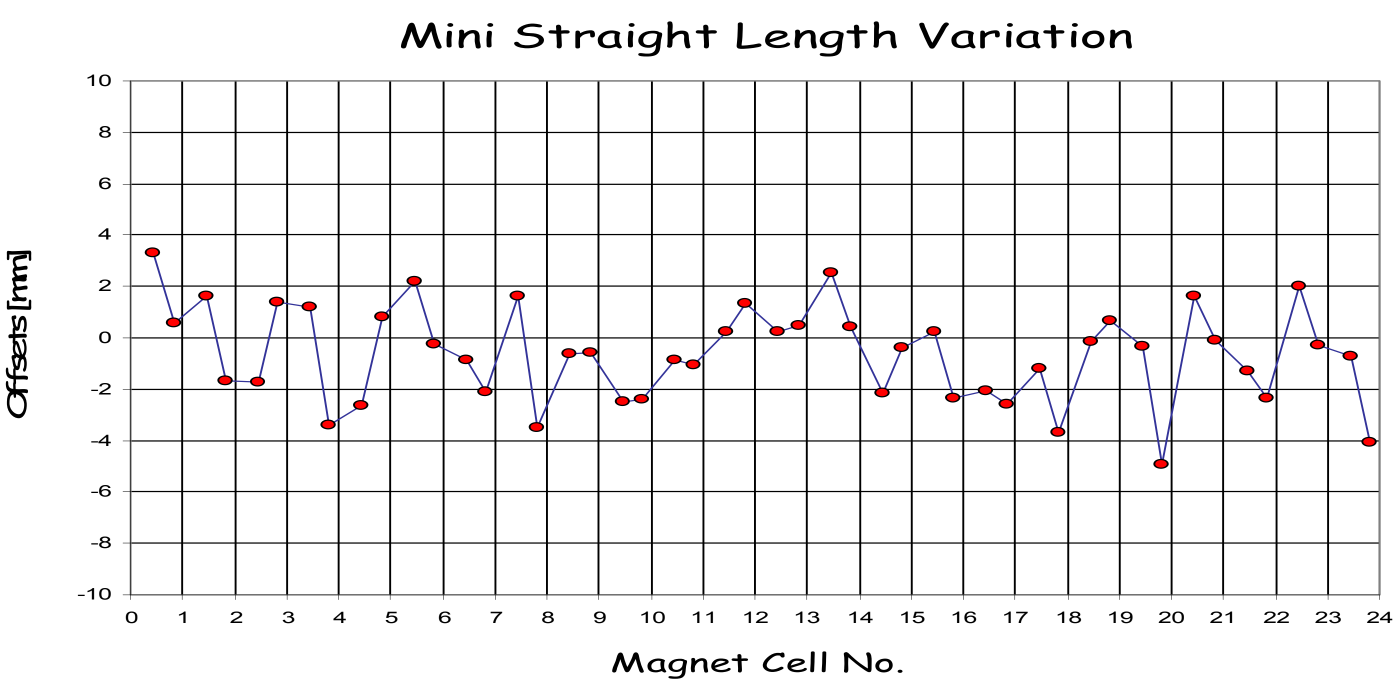
[4] The rms of the distribution of roll angles is 1 mrad. If a roll angle is larger than 1 mrad, the roll angle is taken to be *large*, otherwise *small*.



[Figure 7.18] Variation of the length of Long Straight Section



[Figure 7.19] Variation of the lengths of Mini Straight Section

8. Concluding Remarks

The analysis of the latest magnet survey data was carried out to find out the magnitude and the distribution of magnet alignment error of each type. Now that each magnet is identified with the types and the magnitudes of alignment errors, the Booster alignment modeling can be performed. The magnets with potential survey errors are identified and labeled, so that they can be re-measured in the next survey. All of this analysis results can be used as a reference, when a subsequent survey data is available in coming years.

It is speculated that the calibration of the laser tracker system, to reduce the systematic uncertainties, would be of good help. Also, for the magnet survey for accelerators in a larger scale, the utilizing GPS (Global Positioning System) should be considered for manipulating a large amount of survey data.

7 Acknowledgements

One of the authors (Phil Yoon) is grateful to W. Chou, and the other co-authors of this document, and T. Sager, both in and out of the Accelerator Division, for their helpful discussions at numerous times and their kind provisions for this analysis.

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