Production Measurements of Magnets for the NSLS-II Storage Ring*

Animesh Jain
Superconducting Magnet Division
Brookhaven National Laboratory, Upton, NY 11973

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&

Measurement Teams of All Magnet Vendors for NSLS-II
(Some are present at this workshop)

Introduction

- The National Synchrotron Light Source-II (NSLS-II) is a new light source presently under construction at Brookhaven National Laboratory (BNL).
- The magnets needed for the storage ring of NSLS-II are currently under production by various manufacturers located around the world (7 vendors in 6 countries, 4 continents).
- All manufacturers are responsible for field quality in their magnets, and carry out magnetic measurements as part of magnet check out before shipping magnets to BNL.
- A good fraction of the magnets is also measured at BNL.
- This talk summarizes the current status of magnets, with particular emphasis on vendors vs. BNL measurement results.

List of Magnets in NSLS-II Storage Ring

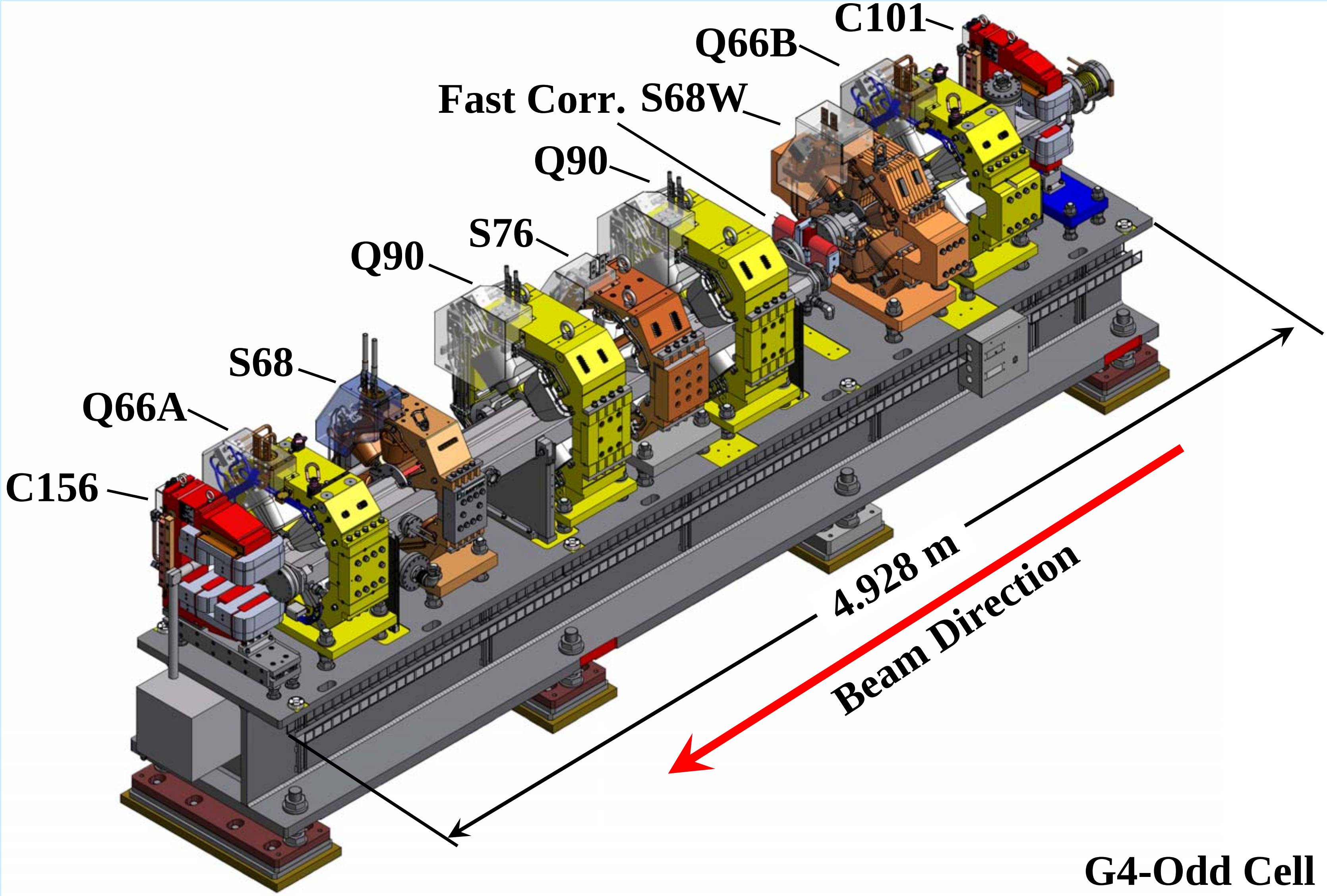
Short Name	Description	Quantity	Vendor	Integ. Strength[1]
Q66A	66 mm Single Coil Short Quadrupole	30	A	2.75 Tesla
Q66B	66 mm Single Coil Short "Wide" Quadrupole	30	A	2.75 Tesla
Q66C	66 mm Double Coil Long Quadrupole	30	A	8.80 Tesla
Q66C'	66 mm Double Coil Long Quadrupole (Kinked)	30	A	8.80 Tesla
Q66D	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	45	F	0.0082 T.m (VF) 0.0092 T.m (HF)
	Fast Orbit Correctors	60	G	

