High Precision Alignment of Multipoles*

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Low Emittance Rings 2010 Workshop (LER2010)
CERN, Geneva, Switzerland, 12-15 January, 2010

* Work supported by the U.S. Department of Energy
under contract DE-AC02-98CH10886

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Acknowledgements

M. Anerella, R. Ceruti, J. Cintorino, T. Dilgen, S. Dimaiuta, L. Doom, J. Escallier, G. Ganetis, P. He, R. Hubbard, P. Joshi, F. Karl, P. Kovach, F. Lincoln, W. Louie, A. Marone, J. Mc Caffrey, D. Oldham, S. Ozaki, S. Plate, P. Ribaudo, A. Sauerwald, S. Sharma, J. Skaritka, C. Spataro, D. Sullivan, P. Wanderer, F. Willeke

D. Harder, G. Rakowsky, NSLS

Alexander Temnykh, Cornell University

L. Rivkin, D. George, Swiss Light Source

Dieter Einfeld, Montse Pont, ALBA

NSLS-II Lattice and Magnets

- **Standard Quadrupole (66 mm):**
- Type A: Single coil, short,11 T/m
- Type B: single coil, wide, 11 T/m
- Type C: Double Coil, long, 22 T/m
- Type D: Doulbe Coil, short, 22 T/m
- Type E: Double Coil, Wide, 22 T/m
- **Large Aperture: 90 mm, 15 T/m**

- **Normal Sextupole**:
- Type A: Symmetric, 68mm
- Type B: Wide, 68 mm
- **Large Aperture: 76 mm**
- All sextupoles have maximum strength of 400 T/m^2

Stability requirements:

Dipole: 25 ppm→ rms $\Delta p/p<5\times10^{-5}$

Quadrupole: 50 ppm →

Peak to peak beta beat <0.5%

and peak to peak tune jitter $<1\times10^{-3}$

Sextupole: 100ppm

Courtesy: Weiming Guo, NSLS-II, BNL.

Alignment Specifications:

100 μm girder to girder; 30 μm magnet to girder; ±0.2 mrad magnet roll

Introduction

- For optimum performance, the magnetic axes of quadrupoles and sextupoles in NSLS-II should be aligned to better than ±30 microns.
- It is difficult to achieve the required accuracy using magnet fiducialization, coupled with optical survey.
- It is difficult, and expensive, to maintain the required machining and assembly tolerances in a long support structure (~5 m) holding several magnets.
- It is desirable to achieve the required alignment using direct magnetic measurements in a string of magnets.
- The vibrating wire technique, developed at Cornell, was deemed to be the most appropriate for this task.

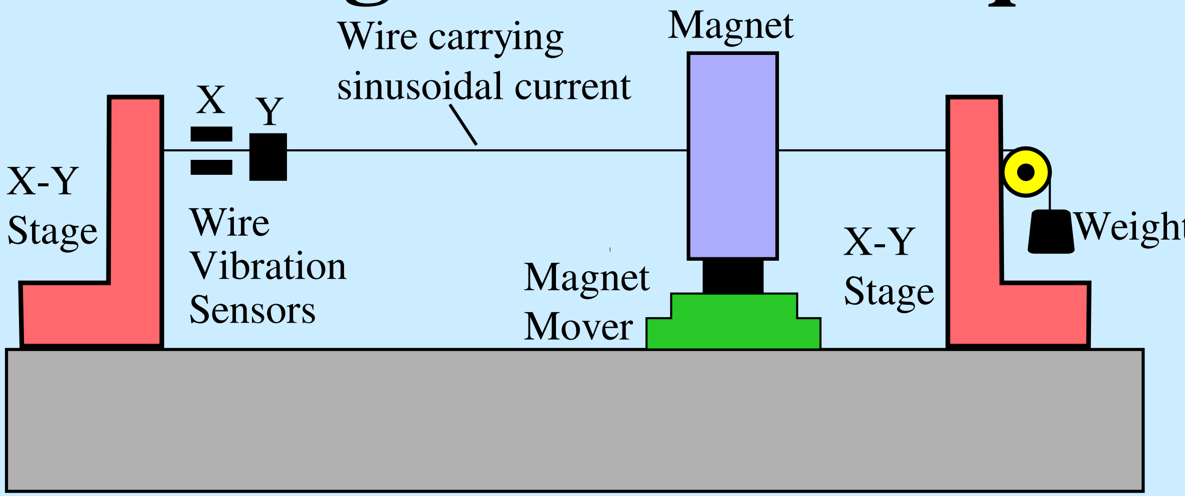
Steps Involved in Alignment

- Determine magnetic axis of all elements on a girder.
- Move magnets on a girder to a common axis.
- Secure magnets to the girder without disturbing the alignment.
- Verify alignment after securing the magnets.
- Fully characterize the magnet and girder positions in space.
- Reproduce the magnet and girder positions during the final installation in the machine.

Magnet Alignment R&D

- Although the vibrating wire technique had been used in the past for quadrupole measurements, very little work had been done in sextupoles.
- An R&D program was initiated to further develop the technique at BNL and demonstrate the required accuracy for both quadrupoles and sextupoles.
- Good measurement reproducibility has been achieved as a result of several improvements made over the course of this R&D program, which started in January, 2007.
- Work is still underway to study alignment stability and to adapt the measurements for a production environment.

The Vibrating Wire Technique: Basics

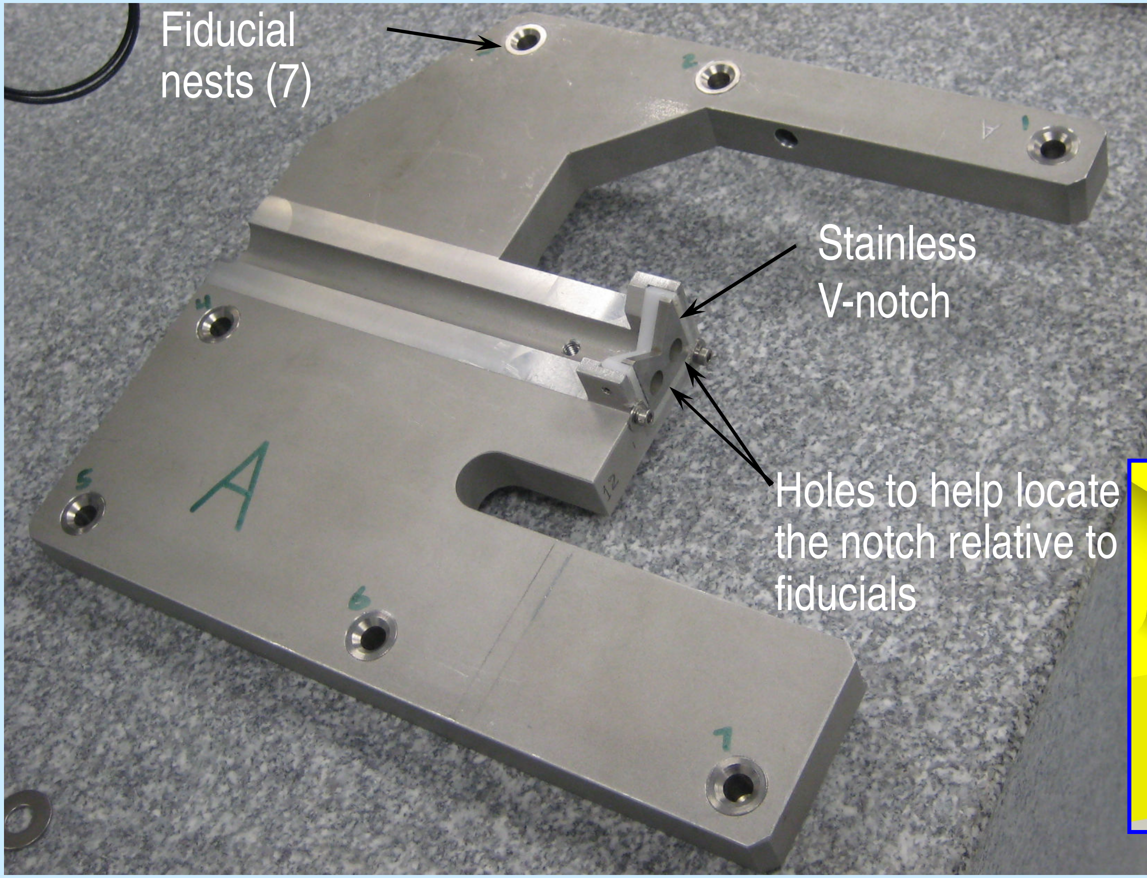


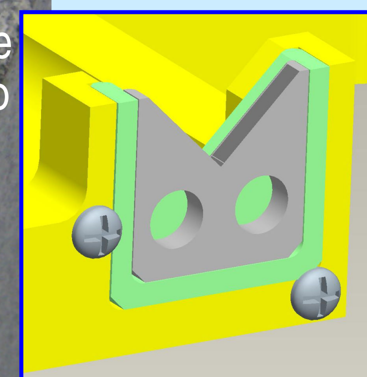
- An AC current is passed through a wire stretched axially in the magnet.
- Any transverse field at the wire location exerts a periodic force on the wire, thus exciting vibrations.
- The vibrations are enhanced if the driving frequency is close to one of the resonant frequencies, giving high sensitivity.
- The vibration amplitudes are studied as a function of wire offset to determine the transverse field profile, from which the magnetic axis can be derived.

Salient Features of the Vibrating Wire System

- Aerotech ATS03005 stages for wire movement (0.1 micron resolution; 2.5 micron/25 mm accuracy).
- Wire ends are defined by stainless steel V-notches.
- Set of 7 fiducials at each end to locate the V-notches.
- A pair of X-Y wire vibration sensors at each end of the wire. Allows two independent, simultaneous measurements for data verification and redundancy.
- Completely rewritten acquisition and analysis software with scripting support for flexibility in experiment control.

Wire End Support (V-notch)

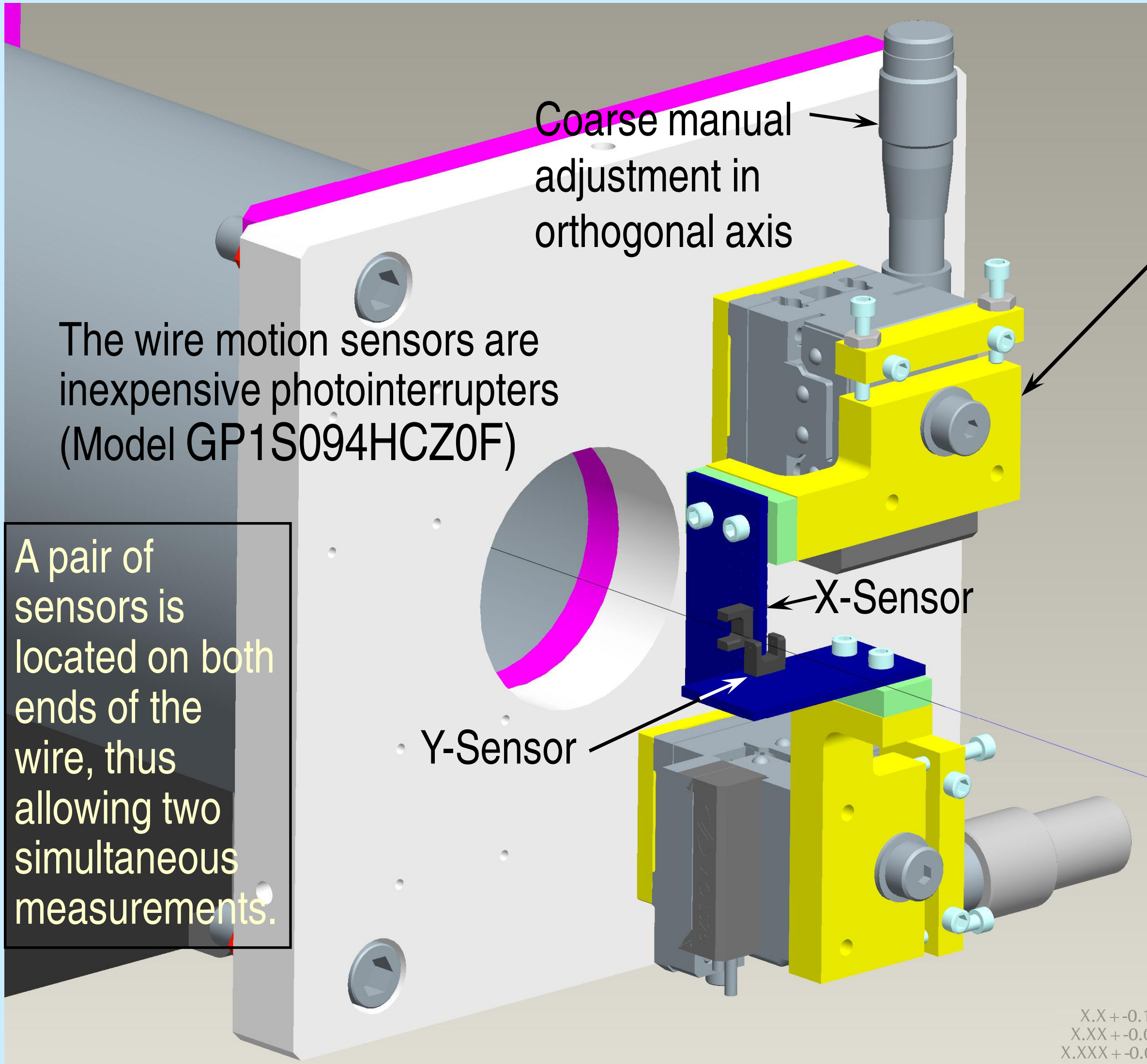




Fiducials relate the wire ends to the overall girder coordinate system.

