Production Measurements for NSLS-II: Lessons Learned*

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&

Measurement Teams of All Magnet Vendors for NSLS-II

Introduction

- The National Synchrotron Light Source-II (NSLS-II) is a new light source just completing construction at Brookhaven National Laboratory (BNL).
- The magnets needed for the storage ring of NSLS-II were produced by various manufacturers located around the world (7 vendors in 6 countries, 4 continents).
- All manufacturers were responsible for field quality in their magnets, and for carrying out magnetic measurements as part of magnet check out before shipping magnets to BNL.
- The plan was to measure only a fraction of magnets at BNL, but in the end all multipole magnets were measured at BNL.
- This talk presents some of the lessons learned in this process.

List of Magnets in NSLS-II Storage Ring

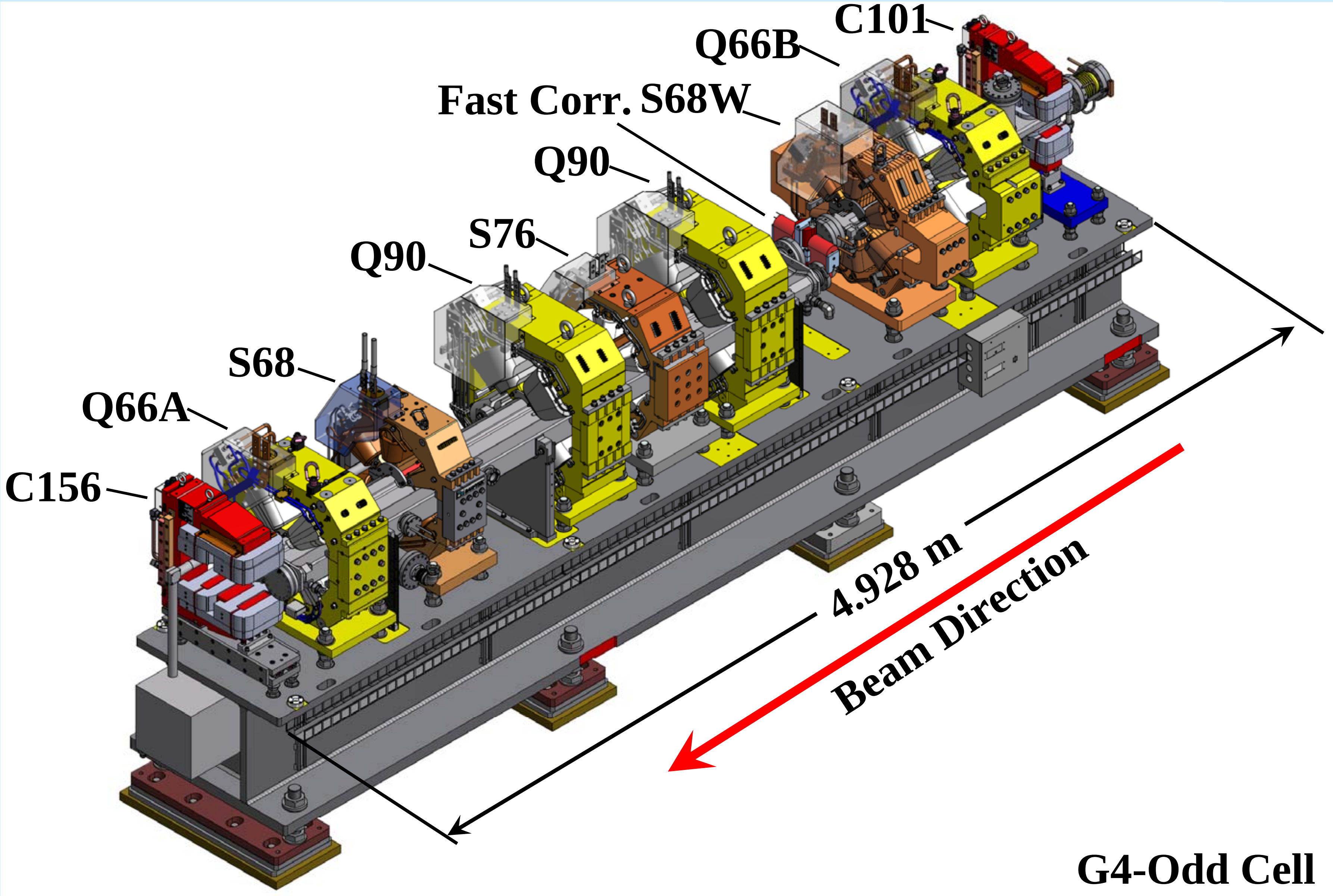
Short Name	Description	Quantity	Vendor	Integ. Strength[1]
Q66A	66 mm Single Coil Short Quadrupole	30	A	2.75 Tesla
Q66B	66 mm Single Coil Short "Wide" Quadrupole	30	A	2.75 Tesla
Q66C	66 mm Double Coil Long Quadrupole	30	A	8.80 Tesla
Q66C'	66 mm Double Coil Long Quadrupole (Kinked)	30	A	8.80 Tesla
Q66D	66 mm Double Coil Short Quadrupole	90	B	5.50 Tesla
Q66E	66 mm Double Coil Short "Wide" Quadrupole	30	B	5.50 Tesla
Q90	90 mm Aperture Quadrupole	60	C	3.79 Tesla
S76	76 mm Aperture Sextupole	30	C	100 Tesla/m
S68	68 mm Aperture Sextupole	165	D	80 Tesla/m
S68W	68 mm Aperture "Wide" Sextupole	75	E	80 Tesla/m
D35	35 mm Aperture Bending Dipole	54	C	1.048 Tesla.m
D90	90 mm Aperture Bending Dipole	6	C	1.048 Tesla.m
C100	100 mm Aperture Dipole Correctors	90	F	0.0082 T.m
C101	100 mm Aperture Correctors with Skew Quad	30	F	0.086 Tesla[2]
C156	156 mm Aperture Correctors	60	F	0.0082 T.m (VF) 0.0092 T.m (HF)
	Fast Orbit Correctors	60	G	

Total number of magnets in storage ring = 870

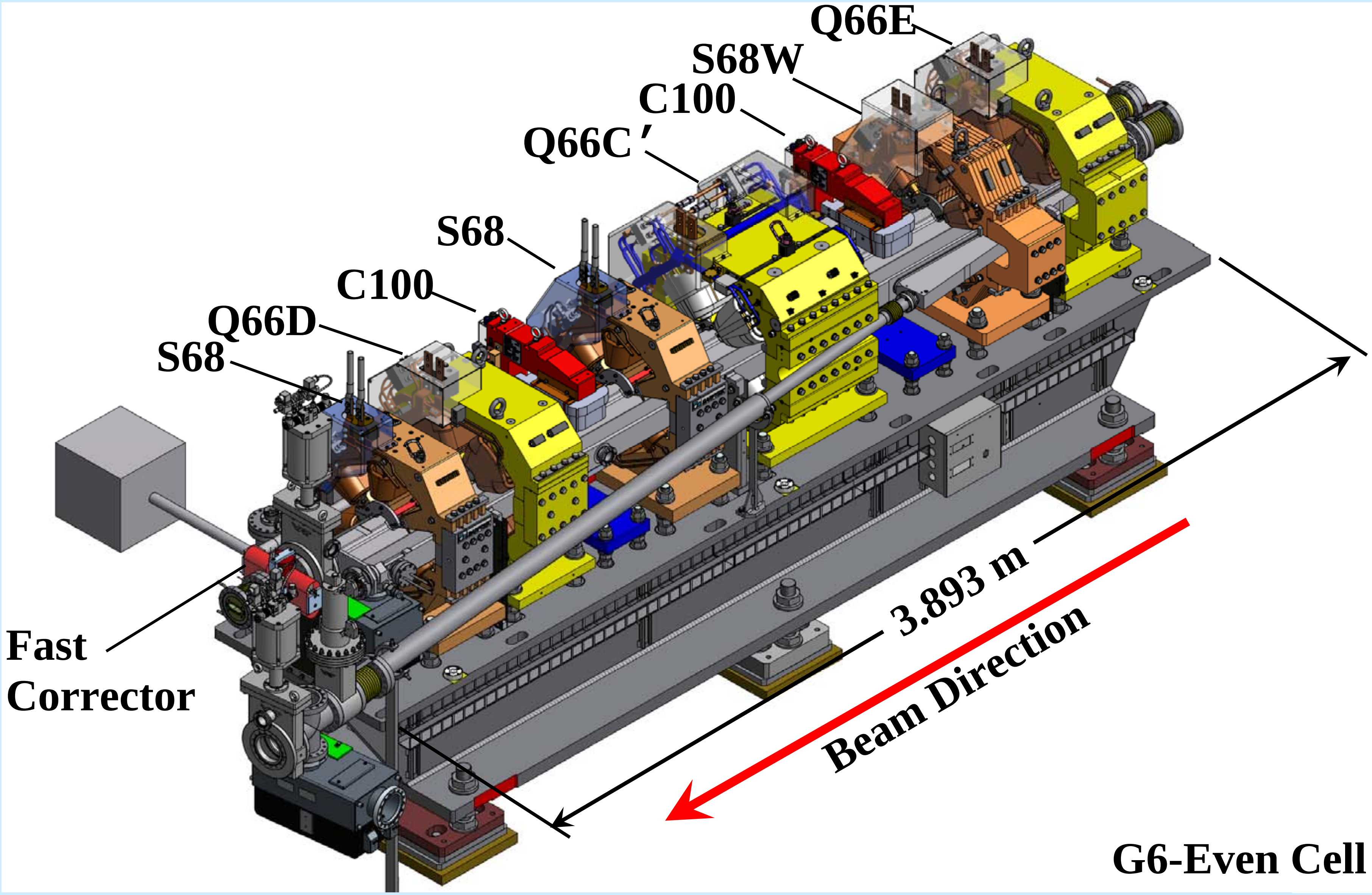
(1) Integrated strength is defined as Int(B.dl) for dipoles, Int(B'.dl) for quads, and Int(B".dl) for sextupoles

(2) Strength listed is of the skew quadrupole; the dipole correctors have the same strengths as in C100