Total number of magnets in storage ring = 855

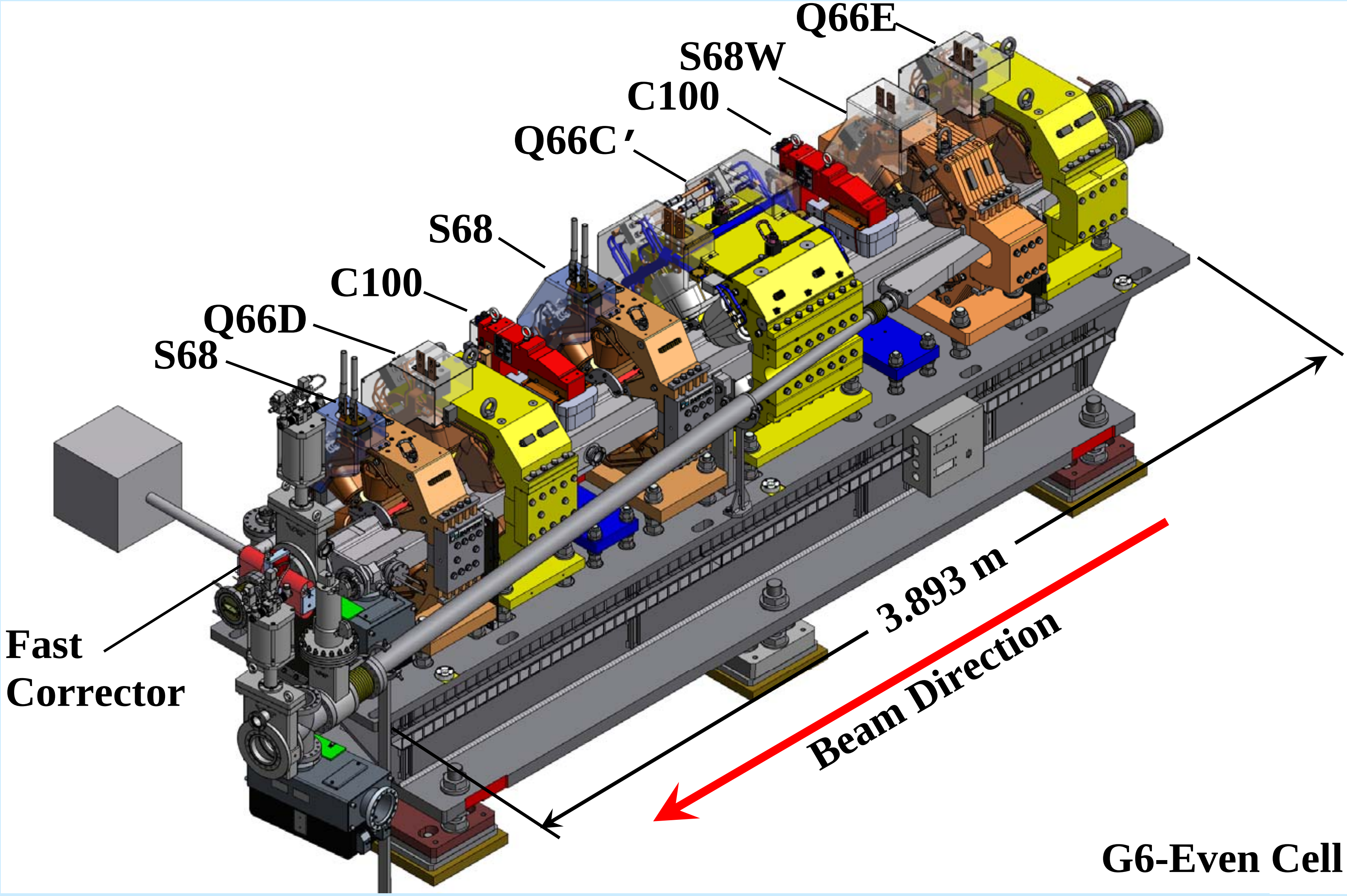
(1) Integrated strength is defined as Int(B.dl) for dipoles, Int(B'.dl) for quads, and Int(B".dl) for sextupoles