A V-notch with radius much smaller than the wire was chosen.
The wire position is thus insensitive to the actual radius of the V-notch.

Wire Vibration Sensors

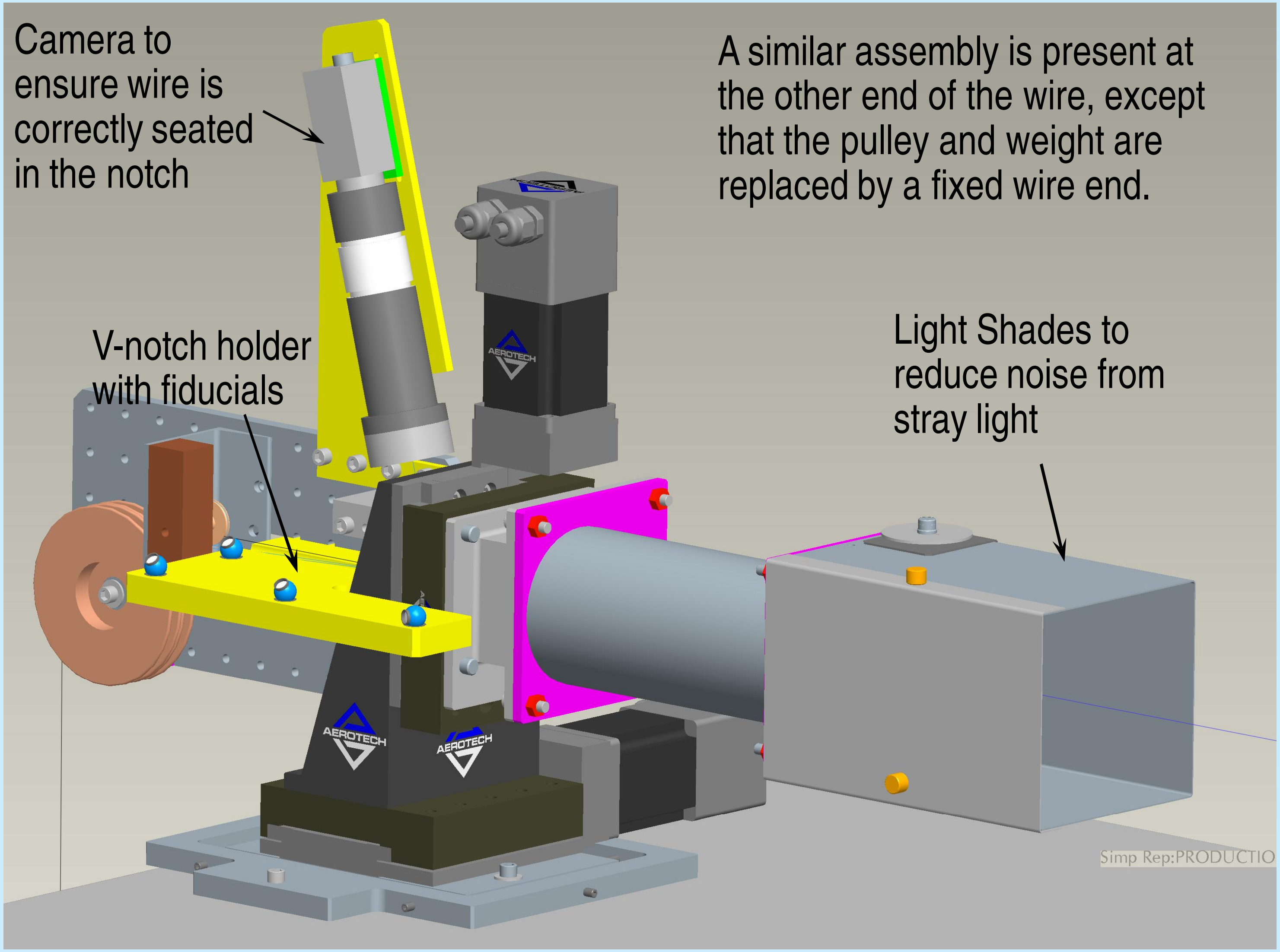


Fine, automated adjustment along measurement axis using piezo stages

As the wire is moved horizontally or vertically, the position of the wire relative to the sensor changes slightly (~ a few microns) due to imperfections in the stage motion. This causes a change in the operating point of the sensor.

An automated piezo stage was added to keep the wire "centered" in the sensors during a scan.

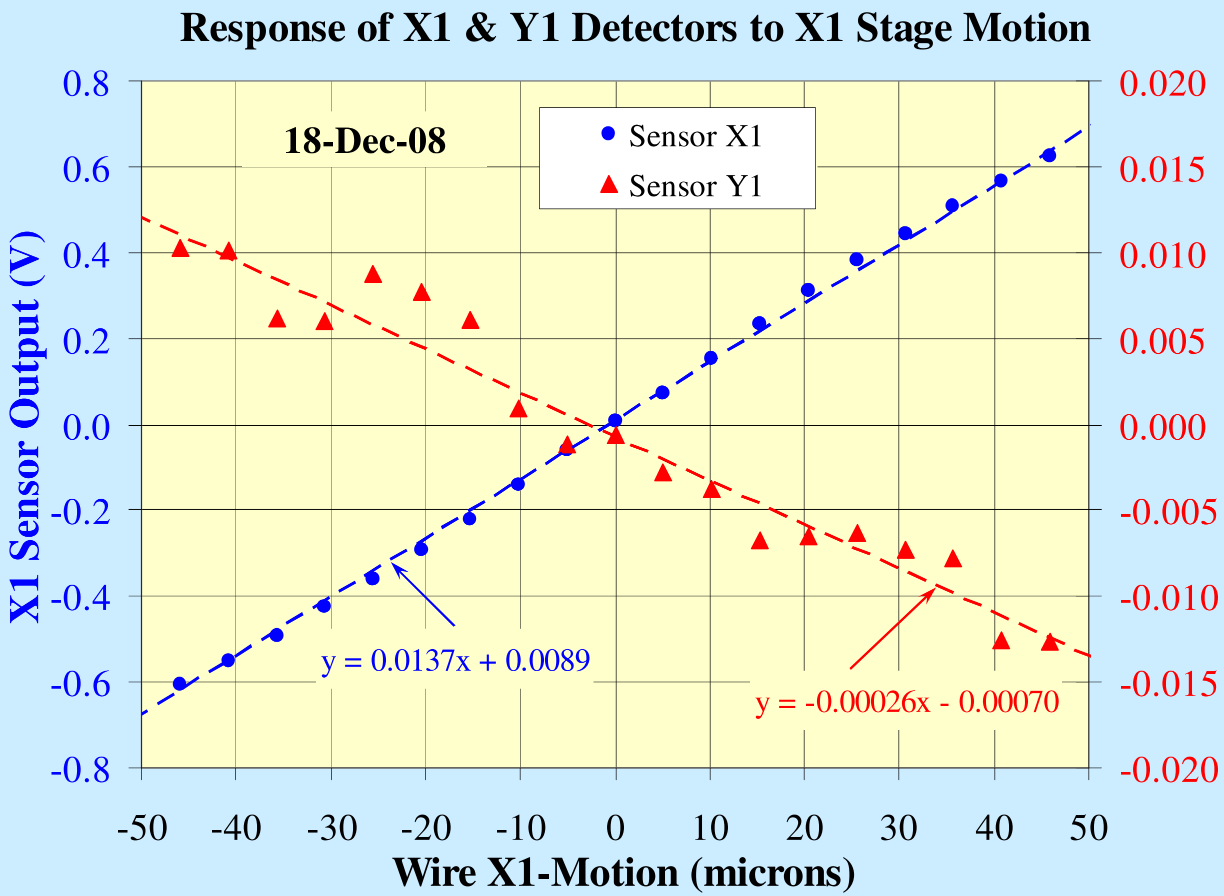
Complete Wire Mover Assembly



Alignment Issues Studied

- Wire sag correction
- Detector sensitivity to orthogonal motion
- Sensitivity to Yaw/Pitch of magnets
- Accuracy of quadrupole center measurement
- Accuracy of sextupole center measurement
- Background field correction
- Ability to precisely move magnets (manually) and secure to the girder.
- Reproducibility of the girder vertical profile.
- Stability of magnet alignment after transporting a girder.

Detector Sensitivity to Orthogonal Motion



Measured signal is contaminated by sensitivity to motion along the orthogonal axis, thus causing errors in the measurement of magnetic center.

A rigorous analysis has shown that the error in horizontal/vertical center is minimized if wire is scanned at the vertical/horizontal center in both quadrupoles and sextupoles. This implies that a rough center must be found first before the final scan.

Resonant Mode to Use: Yaw/Pitch Sensitivity

- Should have a maxima near the axial center of the magnet being measured.
- Preferably even numbered modes should be used to avoid contribution from any axially uniform background fields (e.g. earth's field).
- It may be impractical to find a mode with maxima exactly at the axial center for every magnet on the girder. This causes sensitivity to yaw and pitch.
- One should choose a mode that minimizes sensitivity to yaw and pitch without sacrificing signal strength.