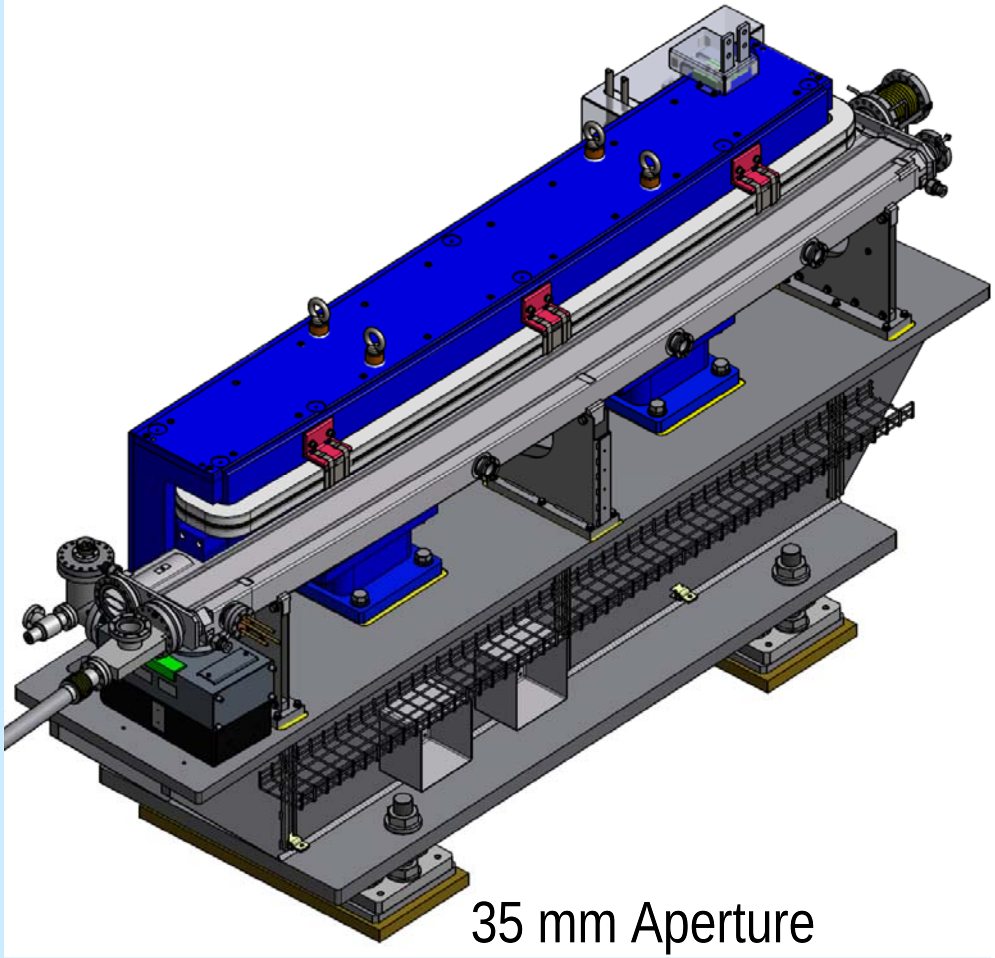
Magnets on Girders in NSLS-II

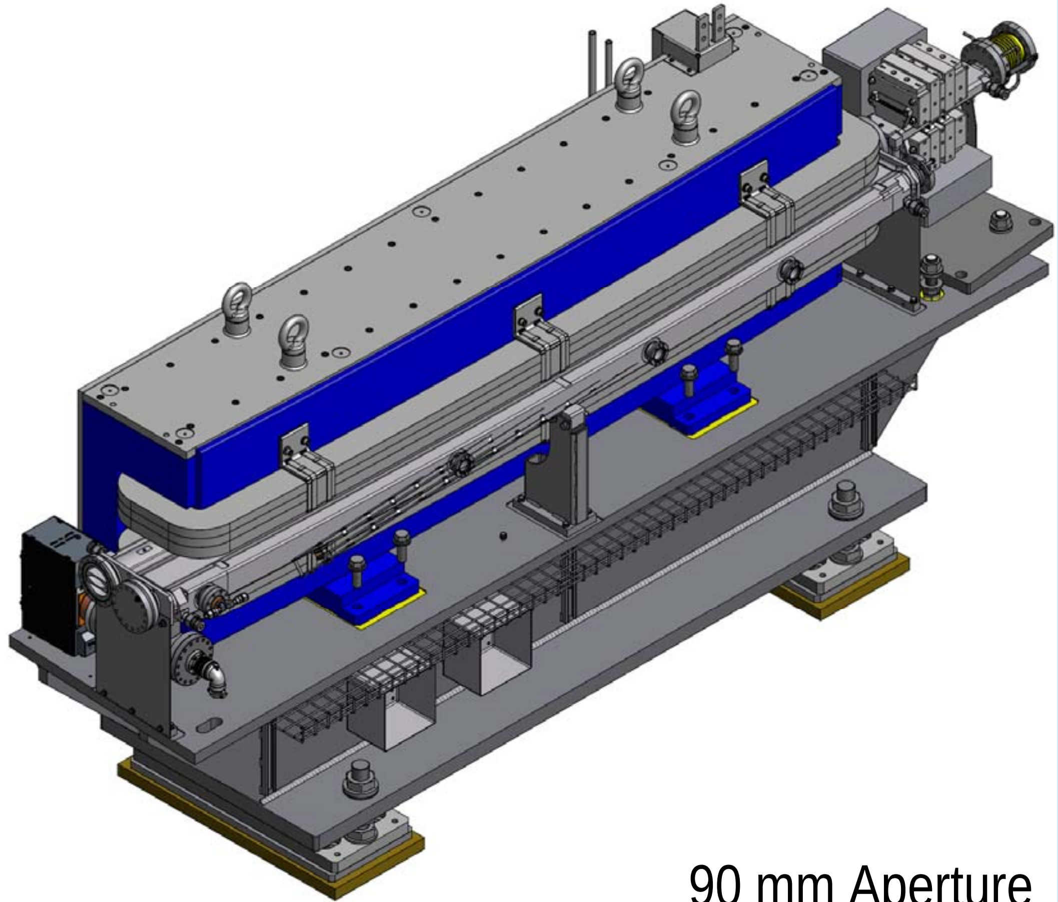


Magnets on Girders in NSLS-II



Main Bending Dipoles





The dipoles were mapped at BNL after installation onto their girders. Only a fraction of the dipoles could be tested at BNL due to time constraints.

The handling of dipole-girder assembly requires caution!

BNL Vs. Vendors' Rotating Coil Systems

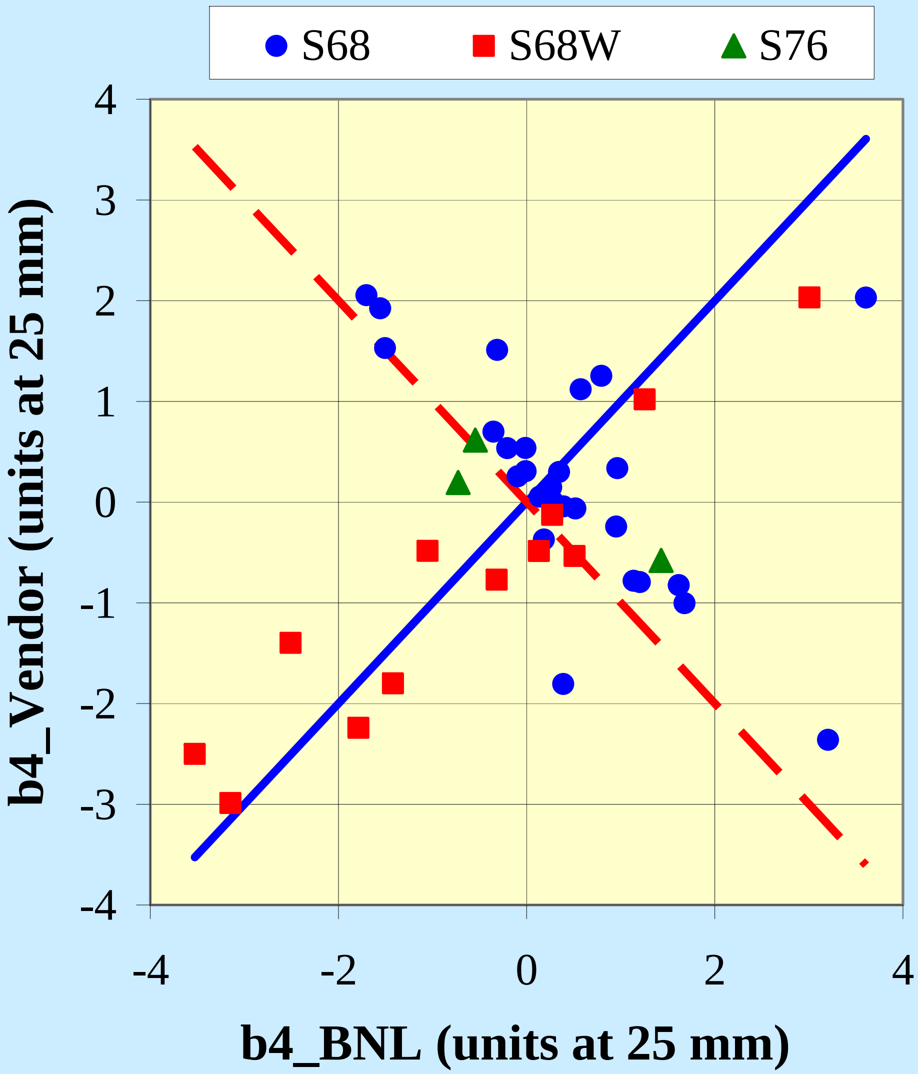
- BNL uses either a 5-winding (RHIC style) or a new 9-winding design (see IMMW16) *tangential* rotating coils, along with digital voltmeters for data acquisition.
- All vendors used *radial* rotating coils of various designs, along with digital integrators for data acquisition.
- Most vendors used Metrolab's PDI integrators, but one of them used home-built integrators with similar performance (see talk by Pavel Vagin on Thursday).
- BNL systems implement bucking digitally, whereas all vendors' systems are based on analog bucking.

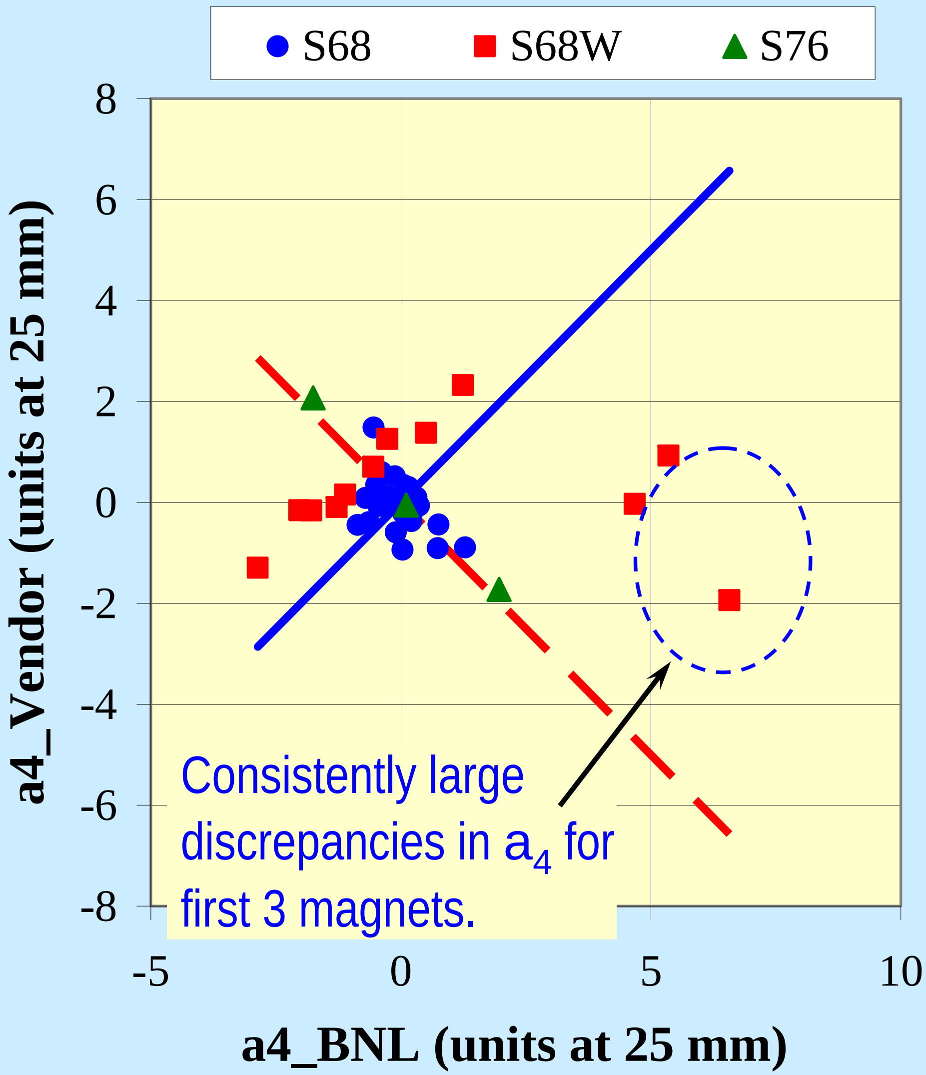
$\Rightarrow$ A wealth of information on performance of different systems!