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

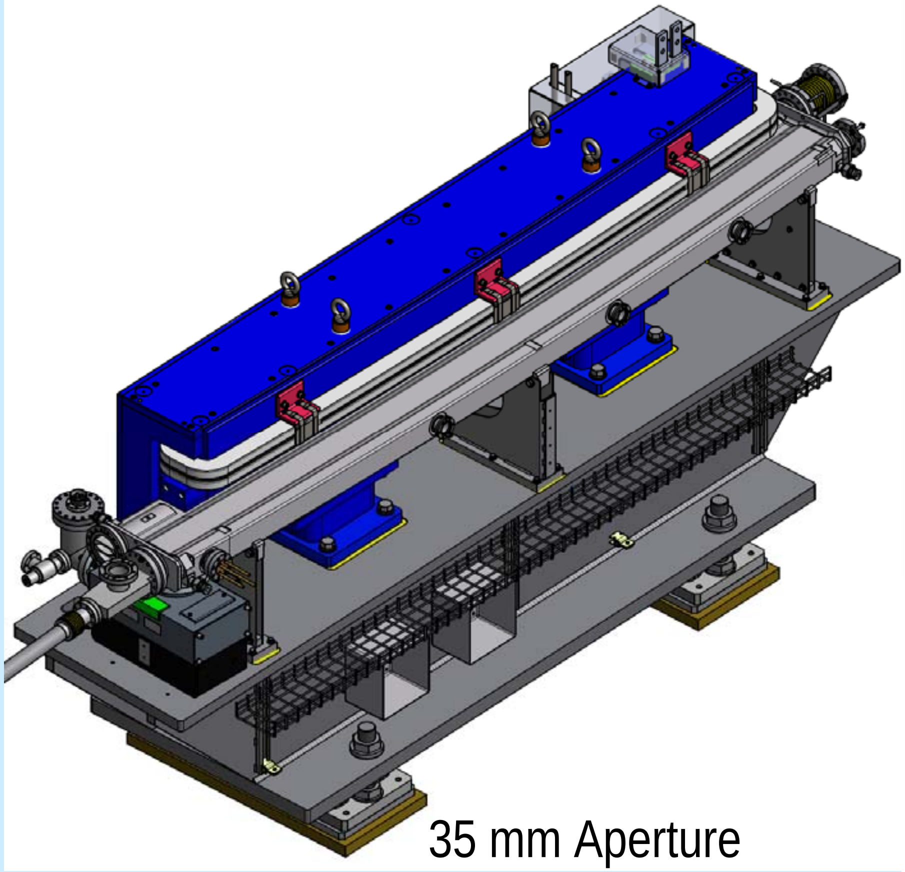
Magnets on Girders in NSLS-II



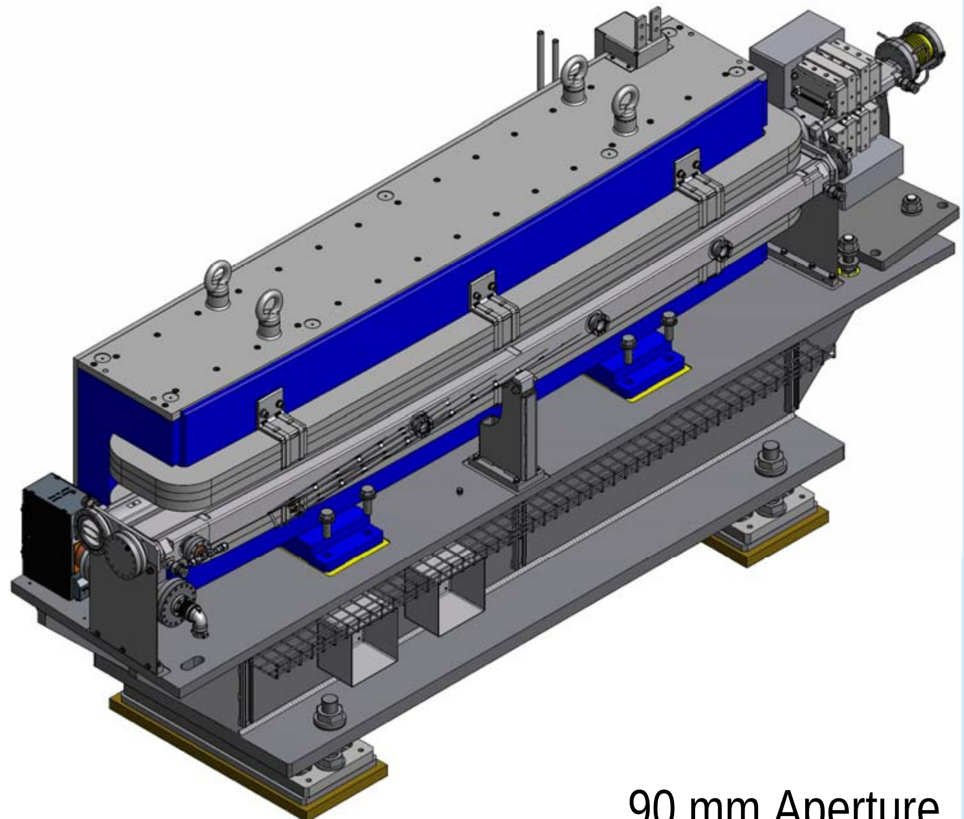
Magnets on Girders in NSLS-II



Main Bending Dipoles



35 mm Aperture



90 mm Aperture

The dipoles are mapped at BNL after installation onto its girder.

The handling of dipole-girder assembly requires caution!

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NSLS-II Storage Ring Magnets Delivered

Short Name	Description	Quantity	Delivered[1]	Vendor
Q66A	66 mm Single Coil Short Quadrupole	30	12	A
Q66B	66 mm Single Coil Short "Wide" Quadrupole	30	7	A
Q66C	66 mm Double Coil Long Quadrupole	30	5	A
Q66C'	66 mm Double Coil Long Quadrupole (Kinked)	30	5	A
Q66D	66 mm Double Coil Short Quadrupole	90	4	B
Q66E	66 mm Double Coil Short "Wide" Quadrupole	30	2	B
Q90	90 mm Aperture Quadrupole	60	12	C
S76	76 mm Aperture Sextupole	30	3	C
S68	68 mm Aperture Sextupole	165	52	D
S68W	68 mm Aperture "Wide" Sextupole	75	12	E
D35	35 mm Aperture Bending Dipole	54	2	C
D90	90 mm Aperture Bending Dipole	6	1	C
C100	100 mm Aperture Dipole Correctors (102?)	90	55	F
C101	100 mm Aperture Correctors with Skew Quad	30	12	F
C156	156 mm Aperture Correctors (60?)	45	33	F
	Fast Orbit Correctors	60	0	G
	Total number of magnets =	**855**	**217**	(25.4%)