Sensitivity to Yaw and Pitch

$$B_y(z) = \sum_{n=1}^{\infty} B_{yn} \sin(n\pi z / L)$$

Signal for mode = *n* is proportional to B_{yn}
(for a given detector position)

In a quadrupole magnet with offset x_0 and yaw angle Θ, located at $z = z_{mag}$:

$$B_y(z) = Gx_0 - G(z - z_{mag})\Theta$$

z_{mag} = magnet axial position; G = Gradient

$$B_{yn} = \left(\frac{4Gx_0}{n\pi}\right)\sin\left(\frac{n\pi z_{mag}}{L}\right)\sin\left(\frac{n\pi L_{mag}}{2L}\right)$$
$$-\Theta\left(\frac{4GL}{n^2\pi^2}\right)\cos\left(\frac{n\pi z_{mag}}{L}\right)\left[\sin\left(\frac{n\pi L_{mag}}{2L}\right)-\left(\frac{n\pi L_{mag}}{2L}\right)\cos\left(\frac{n\pi L_{mag}}{2L}\right)\right]$$

L_{mag} = magnetic length

L = wire length

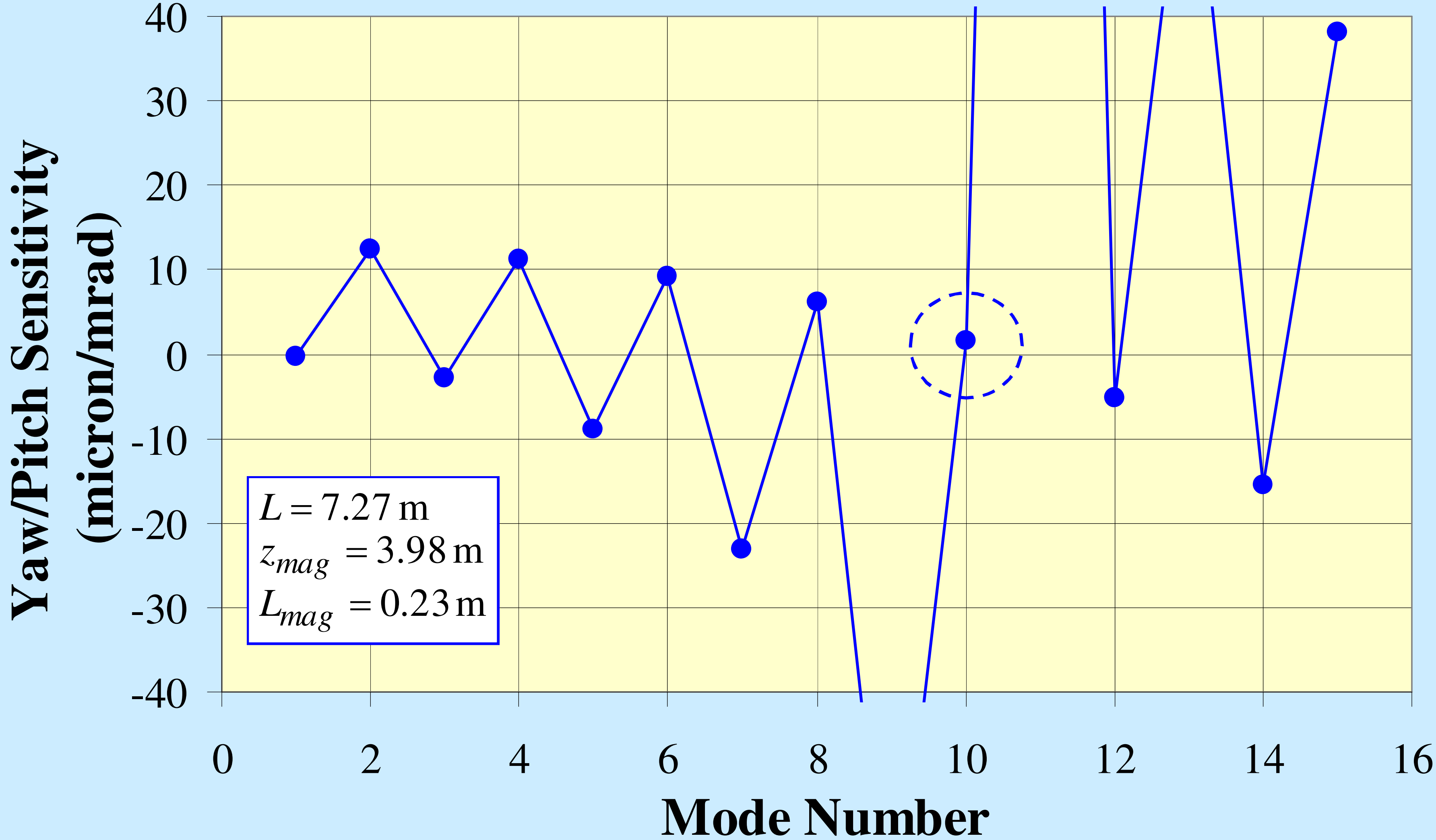
Error in center determination due to yaw:

$$\Delta x_0 = \left(\frac{L}{n\pi}\right)\cot\left(\frac{n\pi z_{mag}}{L}\right)\left[1-\left(\frac{n\pi L_{mag}}{2L}\right)\cot\left(\frac{n\pi L_{mag}}{2L}\right)\right]\Theta$$

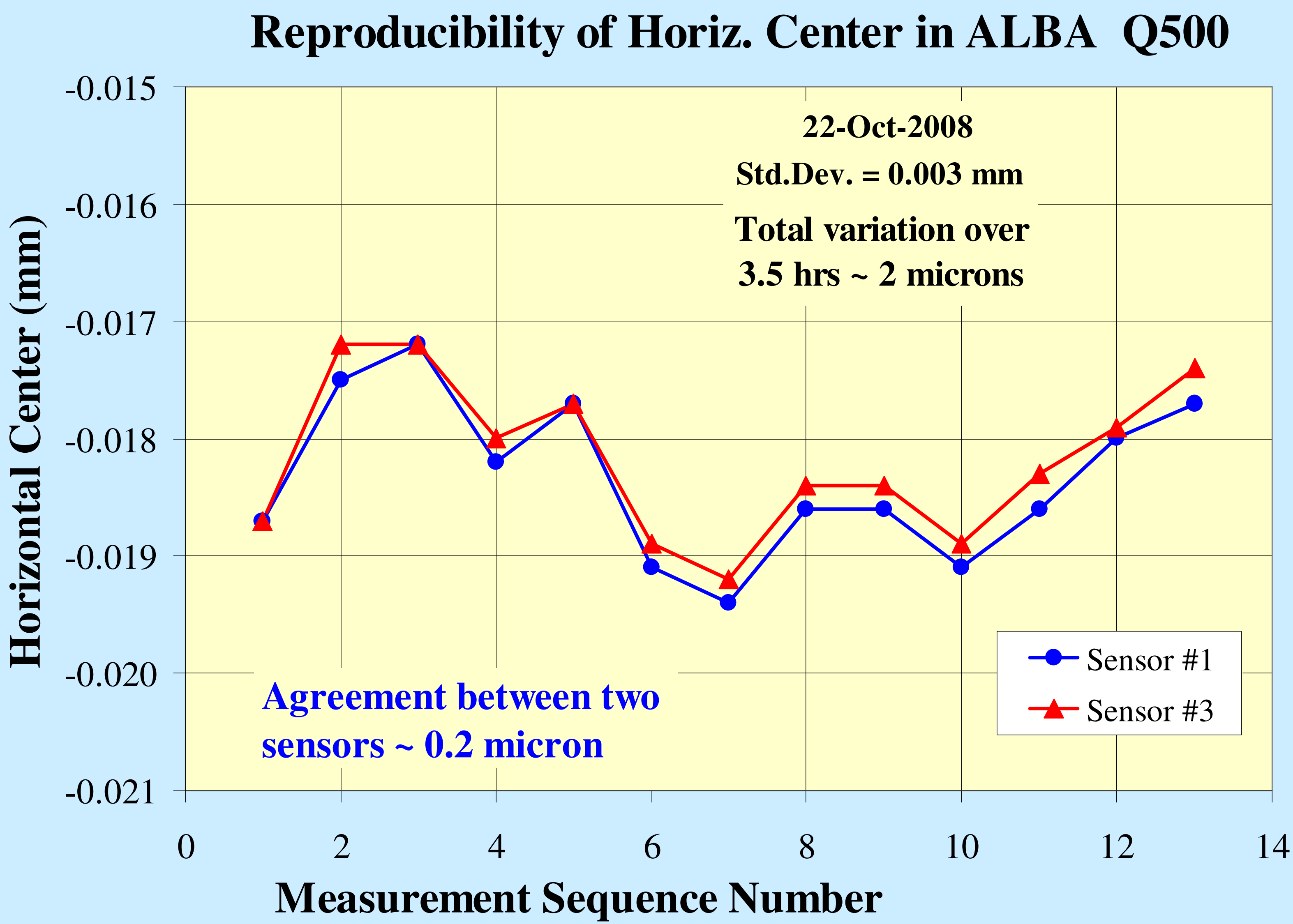
A similar expression applies to vertical offset and pitch angle.

A similar analysis for sextupoles is much more tedious, but the same expression for Δx_0 is obtained in the end!