Issues Encountered in Multipoles Testing

- Disagreement between vendor and BNL measurements
  - Particularly prominent for sextupoles, never fully resolved.
  - Resulted in magnets out of spec, which had to be reshimmed at BNL.
- Coordinate system and sign convention inconsistencies.
- Magnetic roll angles either not measured by vendors, or proved to be of insufficient accuracy.
- Magnet assembly was not reproducible in some cases, requiring extensive studies and design changes.
- Field harmonics found to be dependent on cooling water flow rate.

Vendors Vs. BNL Measurements in Sextupoles for NSLS-II





from IMMW-17

Blue Solid Line = Perfect agreement with correct sign
Red Dashed Line = Perfect agreement, except for a sign error

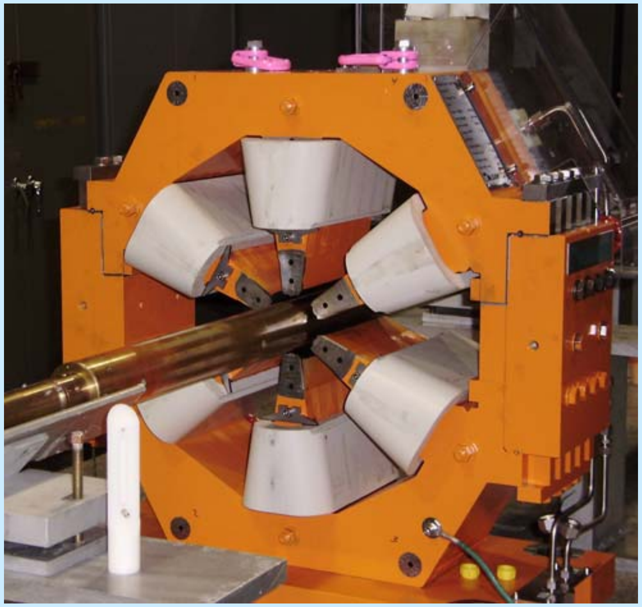
Resolving Measurement Discrepancies

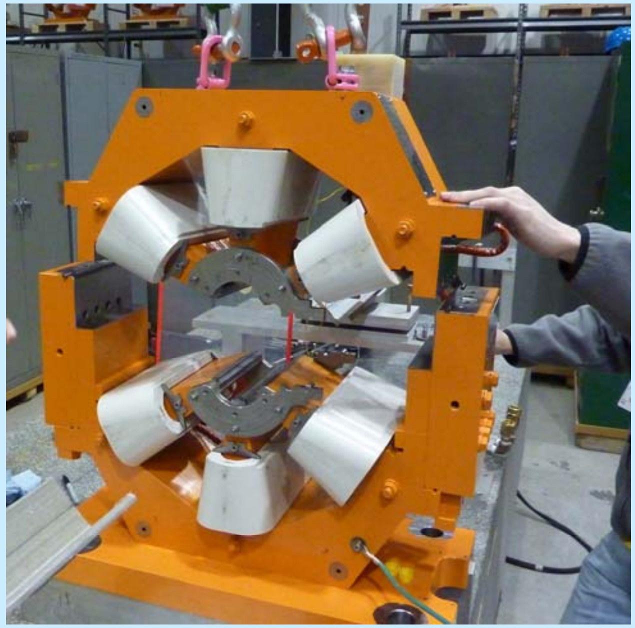
- Discrepancies between vendor and in-house measurements are extremely difficult to resolve during an ongoing production.
- Magnets of similar size and roughly similar field characteristics should be procured (build in-house, borrow, old spares, …) and measured at various production sites, well before regular production starts. (Some vendors did not have a system to test until too late.)
- Measurement differences at ~20% of the specification (or > 0.05 unit for higher harmonics) should not be ignored and need investigation.
- There is no guarantee that the differences will be resolved. In such cases, one can at least have a realistic estimate of what to expect for measurement accuracy.
- At NSLS-II, considerable time and effort was invested in validating measurements made by BNL rotating coil systems.

Reassembly Tests in Multipoles

- All storage ring multipoles will need to be disassembled at least once to install the vacuum chamber.
- It is essential that the field quality remains within specification after the magnet is reassembled.
- Extensive reassembly tests have been done in several magnets of each type.
- The reproducibility of harmonics in the quadrupoles has been generally satisfactory (the higher of ±20% of spec, or ±0.1 unit).
- Some design changes had to be implemented to improve the reproducibility of the 68 mm aperture sextupoles.
- Reassembly tests added significantly to the magnet testing workload.

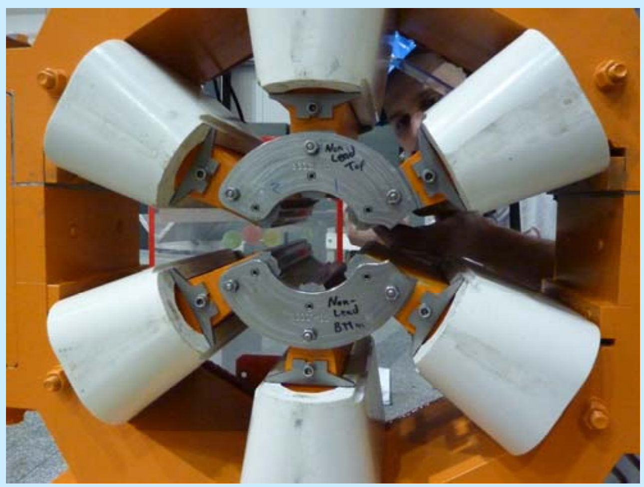
Reproducibility in Sextupoles



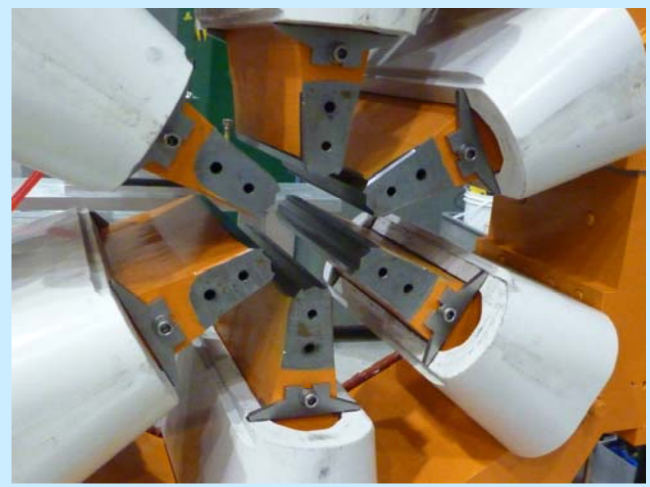


The iron yoke was adequate from a magnetic point of view, but not mechanically. Harmonics were very sensitive to torques and torquing sequence.