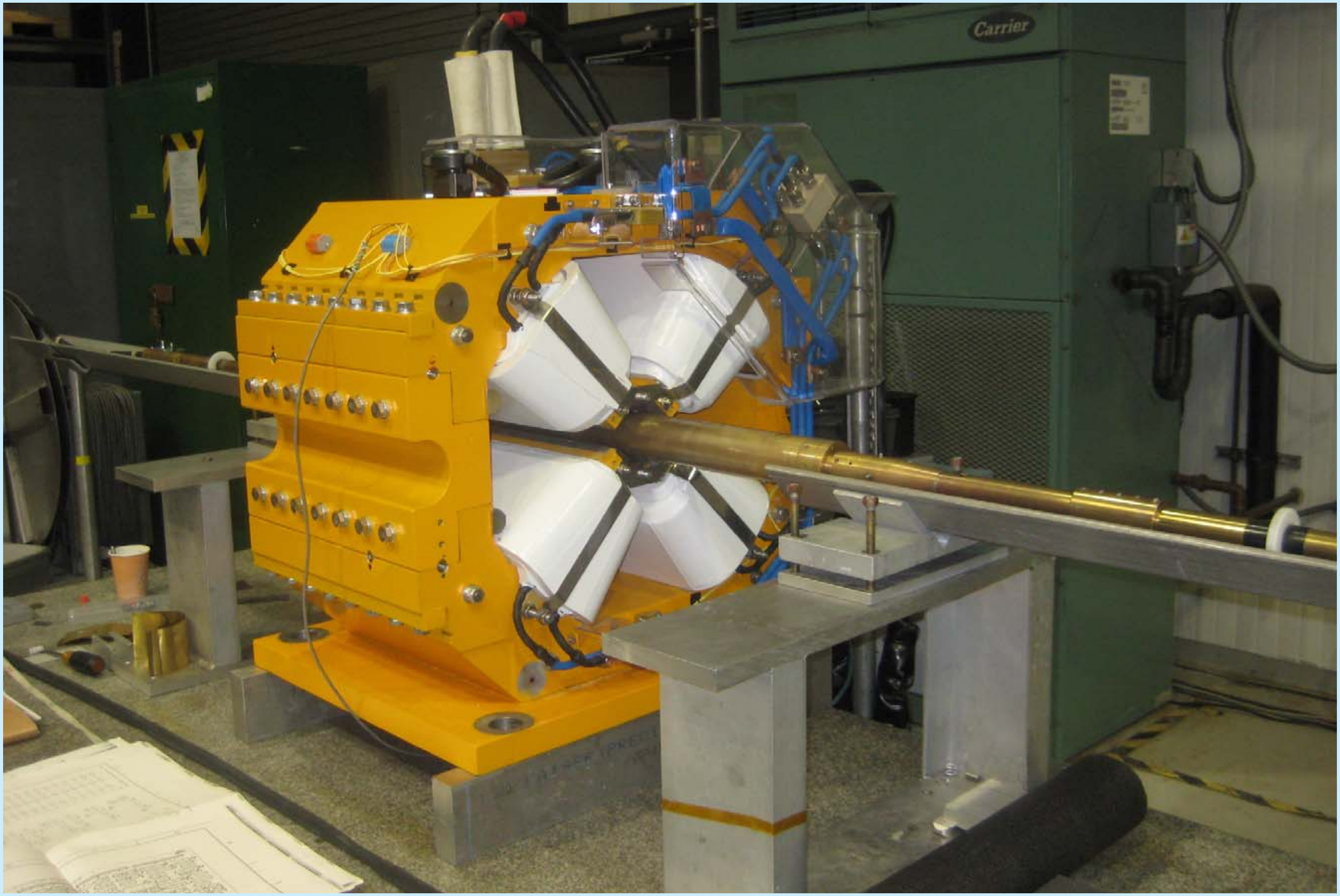
[1] Number of magnets in-house at BNL as of 16-Sep-2011

General Measurement Plans: Multipoles

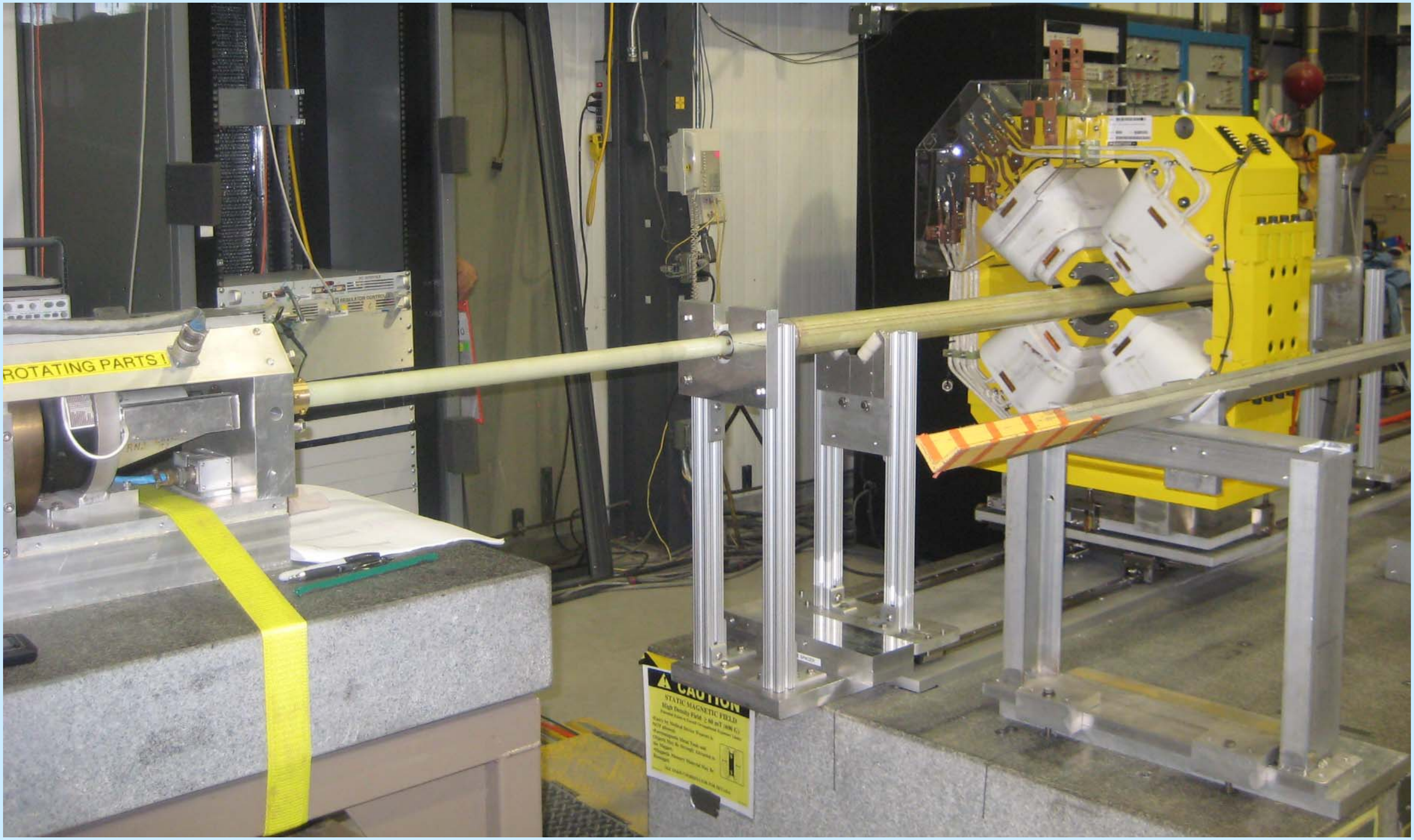
- The multipole magnets are measured by rotating coils at the respective manufacturer's site, as well as at BNL.
- BNL uses either a 5-winding (RHIC style) or a new 9-winding design (see IMMW16) *tangential* rotating coils, along with digital voltmeters for data acquisition.
- All vendors use *radial* rotating coils of various designs, along with digital integrators for data acquisition. Most vendors use Metrolab's PDI integrators, but one of them uses home-built integrators with similar performance.
- BNL systems implement bucking digitally, whereas all vendors' systems are based on analog bucking.