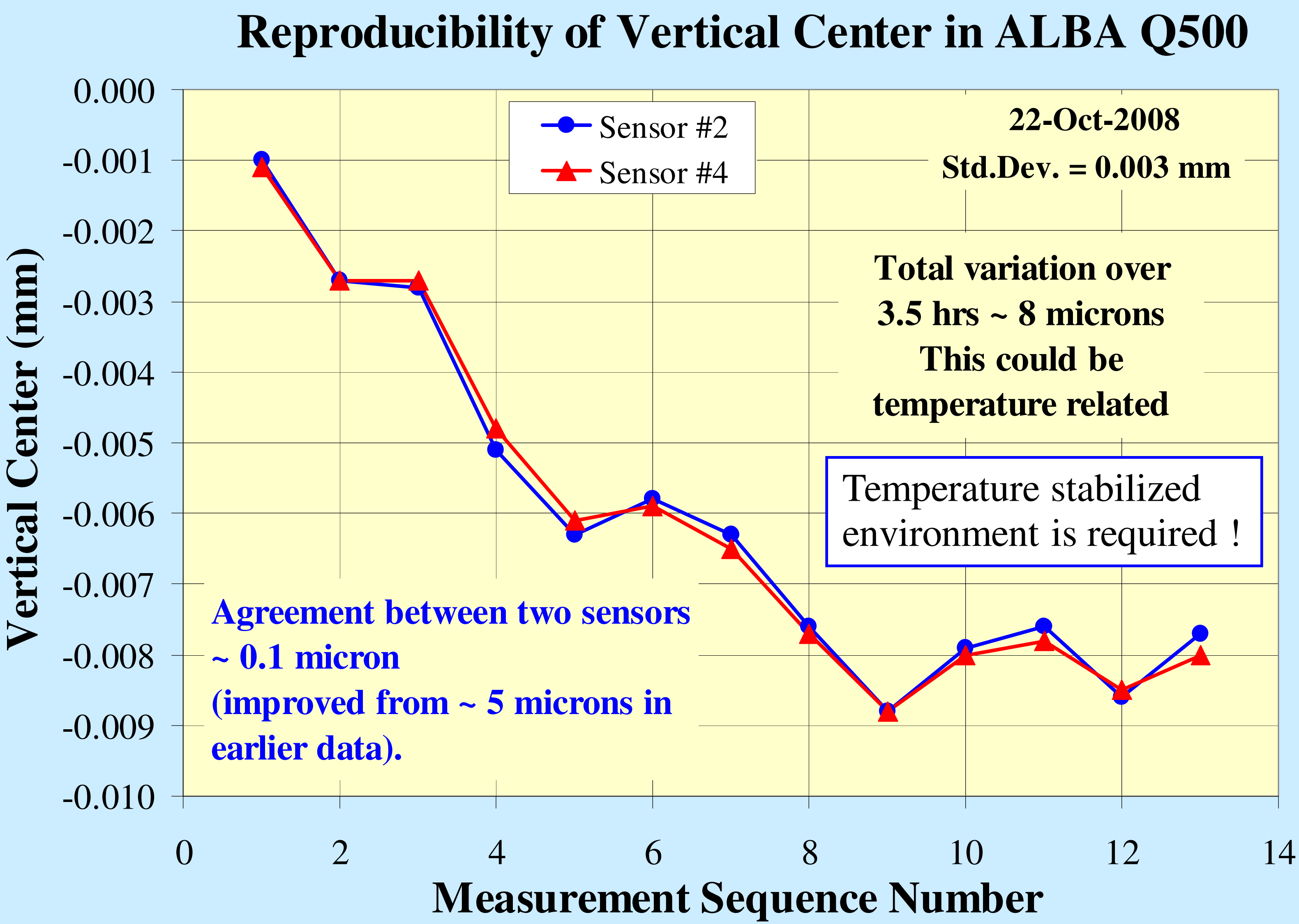
Yaw/Pitch Sensitivity for Various Modes



Reproducibility of Horizontal Center in Quad



Reproducibility of Vertical Center in Quad

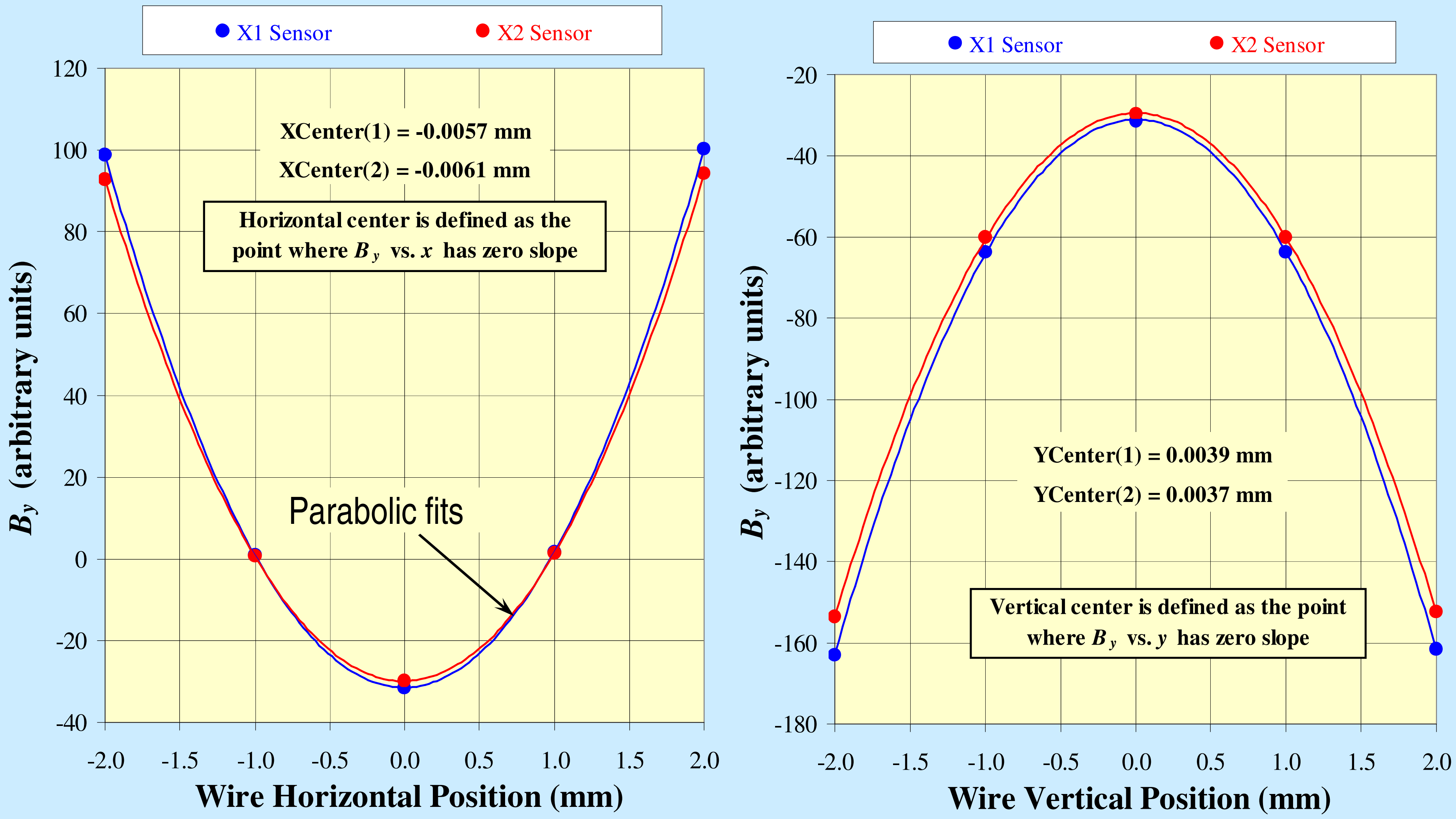


Sextupole Measurements Using B_y and B_x

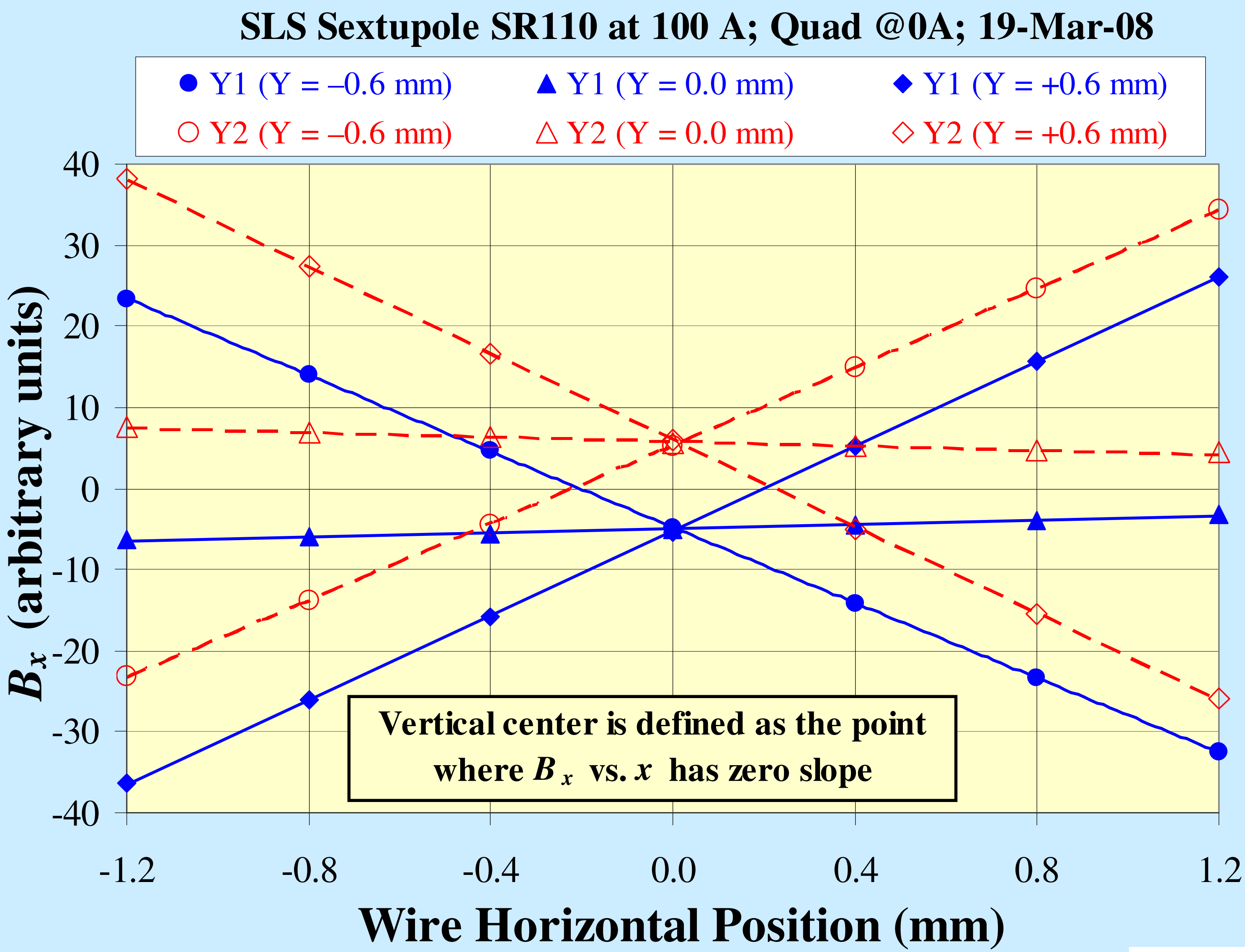
$$B_y = B_3\left[\frac{(x-x_0)^2-(y-y_0)^2}{R_{ref}^2}\right] \qquad B_x = 2B_3\left[\frac{(x-x_0)(y-y_0)}{R_{ref}^2}\right]$$

- Obtaining centers from B_y vs. x and B_y vs. y plots uses only one set of sensors, and requires quadratic fits.
- One could also use scans of B_x vs. x (or y) for various values of y (or x). These plots are expected to be linear with slopes proportional to offsets in y (or x) direction.
- Doing three such scans allows to obtain centers from both B_x and B_y data. With 2 sets of sensors, one gets four values of magnetic center.

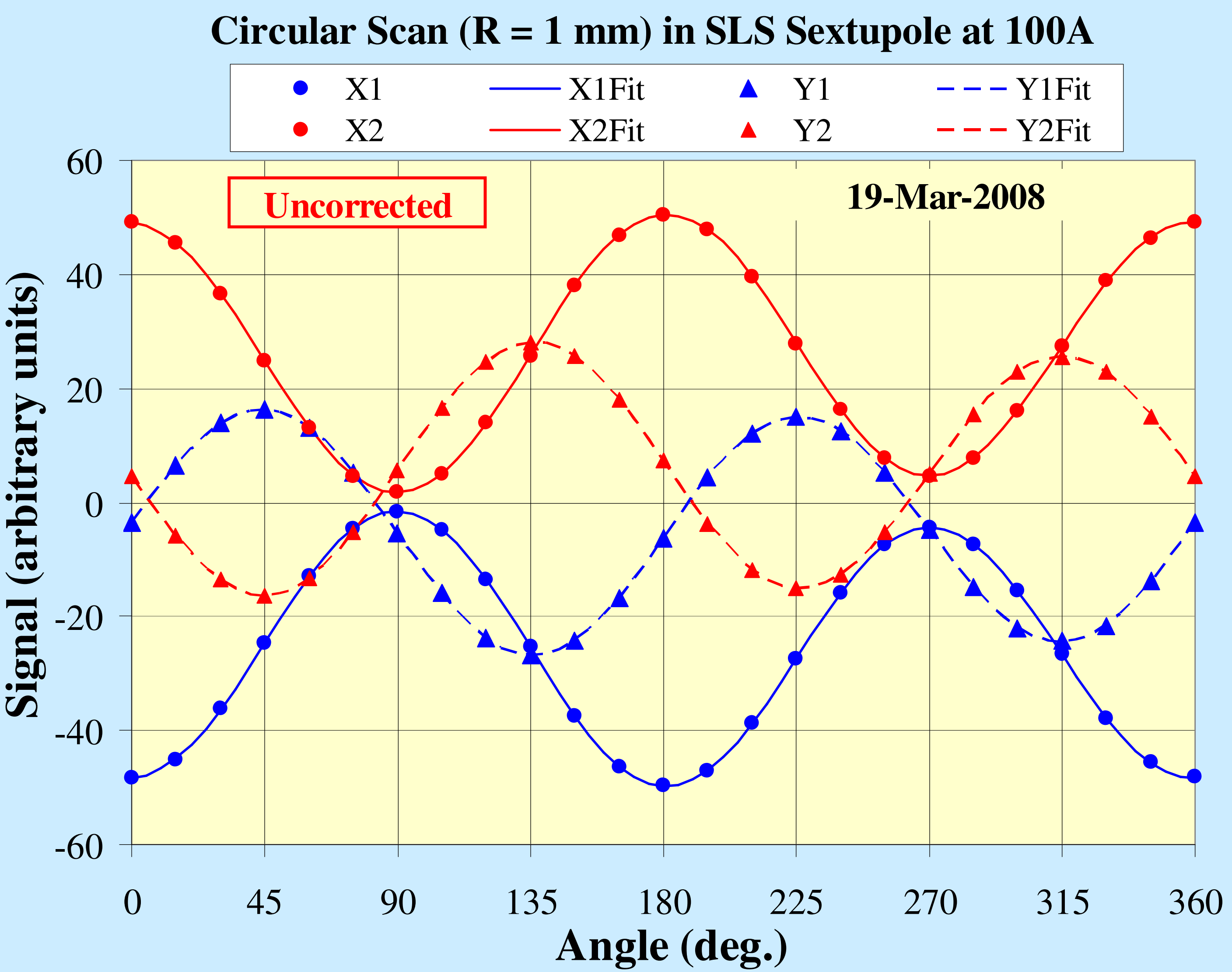
Sextupole Measurements: B_y Scans



Sextupole Measurements: B_x Scans



Yet Another Way to Measure Sextupoles



Fit measured data to a truncated Fourier Series, giving quadrupole and sextupole terms.

Both X and Y Centers can be obtained using any of the 4 detectors in a single scan.