Original Pole Clamps

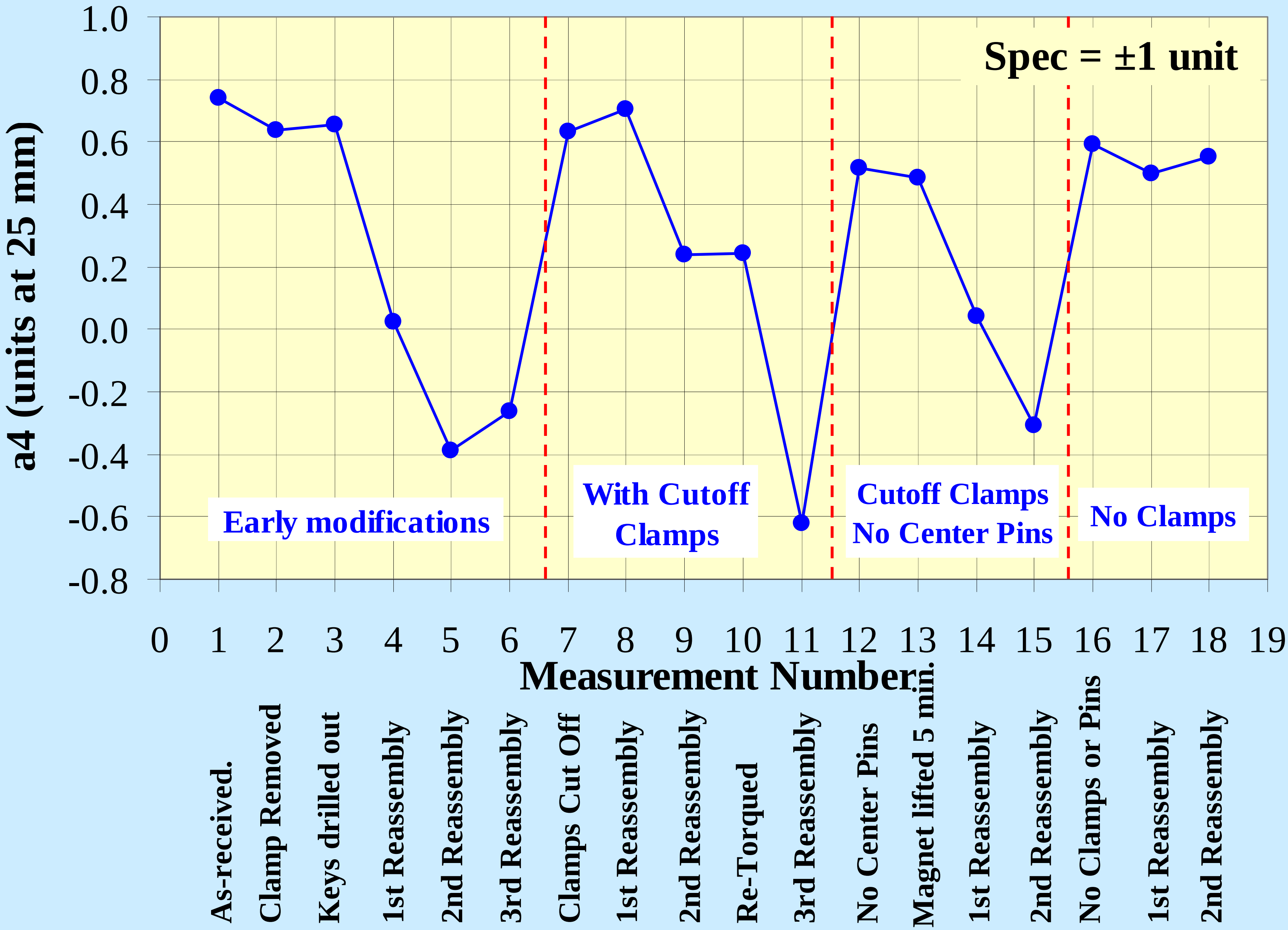


Modified Pole Clamps

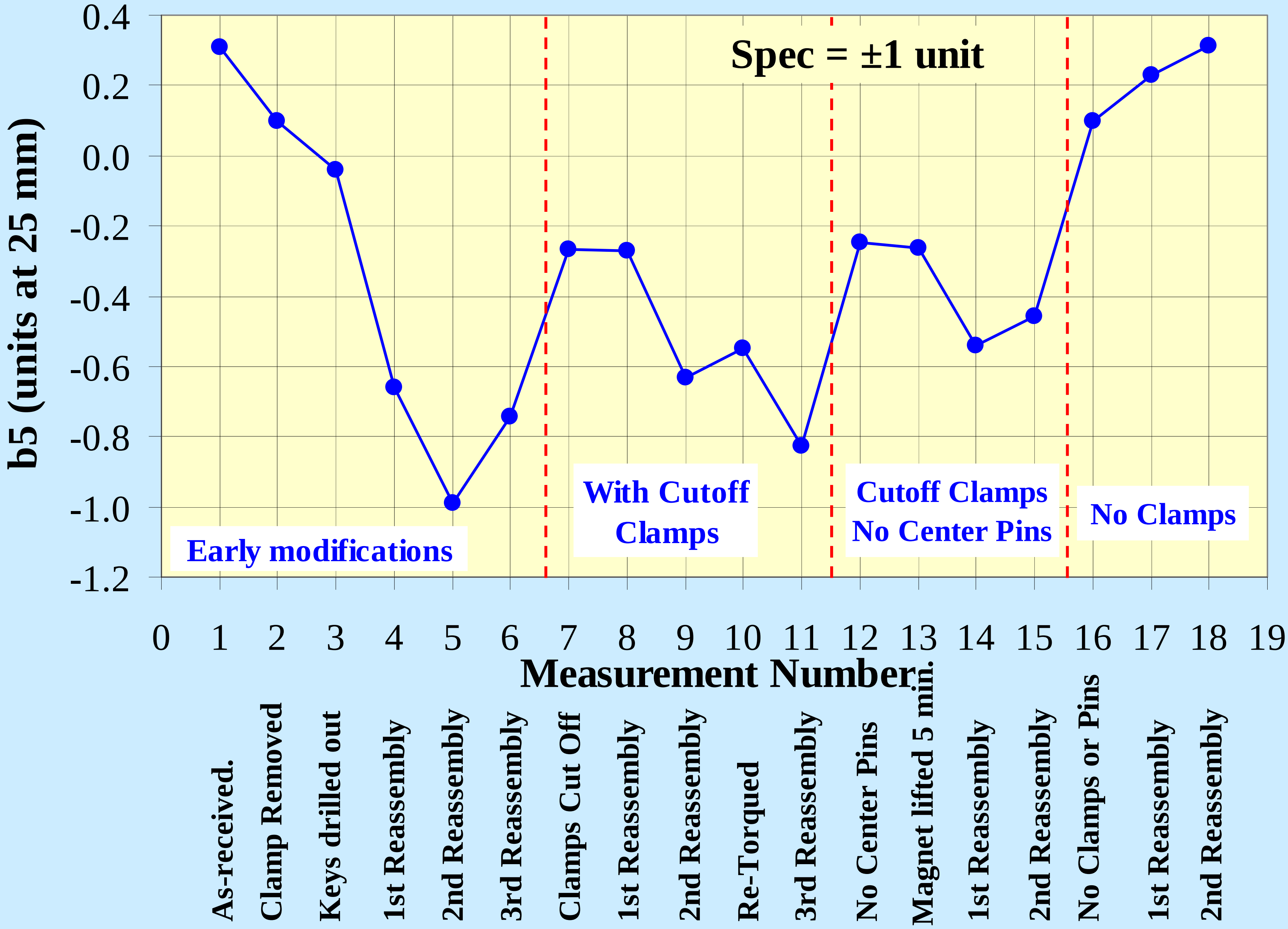


Pole Clamps Removed

Reassembly tests in LT-S68_0005



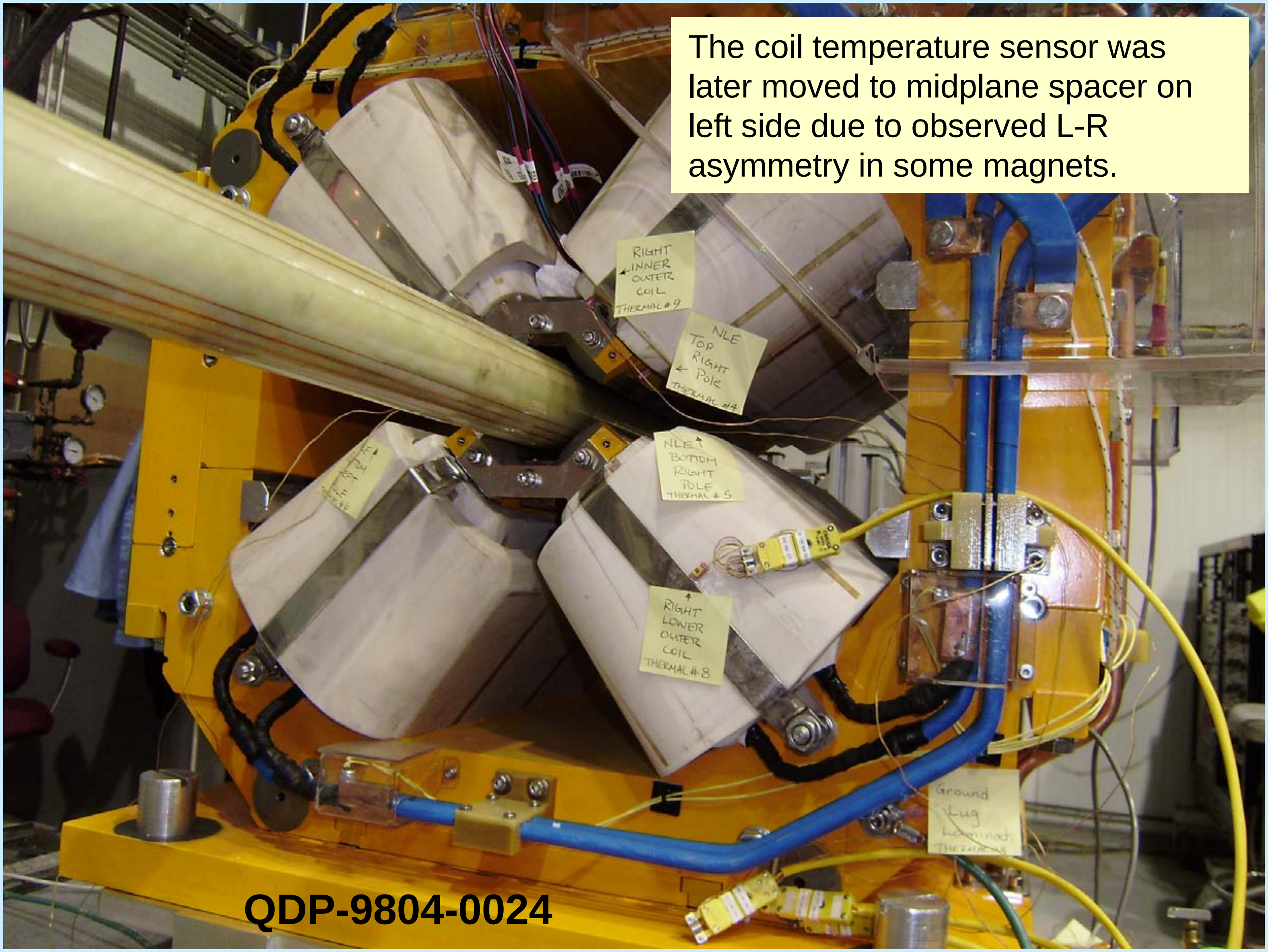
Reassembly tests in LT-S68_0005



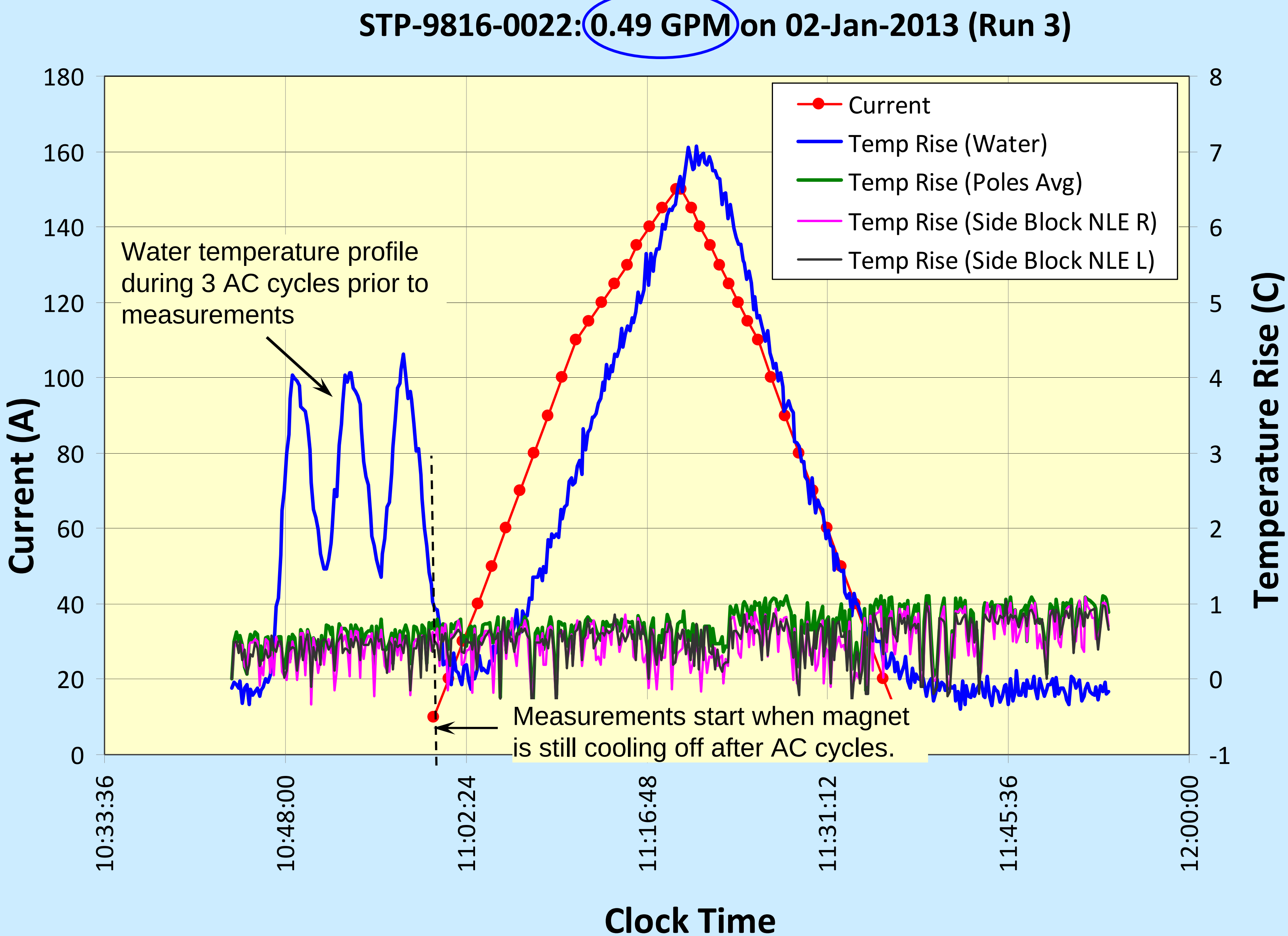
Harmonics Vs. Cooling Water Flow Rate

- Every NSLS-II storage ring multipole magnet was measured at BNL with unrestricted cooling water flow and at a nominal pressure differential of 60 psi.
- In order to achieve a minimum specified water outlet temperature, nearly all magnets will be fitted with flow restrictors, which would change the magnet temperatures as compared to the state in which they were measured.
- Casual observation during the production measurements suggested that noticeable effect on field harmonics can result from temperature variations.
- An extensive program to study such effects was undertaken in order to quantify the extent of the effect, and to establish optimal flow rates while keeping field quality impact small.