⇒ A wealth of information on performance of different systems!

BNL Measurement Systems: Moles



BNL Measurement Systems: External Drive



General Measurement Plans: Multipoles

- The first few multipole magnets of each type were also scheduled for 2-D Hall probe maps in the magnet's midplane.
- The Hall probe maps were required for:
  - Determining magnetic length of the magnets
  - Fringe field harmonics
  - Calibration of absolute strength of main harmonic term measured by rotating coils (goal: ±0.05%).
- The Hall probe maps could be measured in only a few magnet types due to time constraints, and inadequate facilities at most vendor sites, as well as at BNL. Also, not all measurements turned out to be with well calibrated Hall probes.
- A suitable Hall probe bench is now under construction at BNL.

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 were implemented to improve the reproducibility of the 68 mm aperture sextupoles.
- Reassembly tests currently add significantly to the magnet testing workload.

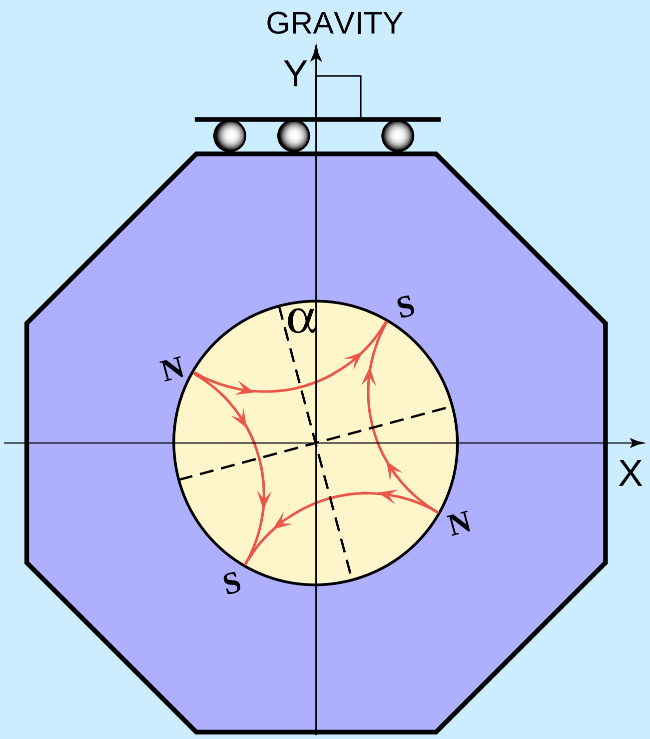
Roll Angle in Multipoles

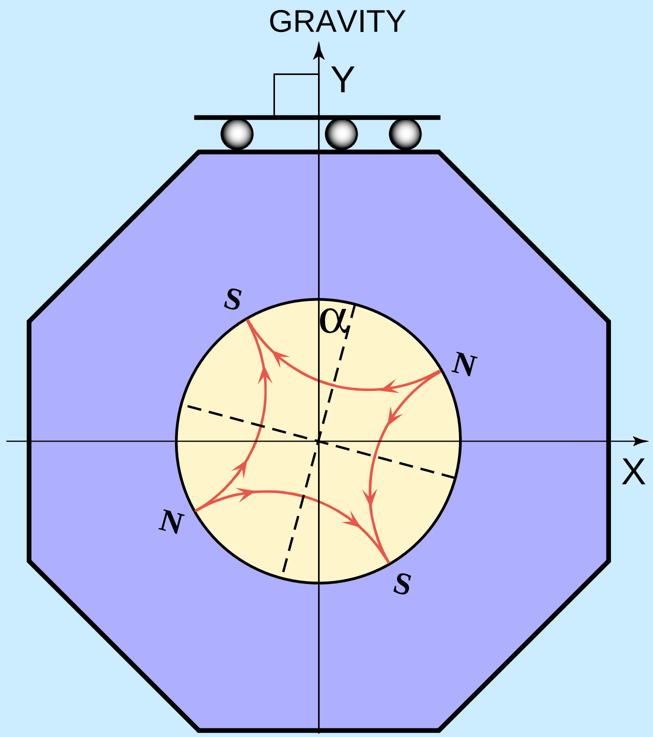
- The tolerance on roll angle for multipoles in NSLS-II was ±0.2 mrad initially, but was later relaxed to ±0.5 mrad.
- For most well-built magnets, the magnetic midplane may be expected to match the mechanical midplane within ±0.5 mrad. However, this may not be true if there are construction errors and large unallowed terms are needed to be shimmed.
- It is desirable to measure the true magnetic roll relative to the plane defined by the fiducials on top of the magnet, and use this information to install the magnets, to achieve the best possible roll alignment of the magnets.
- The magnet vendors are expected to make this measurement, but some of the vendors do not have this capability due to a lack of an absolute angle reference (typically gravity) in their systems.

Rotating Coil Calibration for Roll Angle

- The calibration of angular position of the rotating coil windings with respect to the angular encoder zero needs to be precisely monitored and calibrated often.
- All roll angle calibrations are done by measuring the magnet from both ends.
- In the BNL systems, the connection between rotating coil and angular encoder is never broken. Typical accuracy in roll angle relative to magnet fiducials is better than 0.1 mrad.
- All vendors' systems require the rotating coil to be disconnected to turn it around, which may introduce some extra uncertainty in the calibration.
- Some vendors perform this calibration for every magnet, whereas some do this only occasionally.