Comparison of Sextupole Data Using B_x and B_y

Summary of Sextupole Center Measurements in SR110 at 100A

19-Mar-2008: Comparison of Circular and Linear Scan Results

Method Number	Scan Type	Sensor Used	Uncorrected X_Center (μm)	Uncorrected Y_Center (μm)	Background Corrected X_Center (μm)	Background Corrected Y_Center (μm)	Correction Needed in X_Center (μm)	Correction Needed in Y_Center (μm)
1	CIRCULAR (single scan; 25 points)	X1 (B_y)	13.7	-30.8	-155.1	-31.3	-168.8	-0.5
2		Y1 (B_x)	8.3	-31.8	-160.8	-32.5	-169.1	-0.7
3		X2 (B_y)	13.7	-34.1	-154.5	-33.1	-168.3	1.0
4		Y2 (B_x)	8.7	-31.1	-160.1	-31.5	-168.8	-0.4
5	LINEAR (6 scans; 7 points each)	X1 (B_y)	10.0	-31.5	-160.9	-32.5	-170.9	-1.0
6		Y1 (B_x)	10.8	-32.9	-160.0	-35.0	-170.8	-2.1
7		X2 (B_y)	9.4	-31.6	-161.5	-32.9	-170.9	-1.3
8		Y2 (B_x)	10.1	-32.1	-160.6	-30.5	-170.7	1.6
Mean of all 8 methods:			**10.6**	**-32.0**	**-159.2**	**-32.4**	**-169.8**	**-0.4**
Std. Deviation of all 8 methods:			**2.1**	**1.1**	**2.8**	**1.4**	**1.1**	**1.2**
Mean of Circular Scan Data:			**11.1**	**-31.9**	**-157.6**	**-32.1**	**-168.7**	**-0.2**
Std. Deviation of Circular Scan:			**3.0**	**1.5**	**3.3**	**0.8**	**0.3**	**0.8**
Mean of Linear Scans:			**10.1**	**-32.0**	**-160.7**	**-32.7**	**-170.8**	**-0.7**
Std. Deviation of Linear Scans:			**0.6**	**0.7**	**0.6**	**1.9**	**0.1**	**1.6**
Circular to Linear Scan Diff.:			**1.0**	**0.1**	**3.1**	**0.6**	**2.1**	**0.5**

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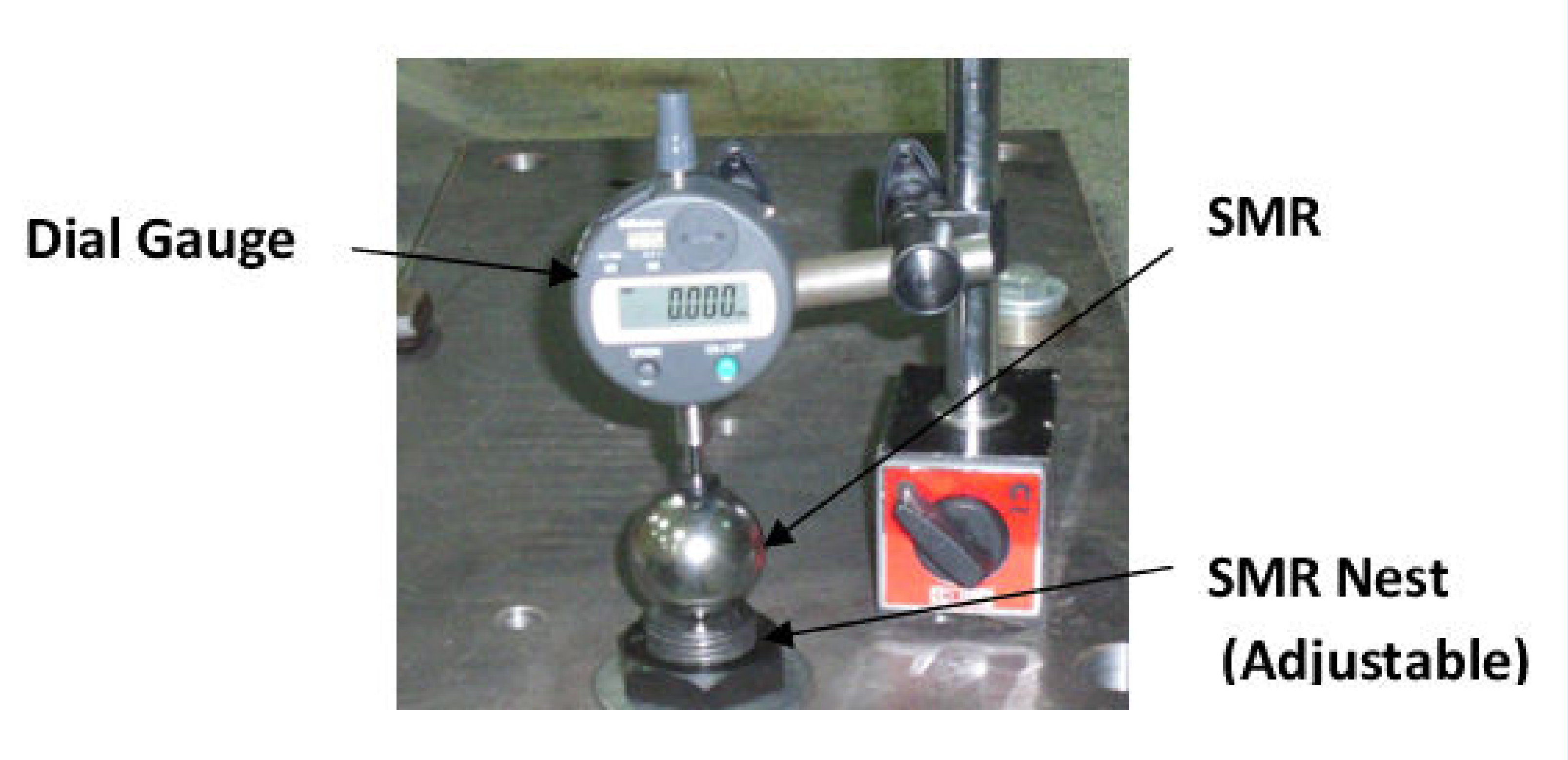
Issue of Background Fields in Sextupole Meas.

- There is a significant quadrupole background field from quadrupole magnet(s) even when these are unpowered.
- Based on rotating coil data, the remnant integrated quadrupole field is ~0.02 T. This could amount to a change in horizontal center by hundreds of microns, depending on quad position and the mode used for sextupole measurements.
- The vertical center measurement is not affected because B_y (or B_x) is independent of y (or x) in a quadrupole field.
- Effectiveness of background correction has been tested by measuring a sextupole in the presence of a quadrupole which was either unpowered, or was powered at 2 A (apparent center shift of ~600 microns). Corrected center = ±5 microns.

Reproducing Girder Vertical Profile

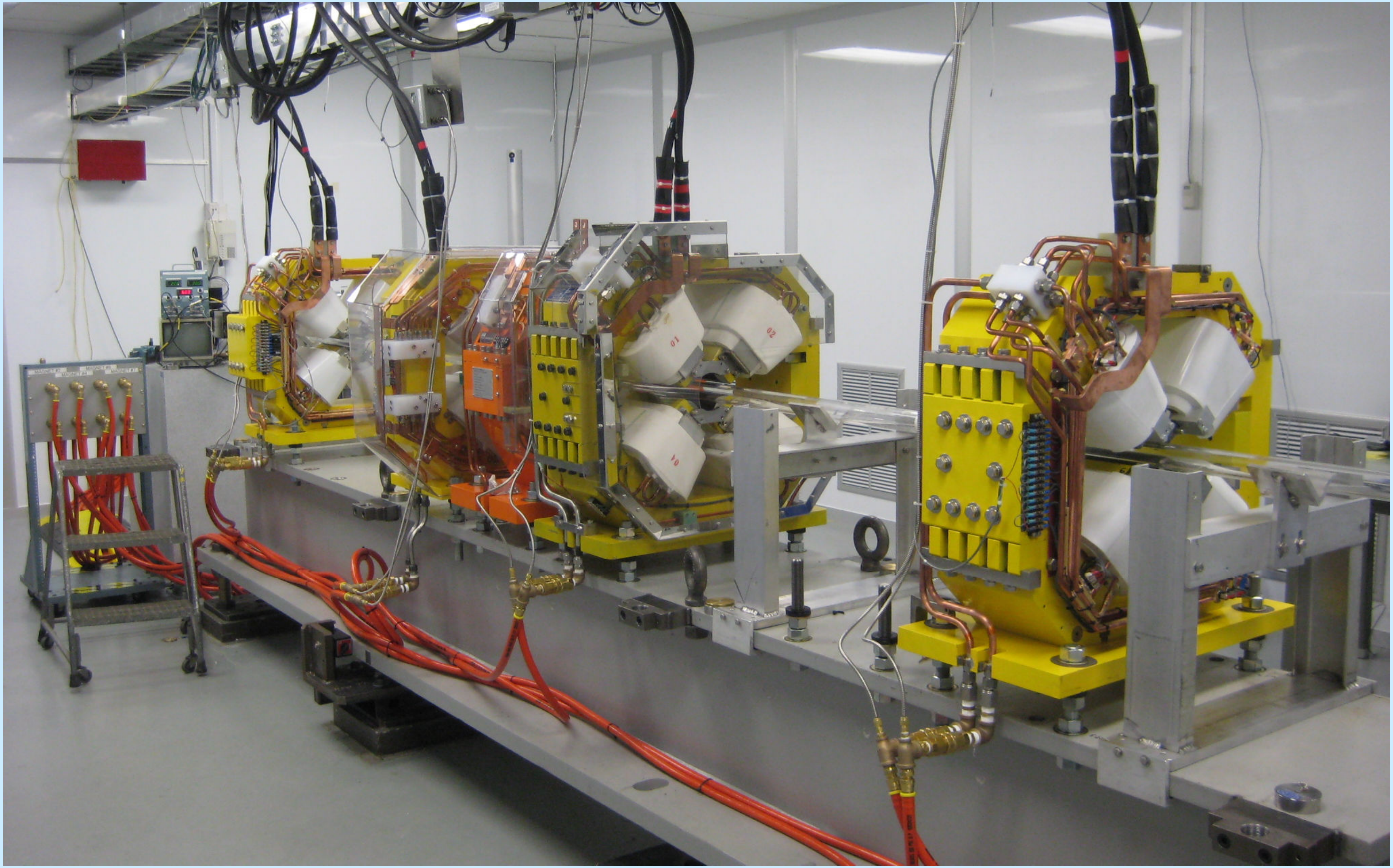
- The girder, if supported at the four corners only, has a sag of about 150 microns.
- Based on studies done in a prototype girder, the vertical profile of the girder could vary by as much as ~30 microns simply as a result of handling.
- It is, therefore, essential to not only measure the magnet centers precisely, but also to have a precise means of characterizing and then reproducing the girder vertical profile during installation.
- It was demonstrated that the girder vertical profile can be measured to better than ~10 microns using multiple laser tracker setups in a temperature controlled chamber (< ±0.1 C).

Feasibility of Profiling by Laser Tracker



A Laser Tracker target was placed on an adjustable mount and its vertical position was monitored with a digital dial gauge. The laser tracker was used to measure changes in the vertical position and the results were compared to the dial gauge readings. Typical agreements were well below 10 microns.