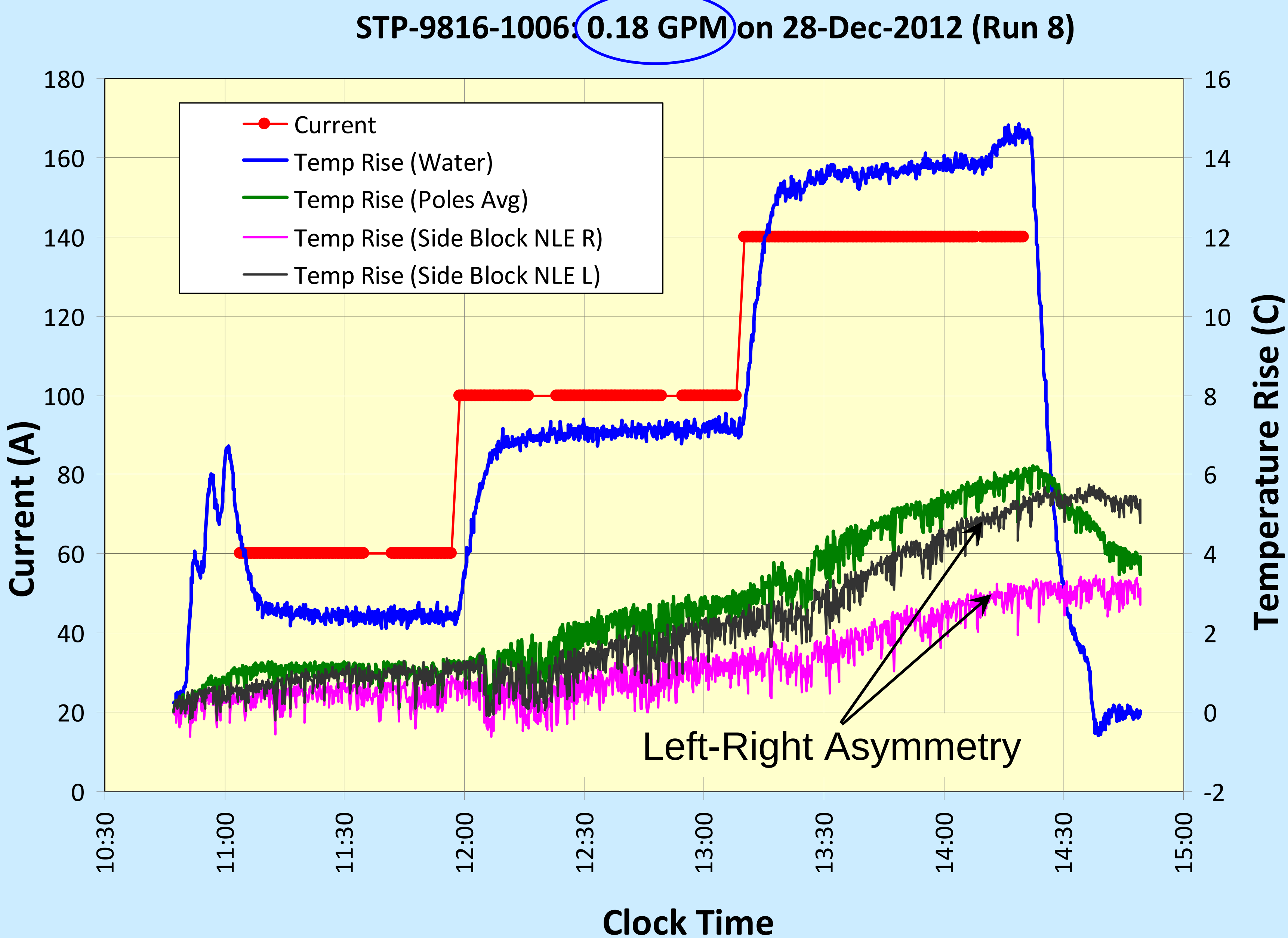
Typical Magnet Setup for Flow Studies



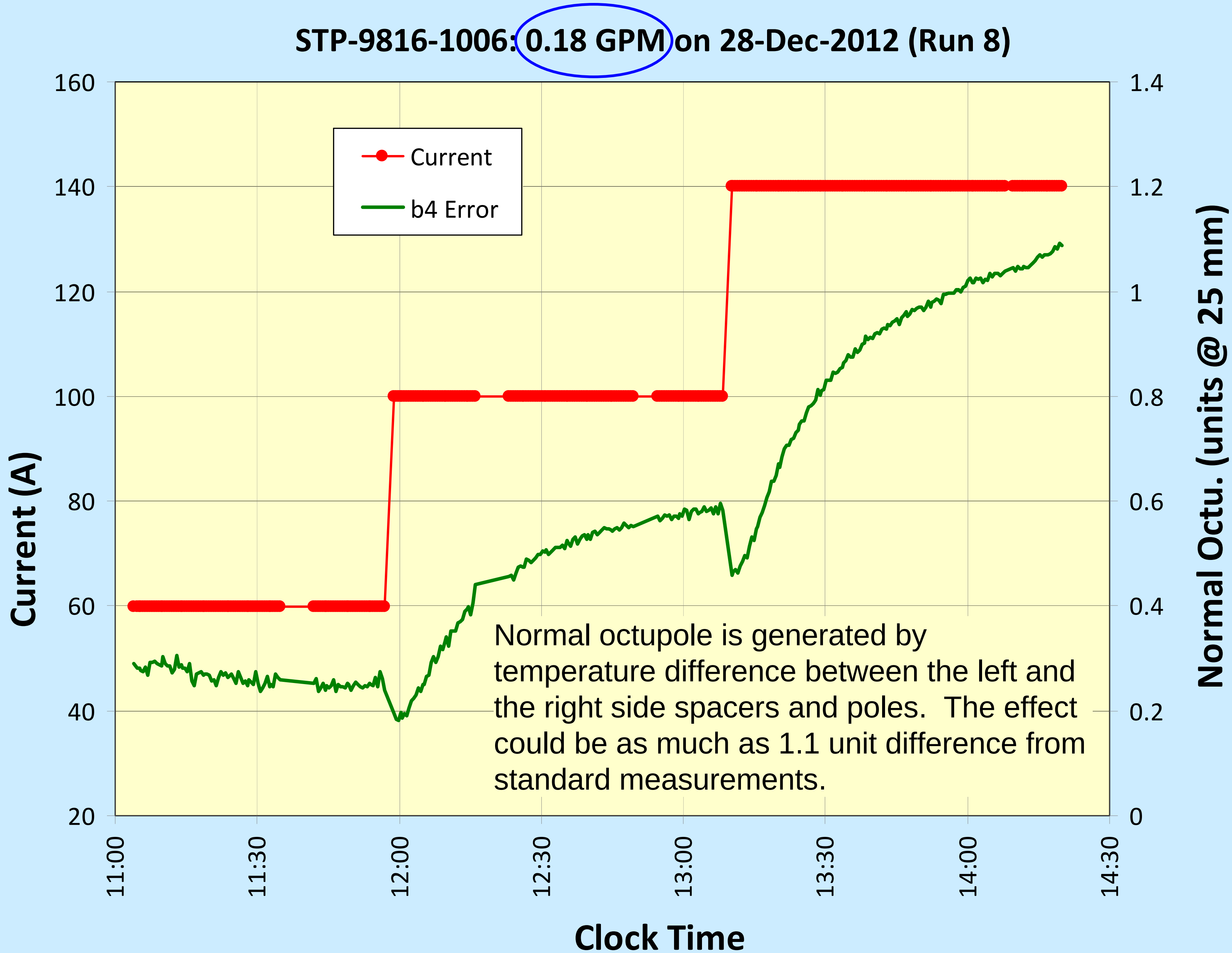
Example: Full Excitation Curve Measurements



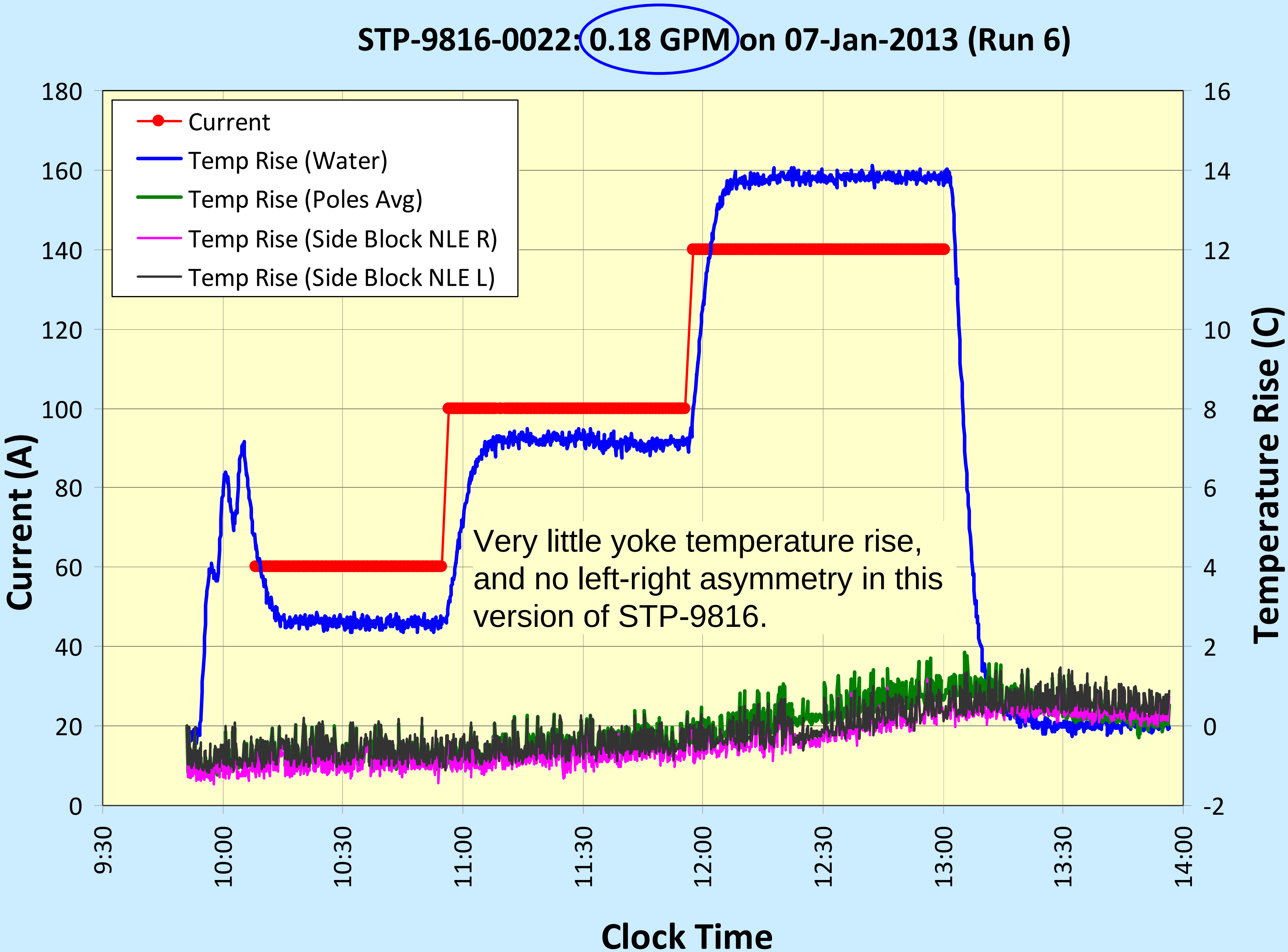
3 Currents at Planned Flow in STP-9816-1006