Roll Angle Measurement Error Correction





View from one end:

True Roll Angle = α

Meas. Roll Angle = $\alpha + \varepsilon = \alpha_1$

View from opposite end:

True Roll Angle = $-\alpha$

Meas. Roll Angle = $-\alpha + \varepsilon = \alpha_2$

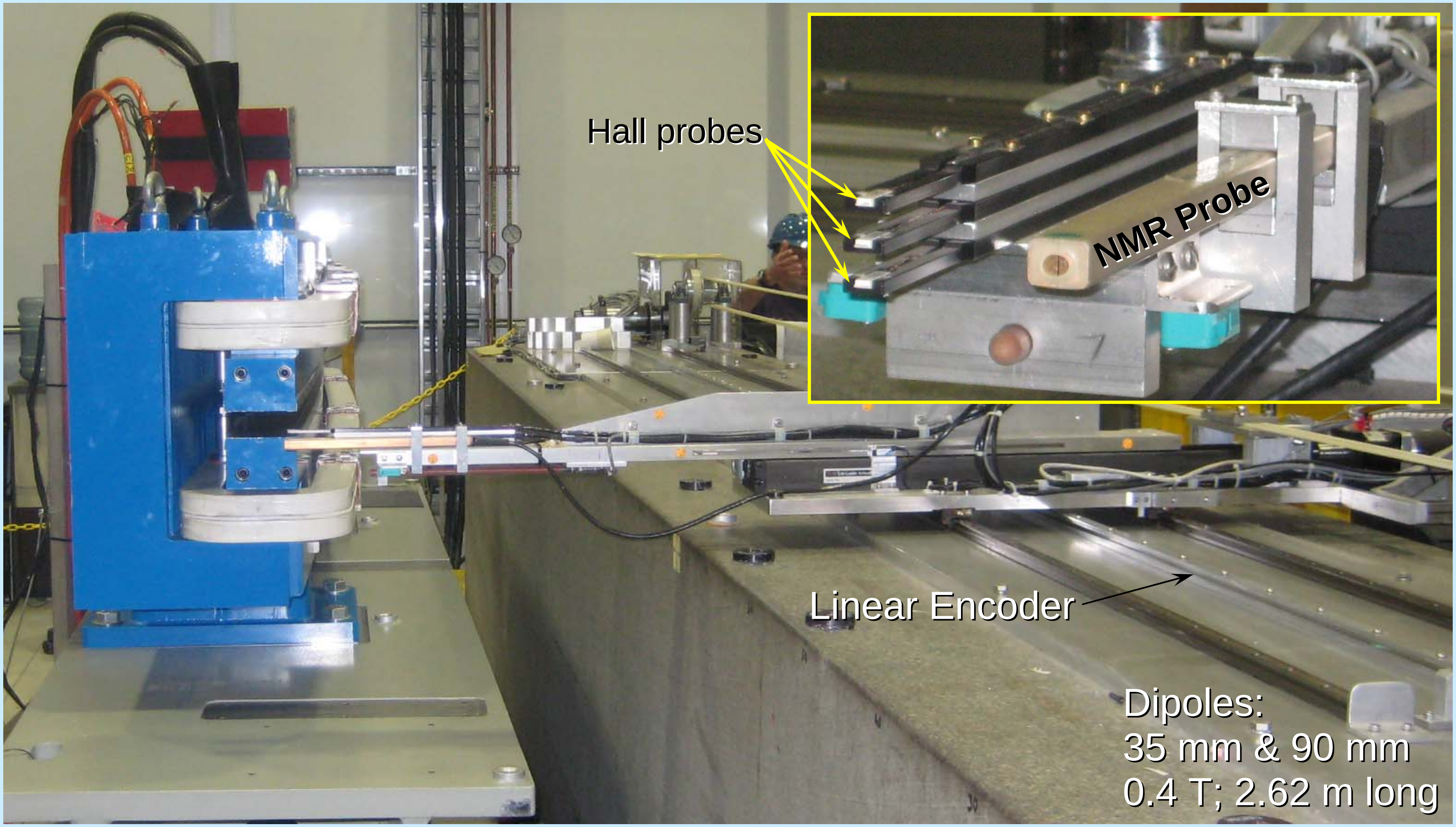
True Roll Angle = $\alpha = (\alpha_1 - \alpha_2)/2$

Meas. Error = $\varepsilon = (\alpha_1 + \alpha_2)/2$

General Measurement Plans: Dipoles

- The main bending dipoles are mapped using a single Group 3 Hall probe by the vendor. The mapping is done in the magnet midplane, as well as two more planes vertically offset by ±10 mm.
- A mapping system employing three Group 3 Hall probes arranged vertically is also used at BNL.
- The BNL system has a NMR probe also for in-situ calibration of the Hall probes.
- The dipole correctors, consisting of vertical and horizontal field dipoles, are mapped by the vendor using a 3-D Hall probe. Axial scans are carried out over a 5 x 5 grid in X-Y.
- Some correctors are measured at BNL using rotating coil.