NSLS-II Prototypes in Vibrating Wire Test Stand



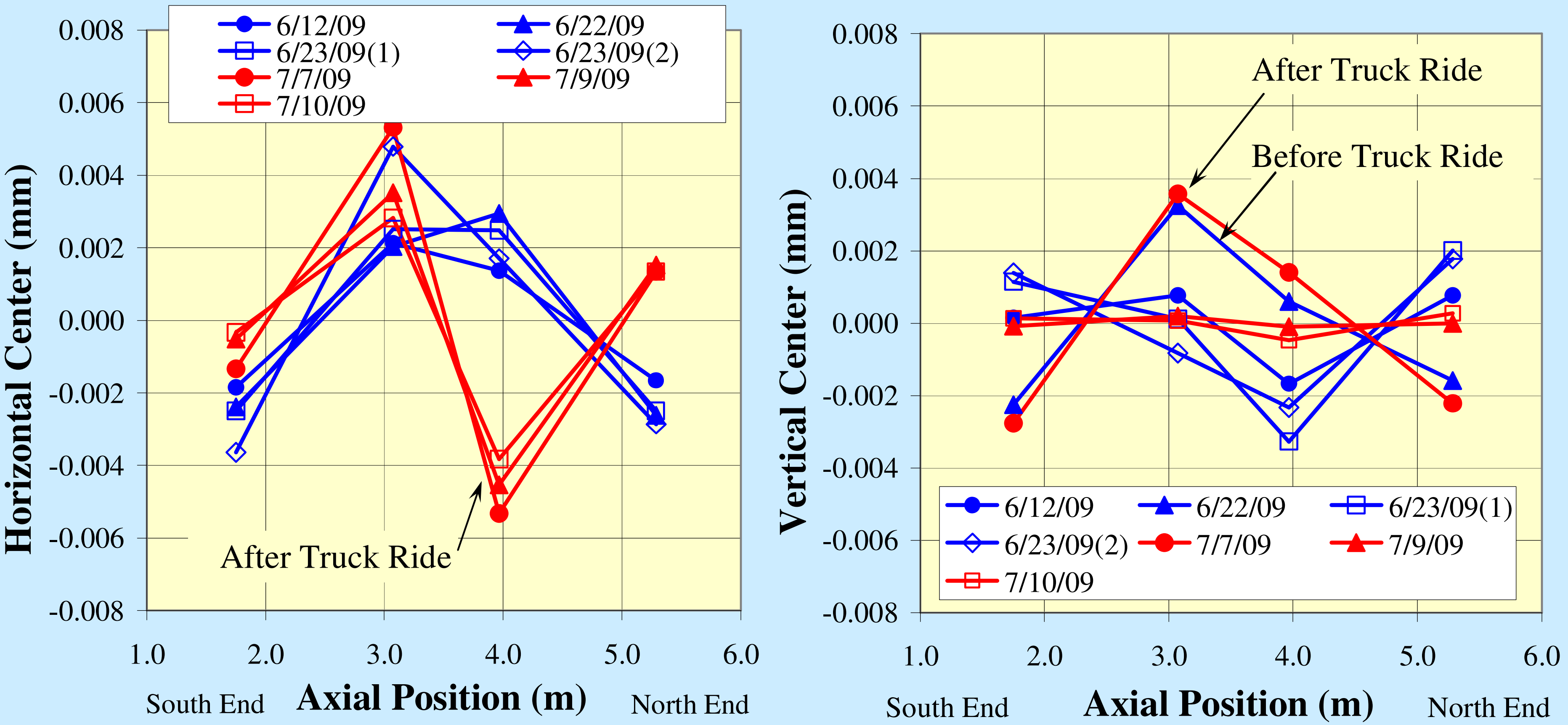
Alignment Stability

- Four NSLS-II prototype quadrupole magnets were mounted on a prototype girder, and prealigned using a laser system.
- The girder was installed in the temperature controlled room and the magnets were hooked up to power and water supplies.
- The magnetic centers of all the magnets were measured, and all the remaining steps in the alignment process outlined earlier were carried out.
- The girder was then removed from the test bench, loaded on a truck, driven around the laboratory site, unloaded and reloaded on the truck, and then brought back to the test area.
- The girder was reinstalled, the girder vertical profile was reproduced using survey, and magnetic centers were measured again to see if the initial alignment of the magnets was maintained.

Alignment Stability During Girder Handling

Four NSLS-II Prototype Quadrupoles on a Prototype Girder

Alignment Errors With Respect to a Best Fit Straight Line



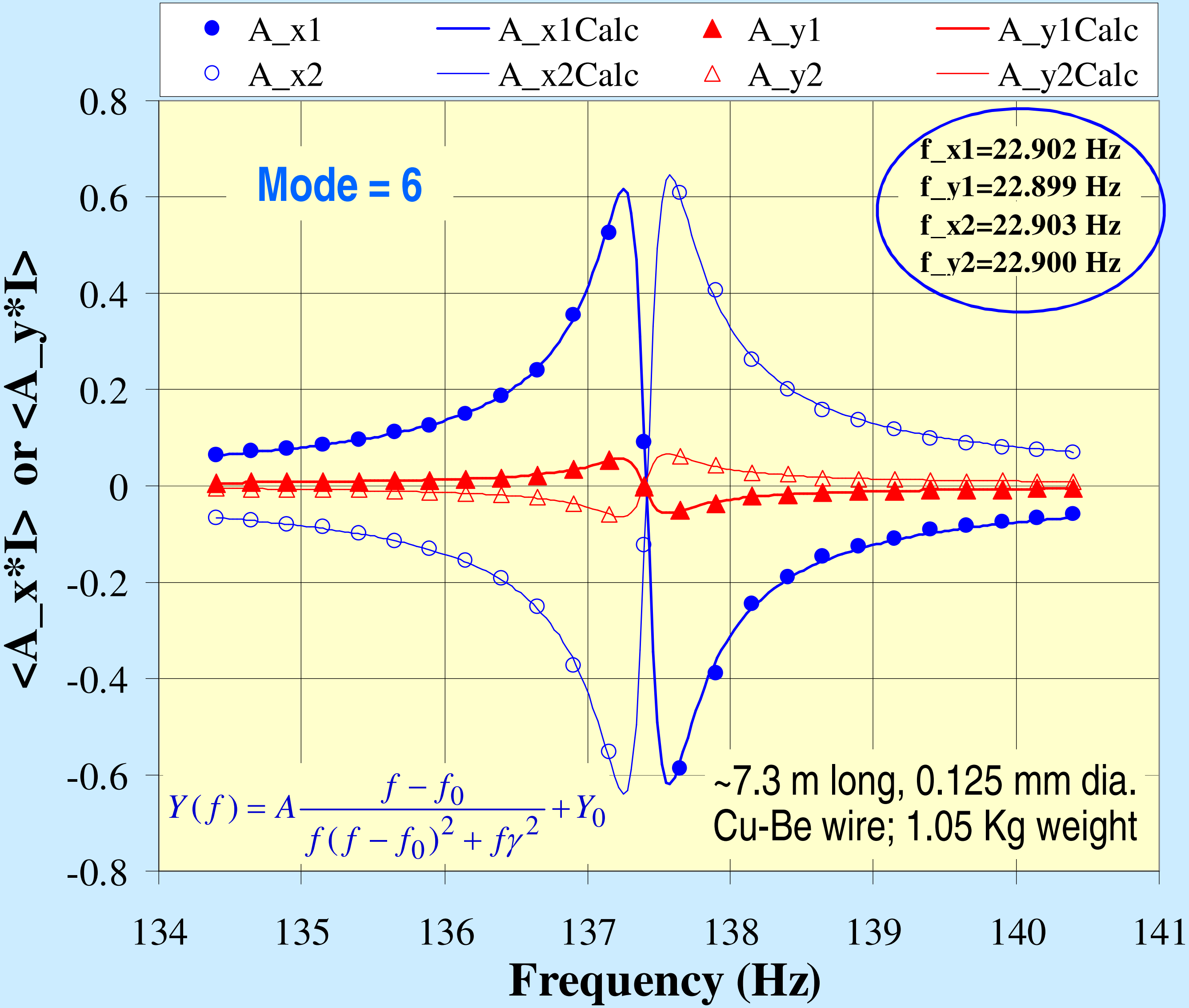
Conclusions

- An extensive R&D program has been carried out to build a state-of-the-art vibrating wire system, and to study various issues.
- Possible sources of error are studied analytically, and the measurement procedures developed to minimize the errors.
- Excellent consistency (at sub-micron level) is routinely achieved between data from two sets of sensors.
- Absolute accuracy of < 5 μm, as judged by correlation with mechanical motion, and consistency between four independent methods of measuring a sextupole, has been demonstrated.
- It has been shown that magnets can be secured to the girder while maintaining alignment within ~ 5 μm.
- The alignment of the magnets was shown to survive careful handling.
- The vibrating wire system is nearly ready for production measurements.

Thank You !

Supplemental Material

Resonant Frequency and Wire Sag



$$f_0 = \frac{1}{2L}\sqrt{\frac{T}{m_\ell}}$$

T = Tension

L = Length

m_ℓ = mass per unit length

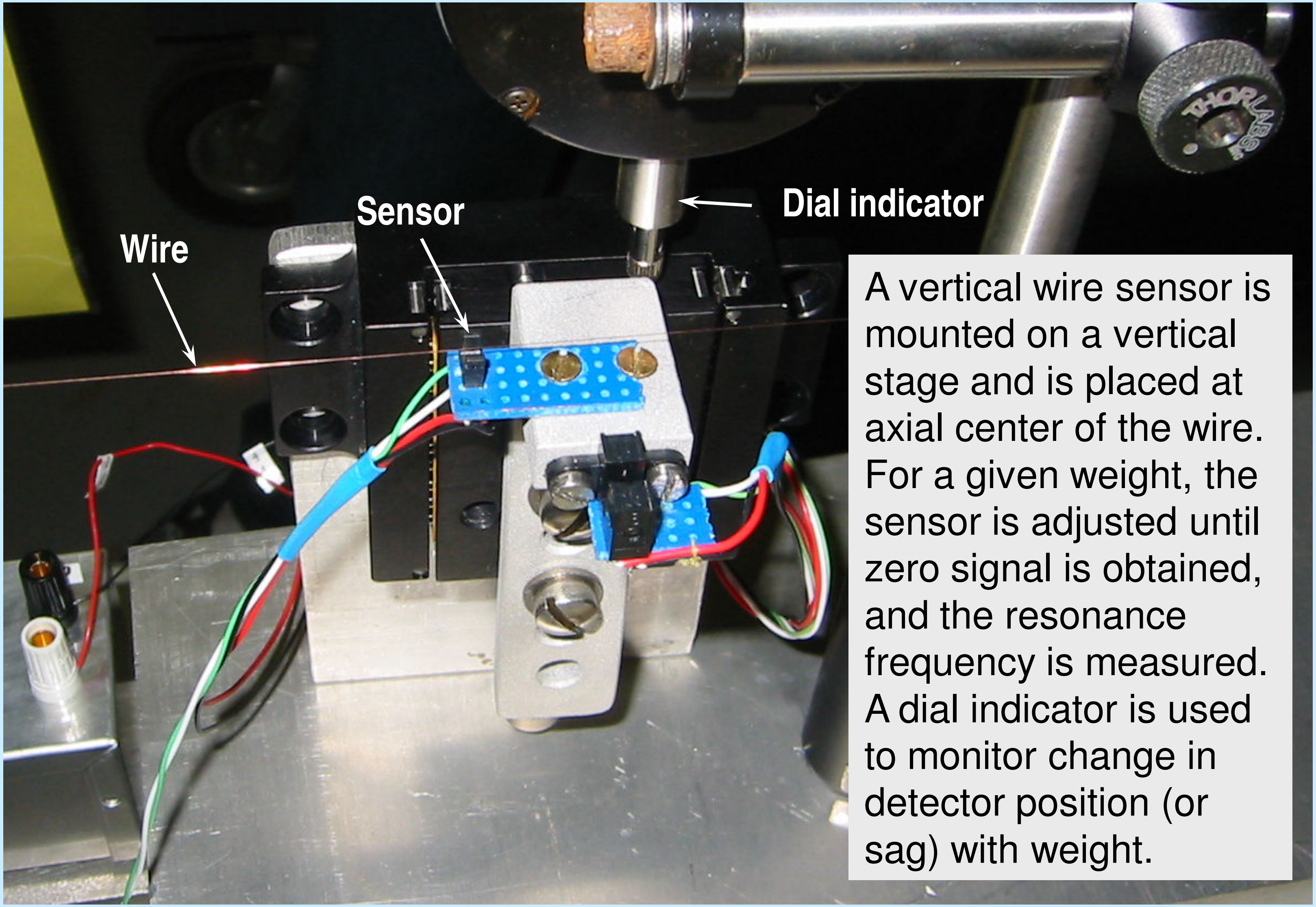
$$Sag = \frac{m_\ell g L^2}{8T}$$

$$Sag = \frac{g}{32 f_0^2}$$

Correction for large wire sag (~550-600 microns for ~7.3 m length) is very important, which in turn requires a very precise knowlege of resonant frequency.