Harmonics Changes at Planned Nominal Flow



3 Currents at Planned Flow in STP-9816-0022



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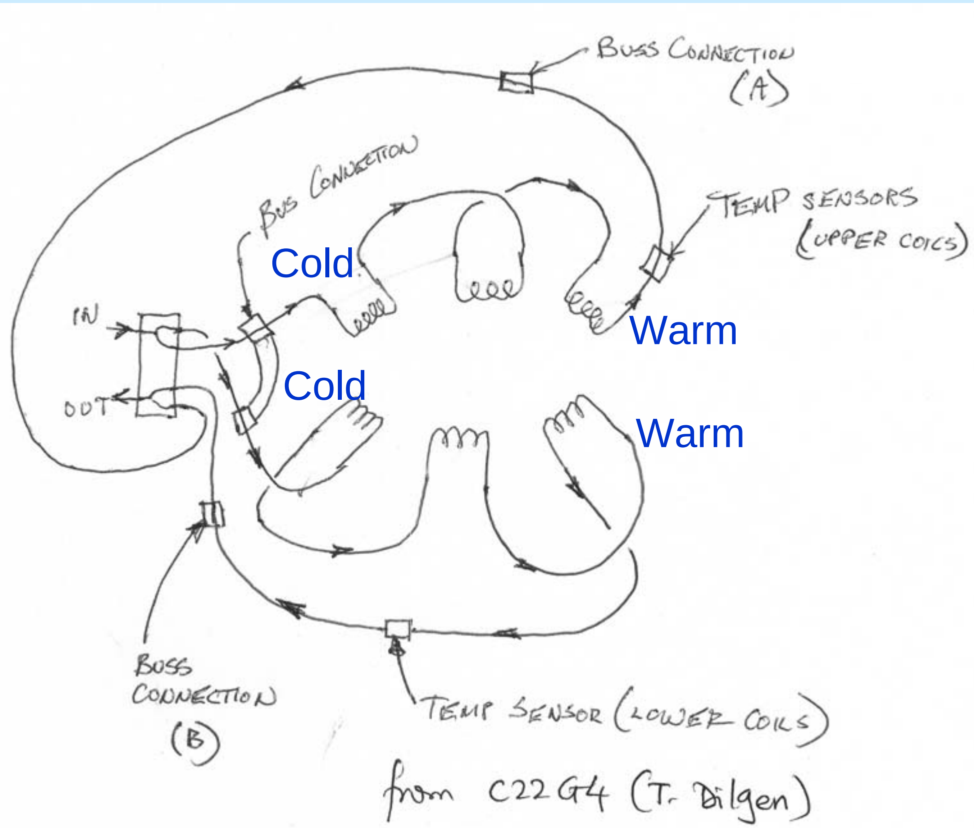
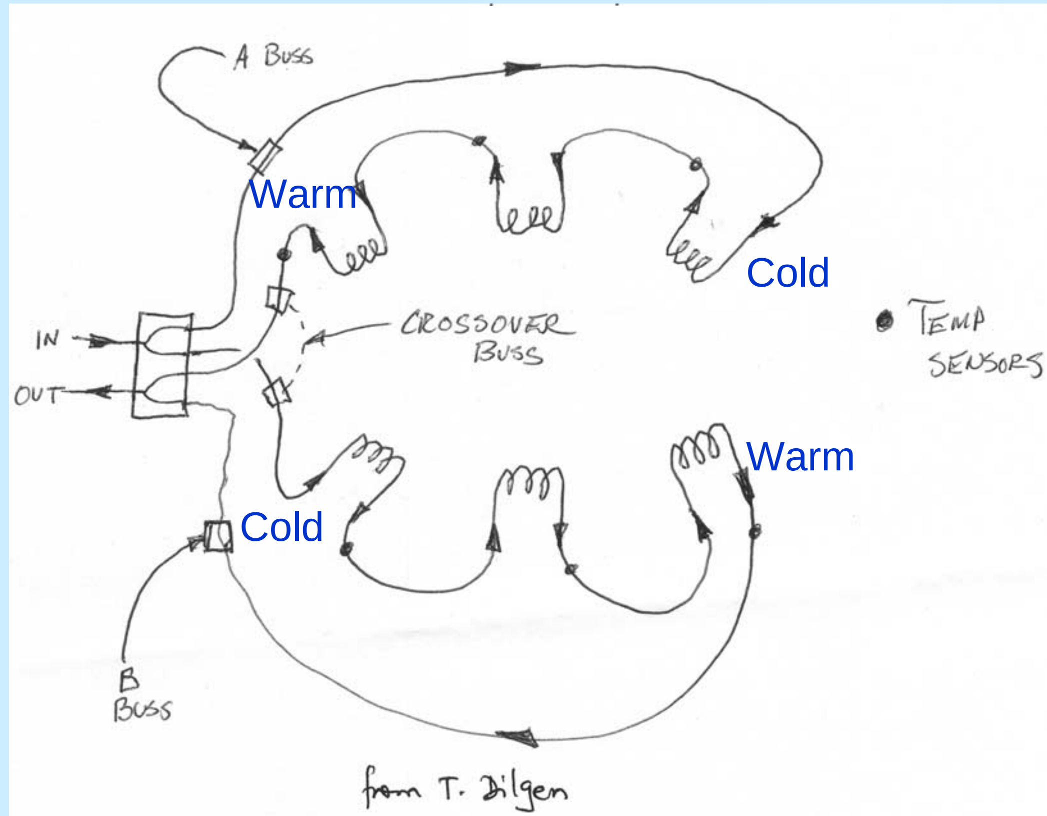
Water Circuits in Two Versions of STP-9816



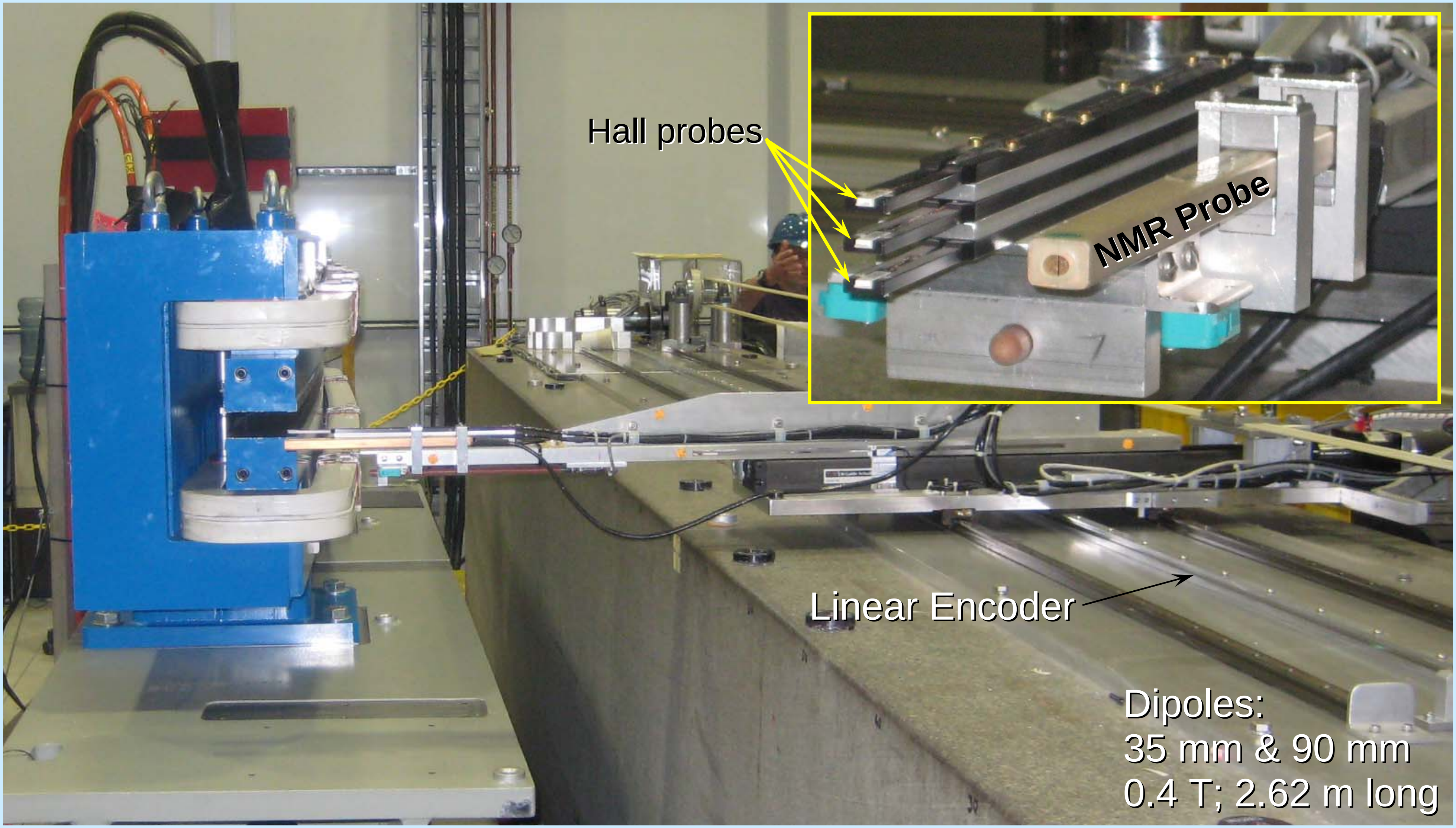


Cold inlet water enters on the *same side* of the magnet on both the top and the bottom halves. This causes a left-right asymmetry in temperature.

Cold inlet water enters on the *opposite sides* of the magnet on the top and the bottom halves. This helps to keep the temperatures on the left and the right halves to be nearly the same.

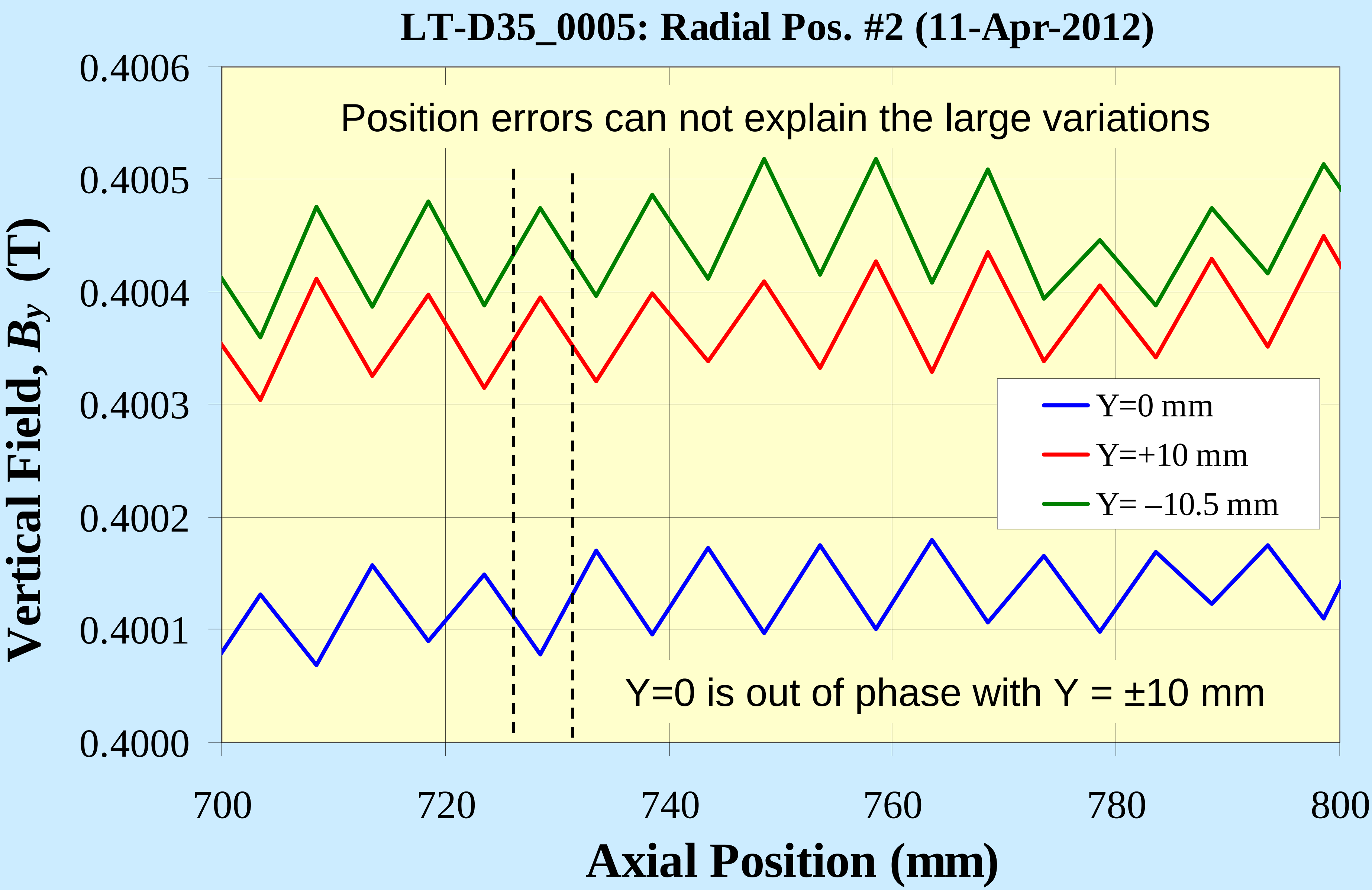
Similar differences exist between the two types of 68 mm sextupoles