Hall Probe Mapping System at BNL

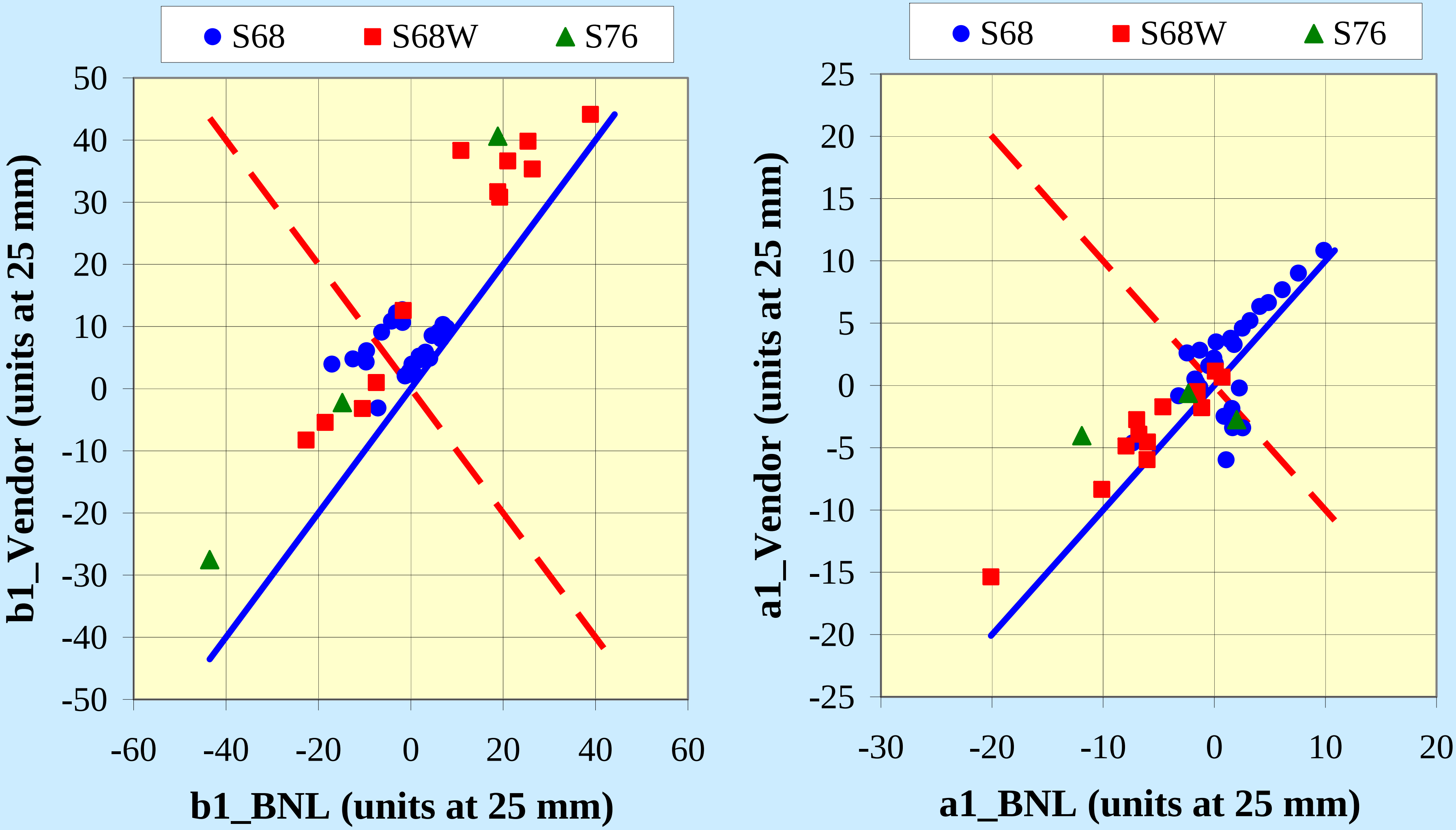


4.28 m axial travel; 0.33 m radial travel; 5 micron resolution position readout

Vendor Vs. BNL Measurements

- A comparison between magnetic measurements results obtained by magnet vendors and the BNL measurements in the as-received magnets is interesting in view of very different hardware used by different manufacturers.
- The agreement, in general, has been within less than ~1 unit (except for sign issues). This *can not* be considered very satisfactory in view of the tight specifications for NSLS-II.
- In some cases, the disagreement has been very large (several units), prompting a detailed investigation of both the BNL and the vendor's systems.
- For small discrepancies, it is hard to say whether it is due to measurement uncertainties, or genuine changes in magnet.
- For large discrepancies, several magnets had to be reshimmed.