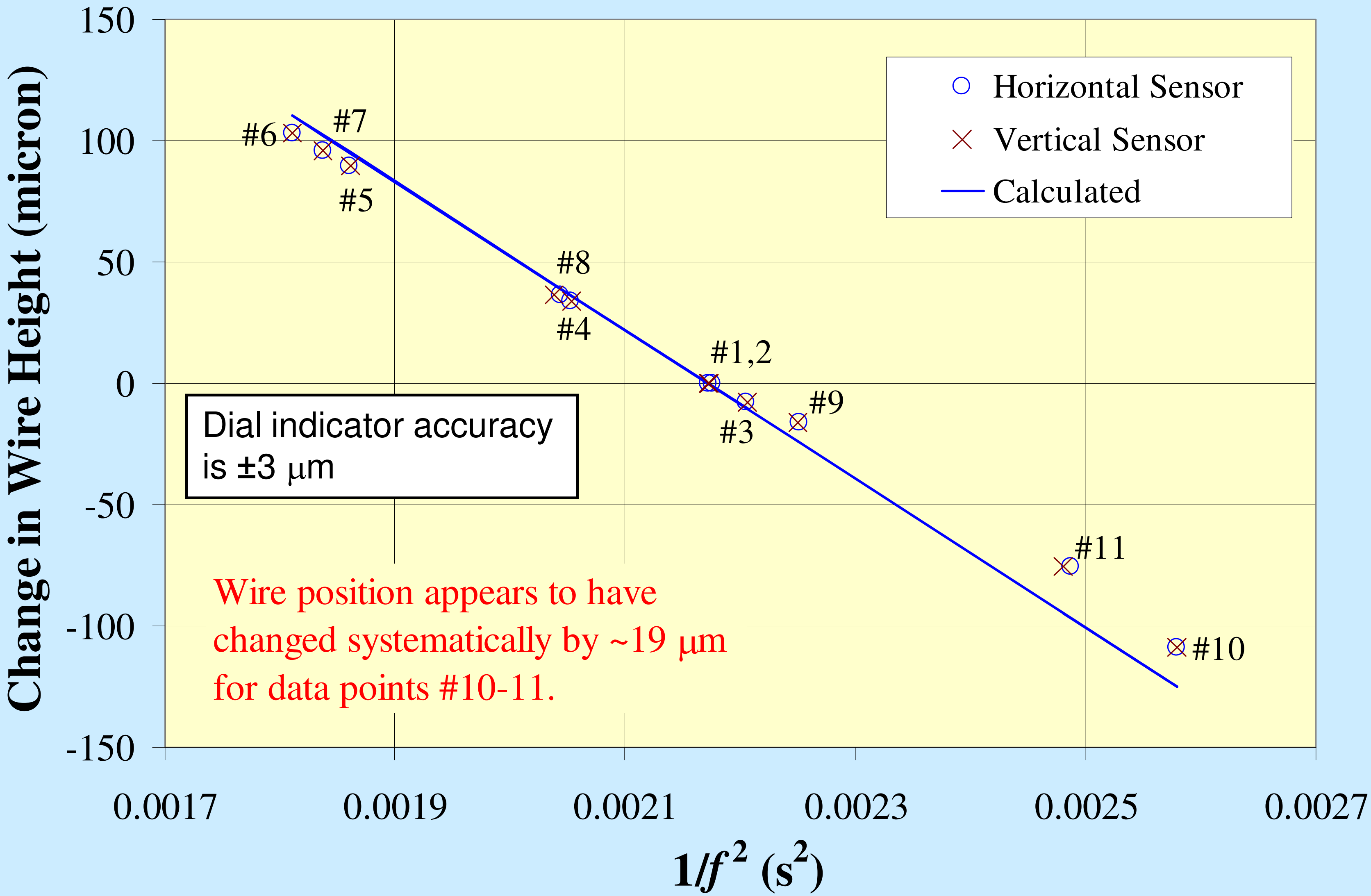
±0.02 Hz ⇒ ± 1 micron

Experimental Setup for Sag Measurements

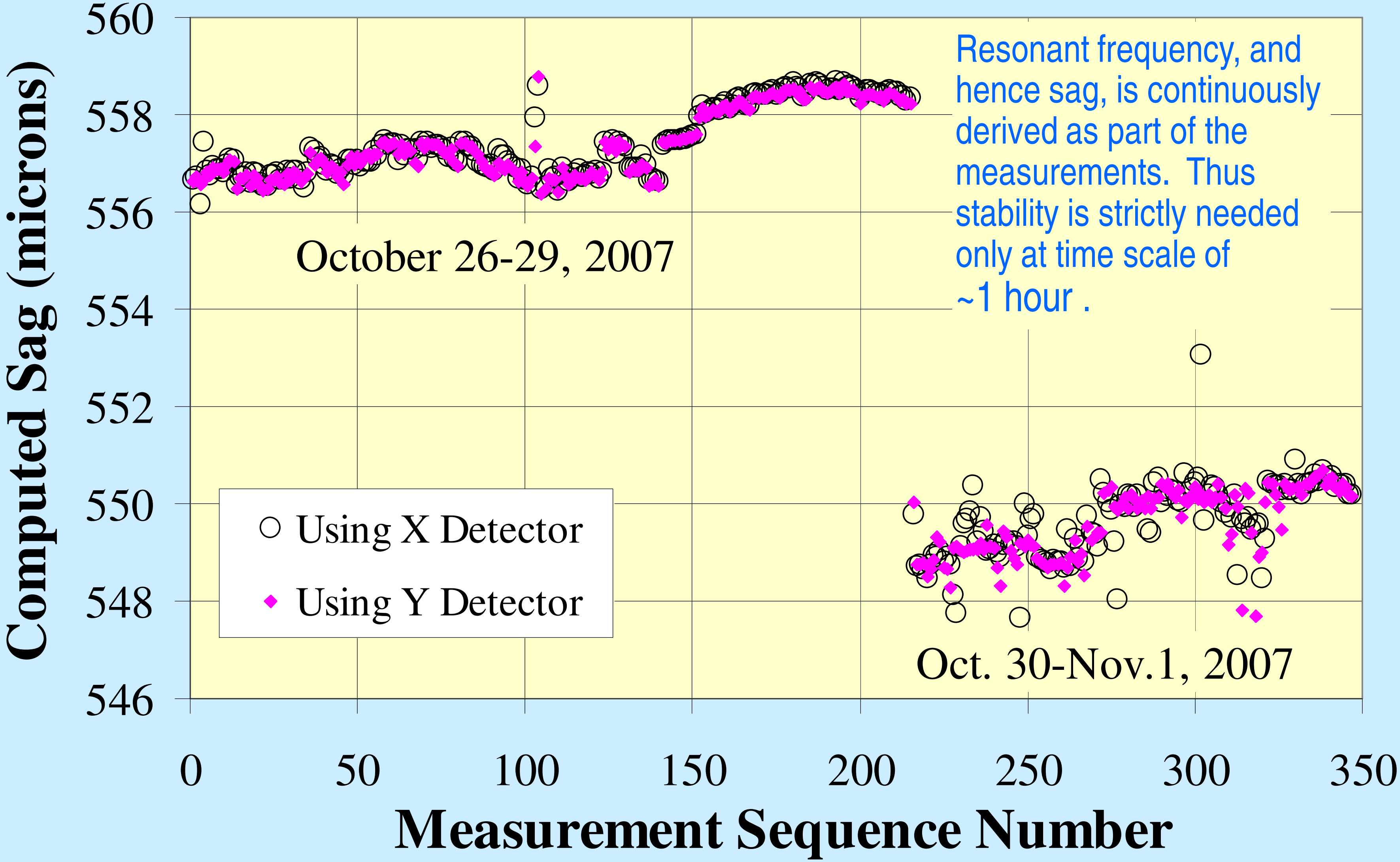


A vertical wire sensor is mounted on a vertical stage and is placed at axial center of the wire. For a given weight, the sensor is adjusted until zero signal is obtained, and the resonance frequency is measured. A dial indicator is used to monitor change in detector position (or sag) with weight.