Dipole Mapping System at BNL

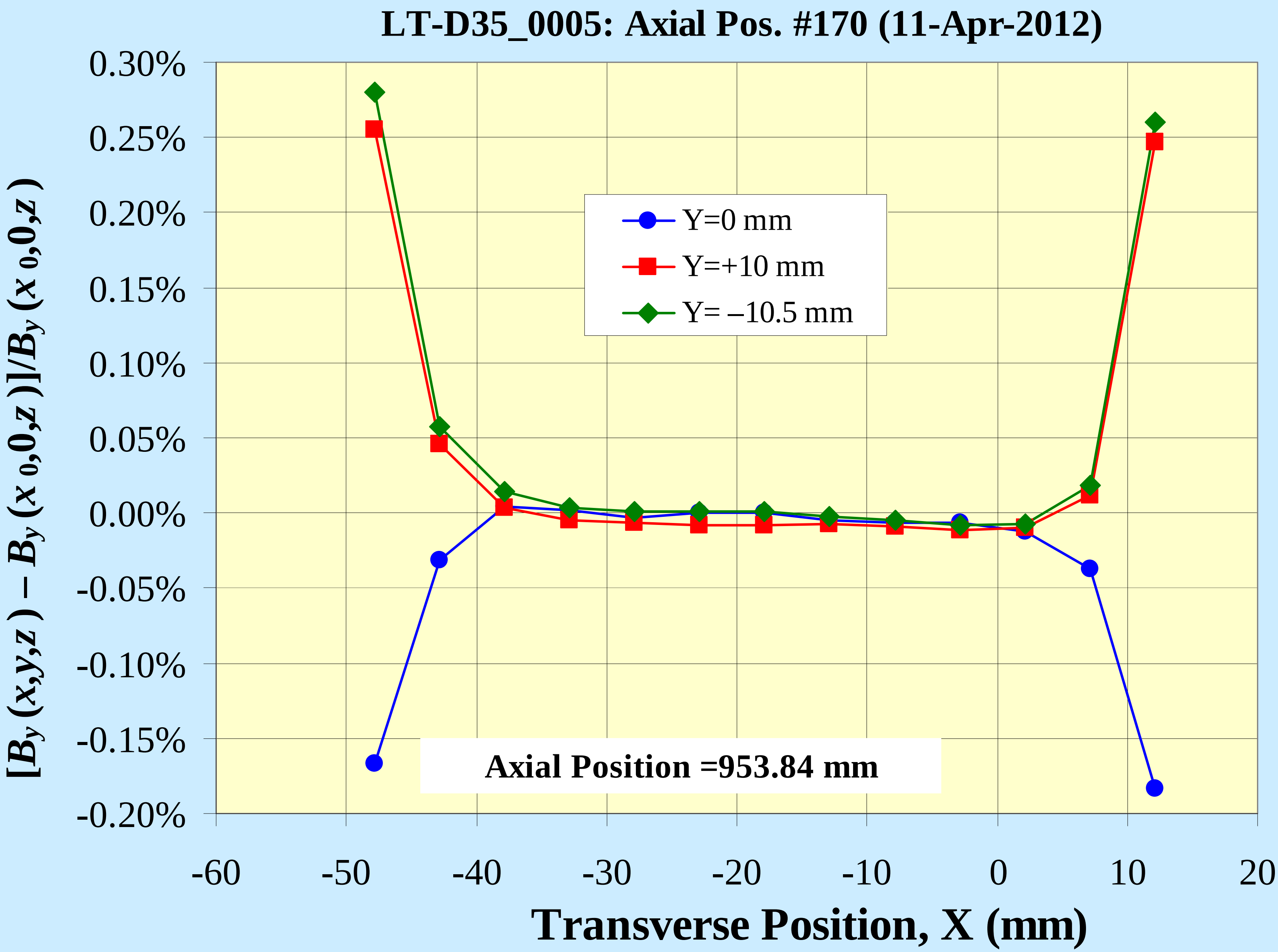


4.28 m axial travel; 0.33 m radial travel;   5 micron resolution position readout