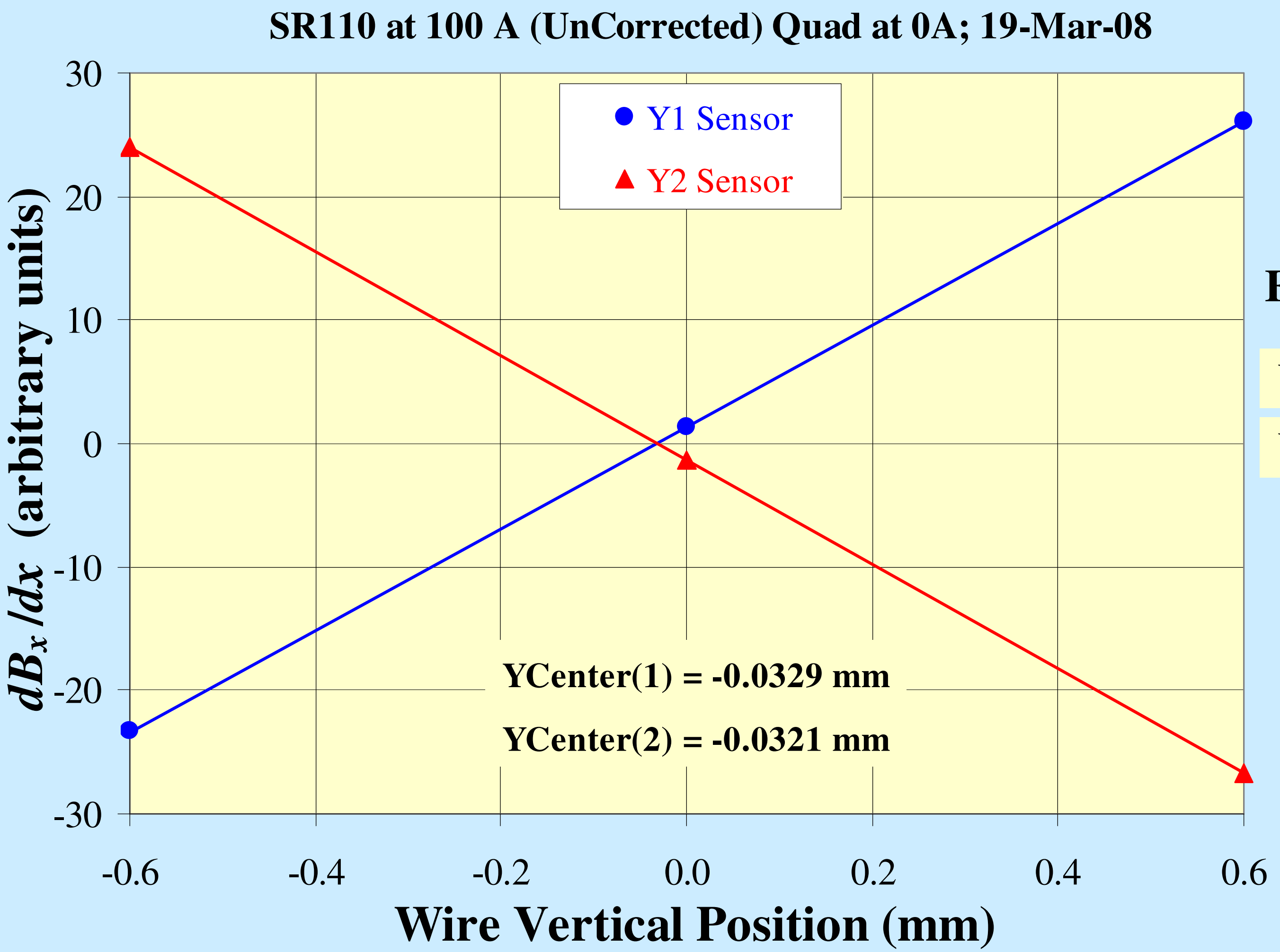
Sag: Measured Vs. Calculated



Stability of Wire Sag Over Several Days



Horizontal Scans (B_x): Slope Vs. *Y* Offset

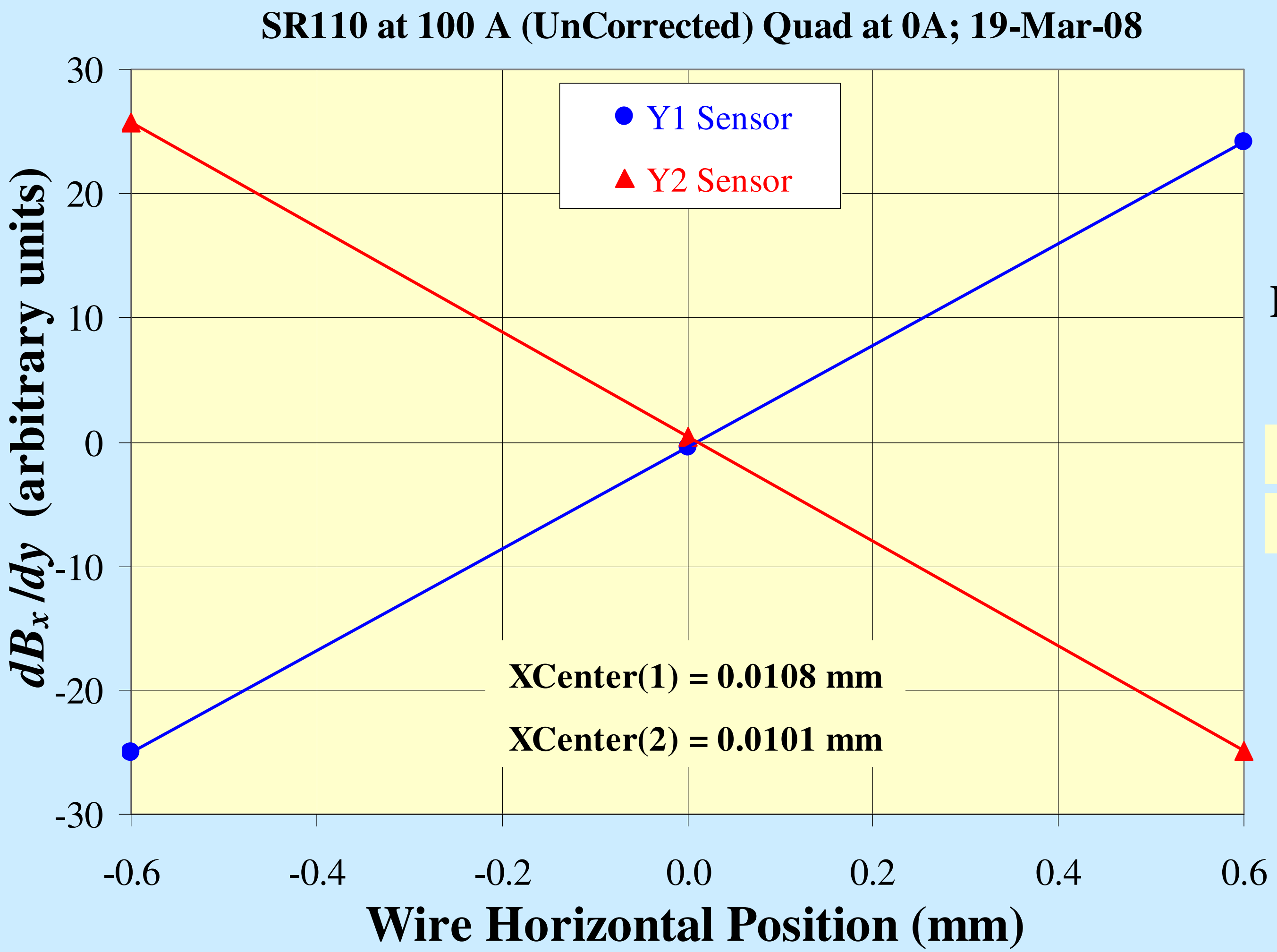


From dB_x/dx Vs *y* Plots:

YCenter(1) = -0.0306 mm

YCenter(2) = -0.0304 mm

Vertical Scans (B_x): Slope Vs. *X* Offset

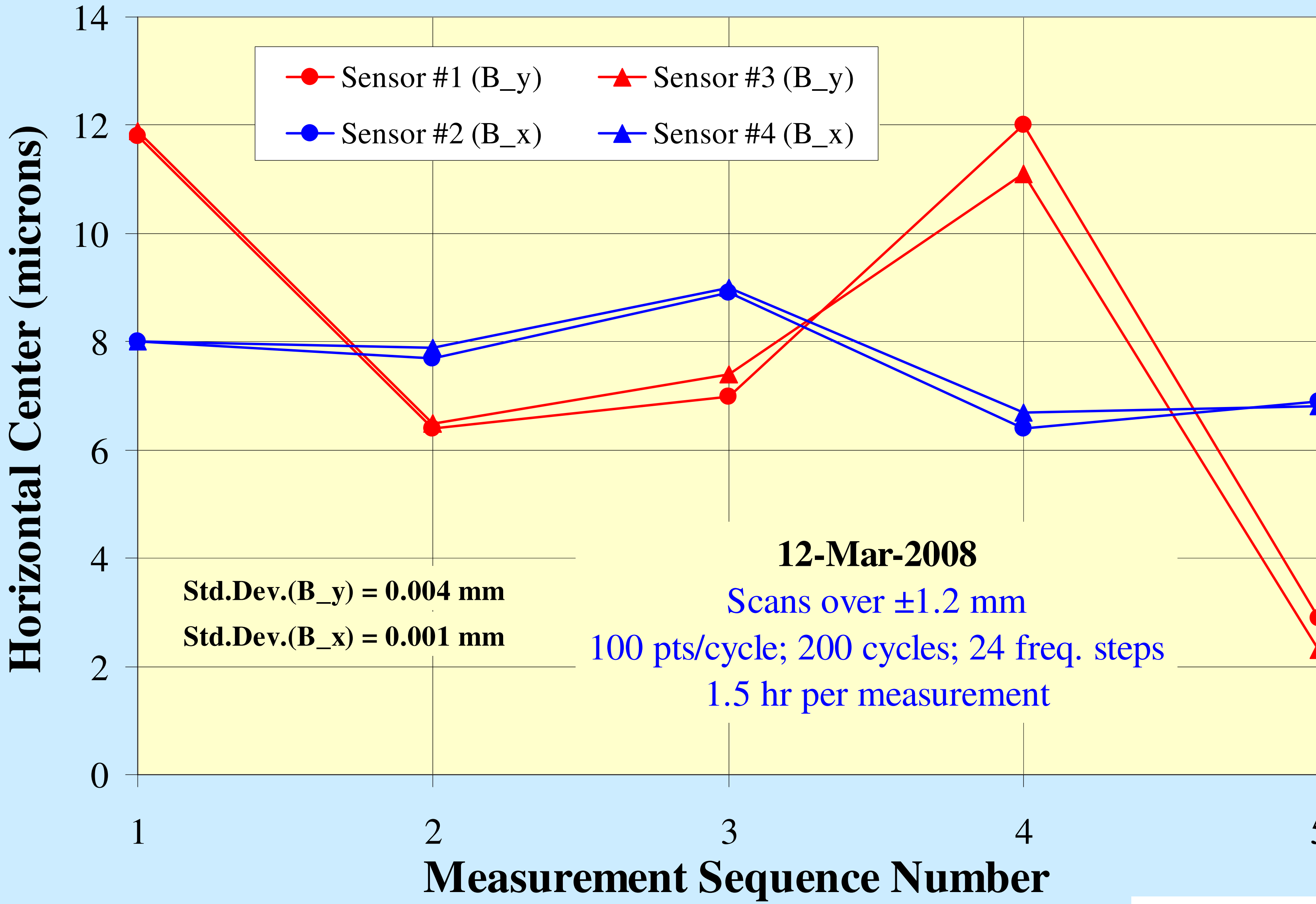


From dB_x/dy Vs x Plots:

XCenter(1) = -0.0100 mm

XCenter(2) = -0.0094 mm

Horizontal Center Reproducibility in Sextupole

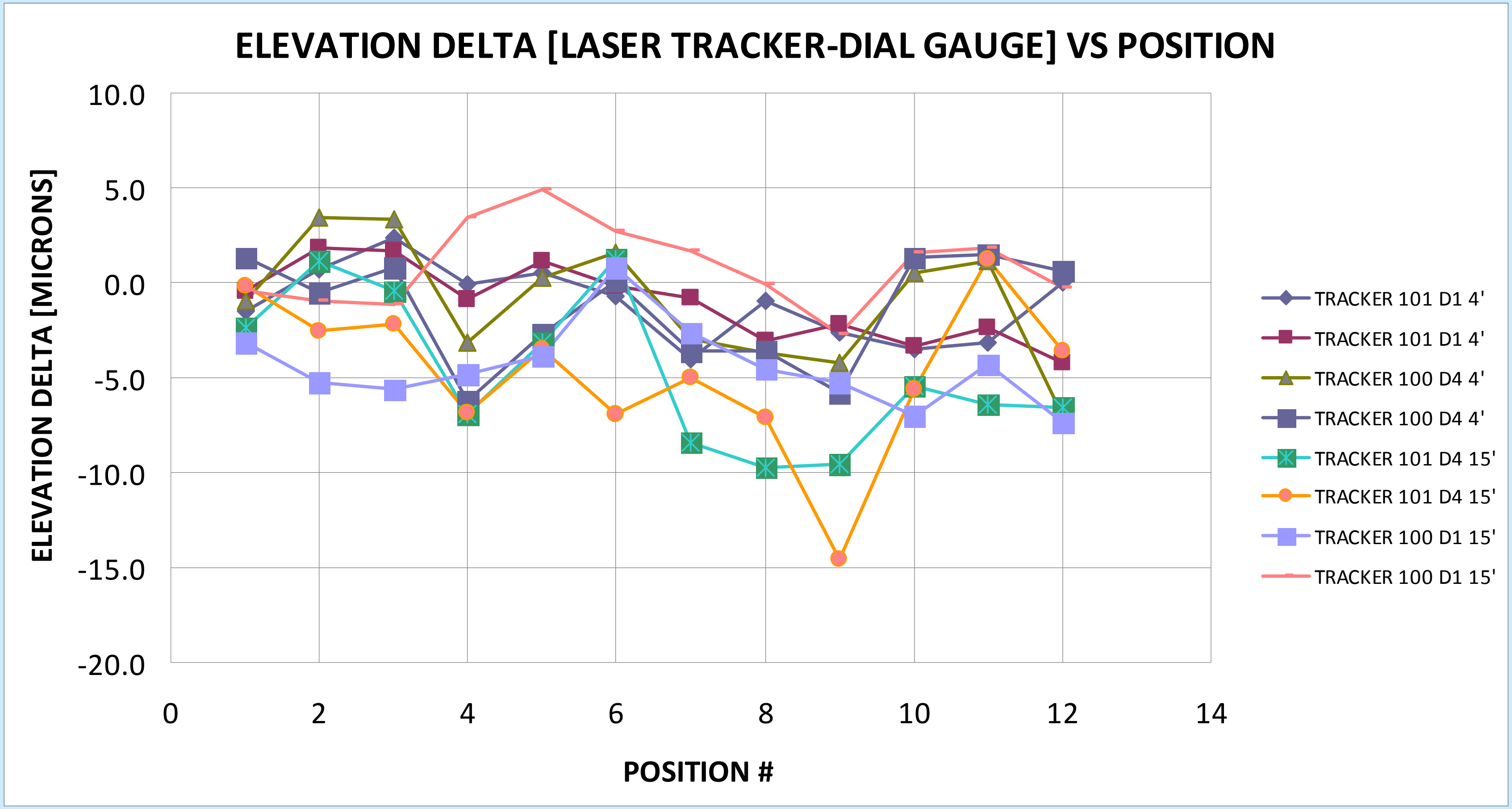


Procedure for Multipole Alignment on a Girder

- Install magnets on a girder, install vacuum chamber, and carry out a rough alignment using a laser system (horizontal and vertical offsets, pitch and yaw) and inclinometers (roll).
- Set up girder on a vibrating wire test stand in a temperature controlled environment (±0.1C), and wait for steady state.
- Tighten the 4 corner studs on the girder to several hundred ft-lbs, secure center bolts and tighten to ~ 100 ft-lbs.
- Power one magnet at a time and measure the magnetic center using vibrating wire technique in the vibrating wire coordinate system, including appropriate correction for wire sag.
- Repeat for all magnets on the girder.

Procedure for Alignment on a Girder (contd.)

- Force all displacement gauges to display the corresponding measured magnet offsets.
- Lock the magnets in place, while monitoring the magnet positions to bring the magnets on-axis by making all gauges to read zero again.
- If required, carry out vibrating wire measurements again to confirm alignment.
- Survey the wire ends, and all girder and magnet fiducials using laser trackers. **In particular, measure the girder vertical profile precisely (better than ±10 microns).**
- Disconnect and remove the girder from the test stand.


ELEVATION DELTA [LASER TRACKER-DIAL GAUGE] VS POSITION
ELEVATION DELTA [MICRONS]
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
0
2
4
6
8
10
12
14
POSITION #
TRACKER 101 D1 4'
TRACKER 101 D1 4'
TRACKER 100 D4 4'
TRACKER 100 D4 4'
TRACKER 101 D4 15'
TRACKER 101 D4 15'
TRACKER 100 D1 15'
TRACKER 100 D1 15'