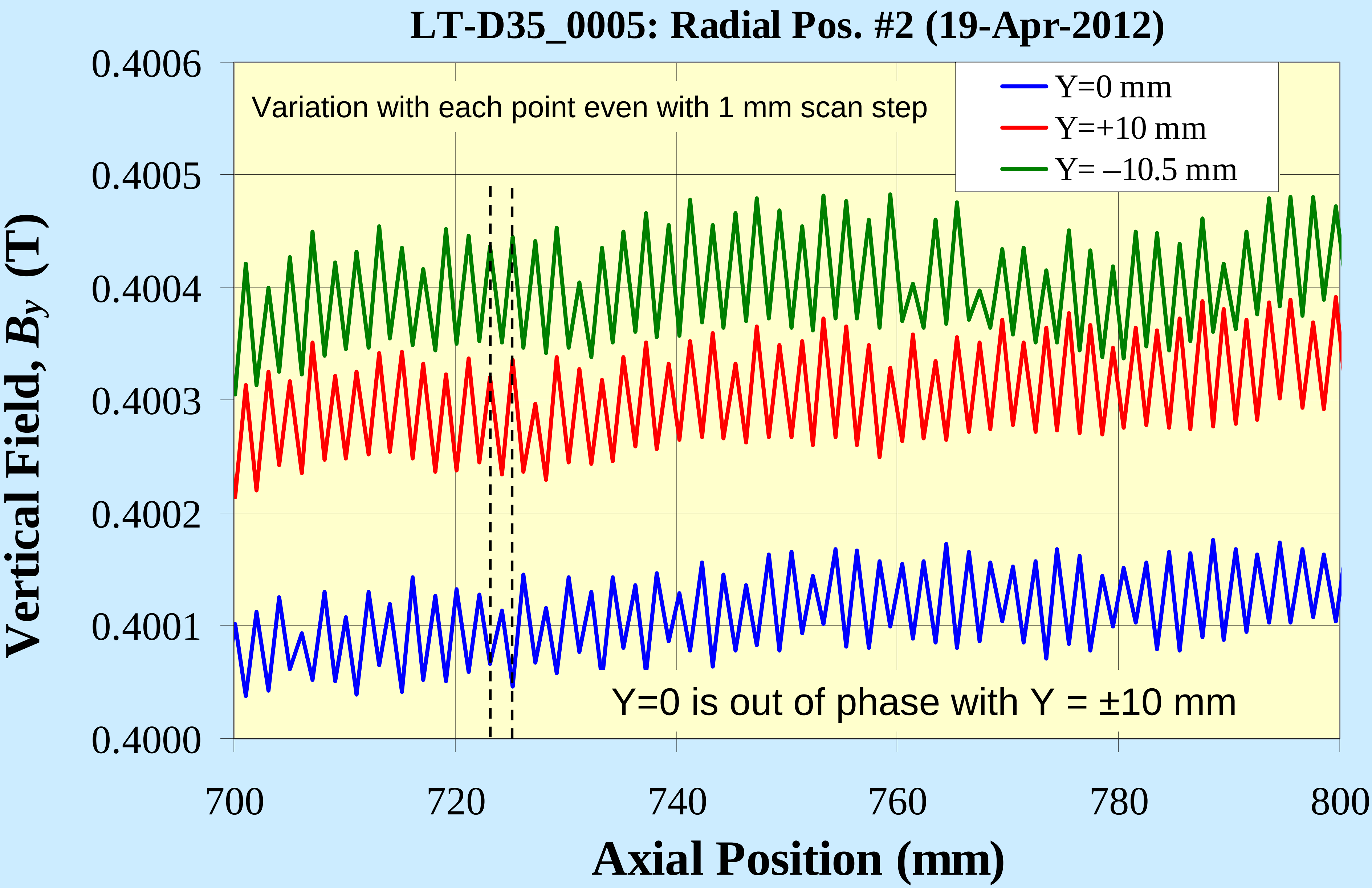
Unexpected Variation of Field Readings



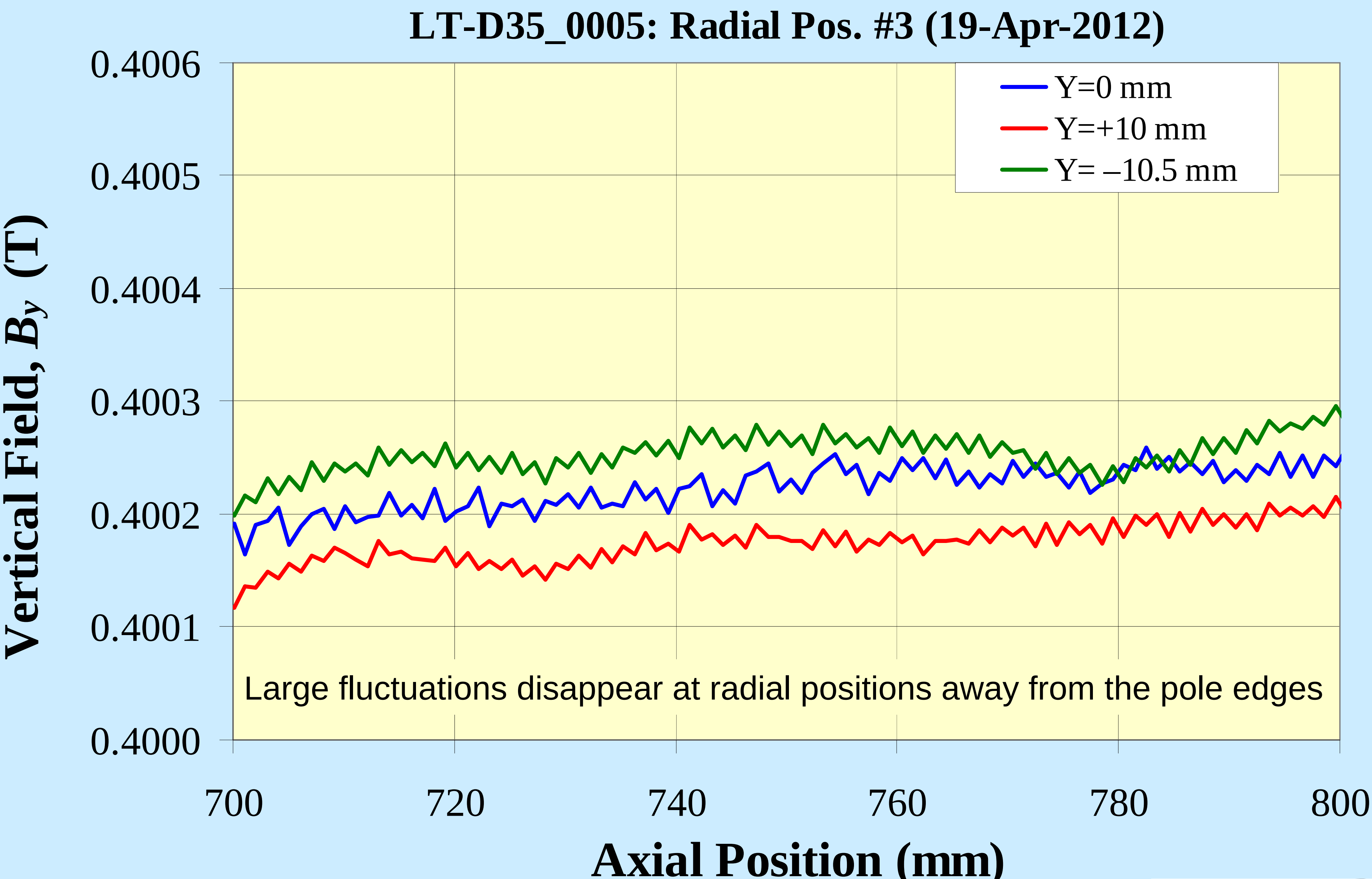
Radial Variation of Field



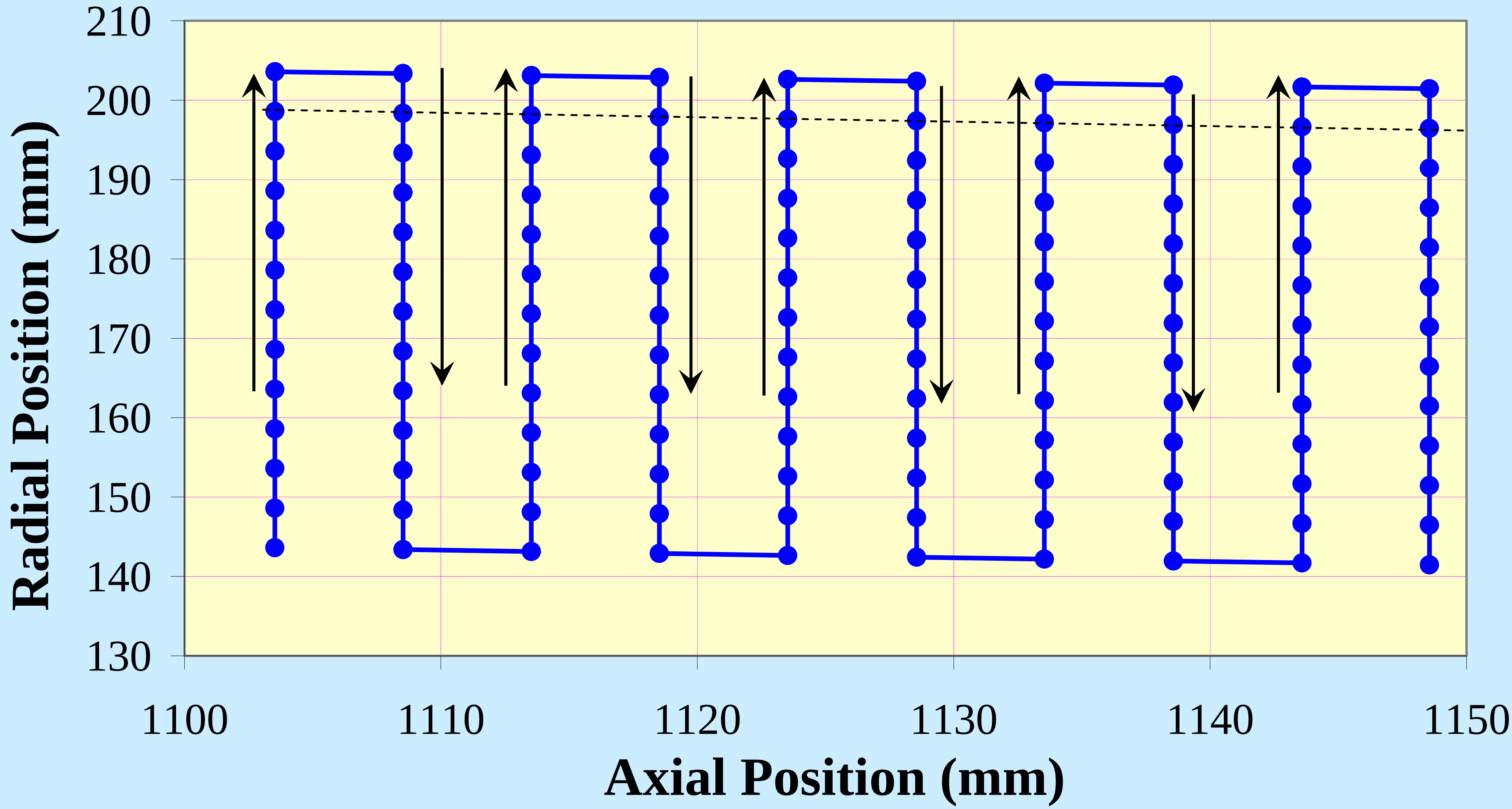
Unexpected Variation of Field Readings



Axial Profile away from Edges



Scan Trajectory in Dipoles



Near the edges, the Hall probe goes from low field to high field at one axial position, and from high field to low field at the next axial position.

Effect of Digital Filtering in Teslameter

- The Group3 Teslameters take continuous readings at 10 Hz, and supply a reading for readout when instructed.
- If Digital Filtering is ON, the readings are smoothened using:

From DTM151 manual

$$F(new) = F(old) + \frac{F - F(old)}{J},$$

where F(old) is the previous field reading display
F(new) is the updated field reading display
F is the most recent unfiltered field reading
J is the filter factor.

The effective time constant of the filter is dependent upon both the rate at which field measurements are made and the value of J, according to the formula:

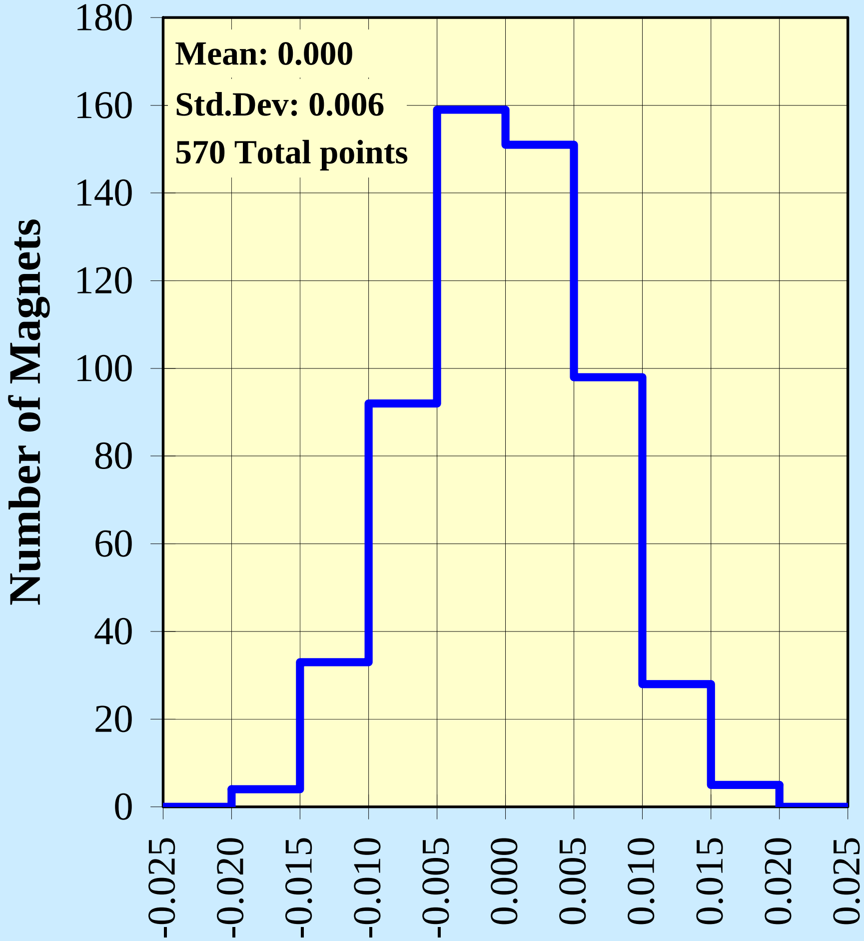
$$T = P/\{\ln[J/(J-1)]\}$$

where T is the filter time constant
P is the period between field measurements.

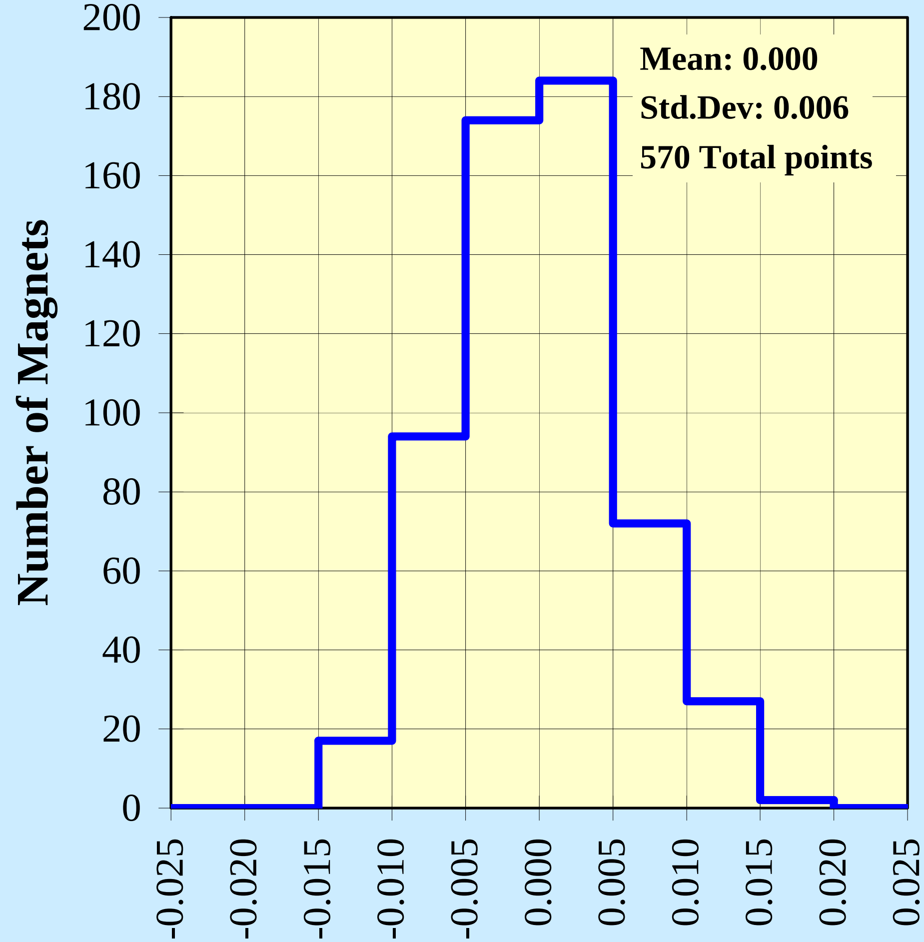
The spurious fluctuations disappeared after a smaller value of J was used, and an additional 1 sec wait was added after probe was moved to position.

Magnet Alignment on Girders

Magnet Offsets from Best Fit Line in All Girders (17-Jan-2013)



Horizontal Offset (mm)



Vertical Offset (mm)

Magnet alignment using vibrating wire technique was very successful
Achieved ~ 6 micron RMS offsets, as against a specification of 30 microns.

Summary

- Measurement capability of magnet manufacturers has improved in recent years, but there are still issues with data accuracy and consistency.
- Quadrupole measurements were more reliable than sextupoles.
- Measurement differences are hard to resolve. There is a need for "standard" magnets.
- Precise roll angle measurements are still a problem for most vendors.
- Mechanical reproducibility of assembly should be considered in magnet design, in addition to magnetic requirements.
- Magnetic measurements must be carried out in conditions as close as possible to the actual use conditions.
- Instrument characteristics and limitations should not be forgotten.