Vendors Vs. BNL Measurements in Sextupoles for NSLS-II



Blue Solid Line = Perfect agreement with correct sign

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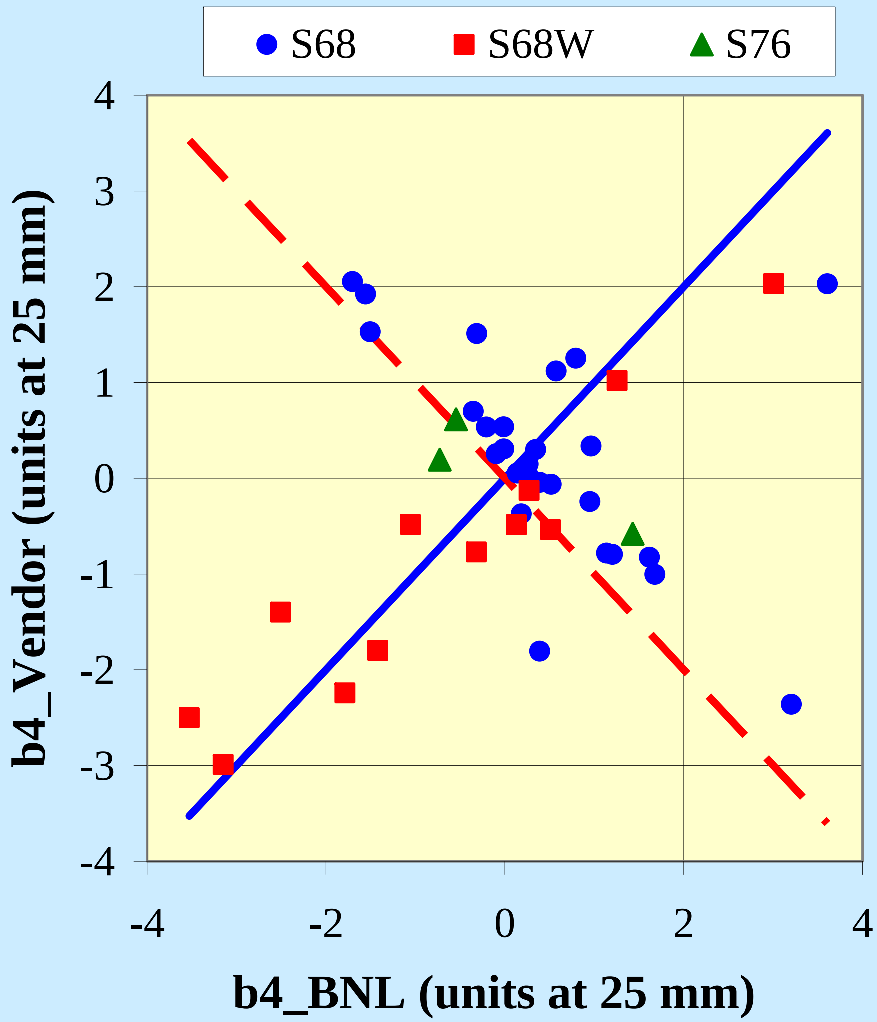
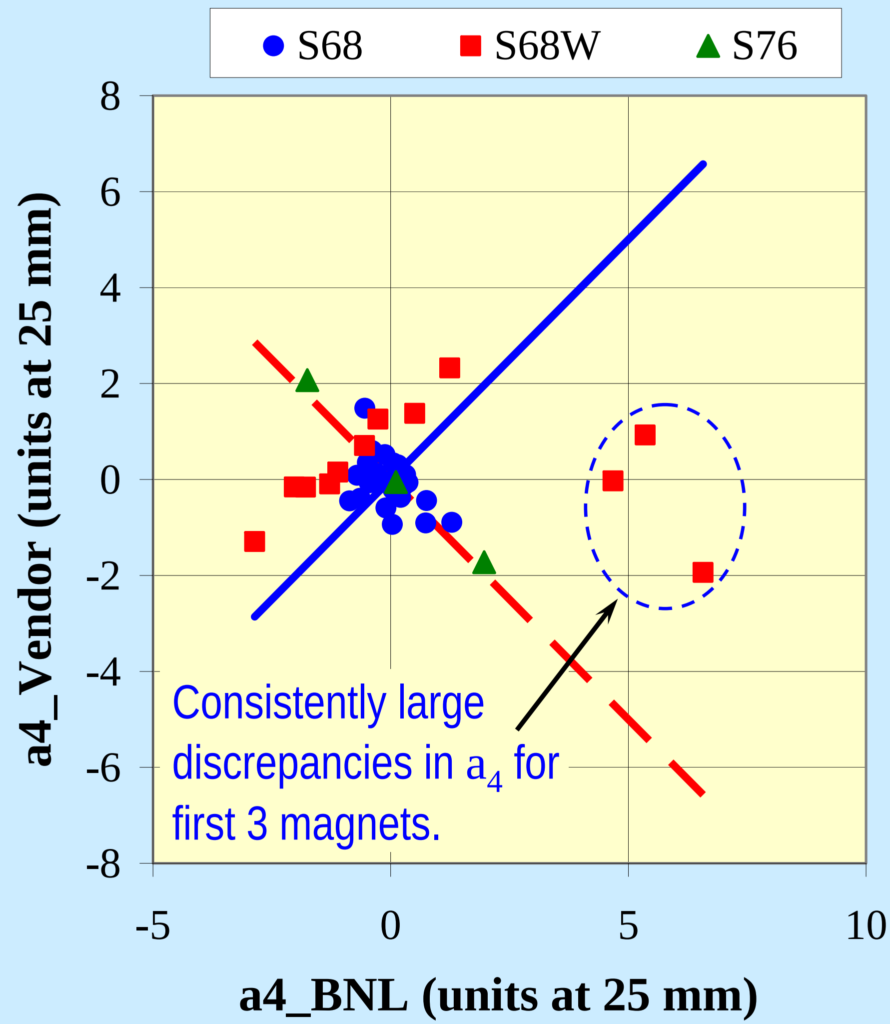
Vendors Vs. BNL Measurements in Sextupoles for NSLS-II





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Validation of BNL Digital Bucking

- The sextupoles were measured at BNL using a RHIC style “mole” which has only dipole and quadrupole bucking windings.
- We could still measure sextupoles with this “mole” by using the dipole windings to buck out the sextupole terms by readjusting the bucking coefficients in digital bucking.
- To validate the digital bucking scheme, we built a summing amplifier with the right amplification factors for the 5 coil signals such that the summed signal had zero sextupole and quadrupole terms. Actual bucking ratios achieved were ~1800 for the sextupole term and ~350 for the quadrupole term.
- All individual signals, as well as the bucked signal, were acquired simultaneously. The harmonics were obtained by digital bucking, as usual, and also from the analog bucked signal.

Validation of BNL Digital Bucking

NSLS-II Wide Sextupole #7; As Received; 95 A; LT-S68W_0007.0002; 1-Oct'10

C(3)=	0.024729	T.m at 25 mm (95A)		*B''.L* =	79.133	T/m (95A)	Vendor – BNL		
n	bn_analog	bn_digital	bn_Vendor	an_analog	an_digital	an_Vendor	*n*	bn_diff.	an_Diff.
1	**-21.83**	**-21.83**	-8.08	**-6.29**	**-6.29**	-4.14	1	**13.8**	**2.1**
2	--	--	--	--	--	--	2	--	--
3	--	--	--	--	--	--	3	--	--
4	**-3.34**	**-3.33**	-2.99	**5.34**	**5.34**	0.93	4	**0.3**	**-4.4**
5	**-1.39**	**-1.39**	-0.65	**-0.43**	**-0.43**	-0.53	5	**0.7**	**-0.1**
6	**0.58**	**0.58**	0.80	**-0.27**	**-0.26**	-0.22	6	**0.2**	**0.0**
7	**-0.22**	**-0.22**	-0.05	**0.05**	**0.05**	0.09	7	**0.2**	**0.0**
8	**0.55**	**0.55**	0.55	**-0.06**	**-0.06**	0.01	8	**0.0**	**0.1**
9	**-0.47**	**-0.47**	-0.40	**-0.08**	**-0.08**	-0.18	9	**0.1**	**-0.1**
10	**-0.32**	**-0.32**	-0.34	**0.41**	**0.41**	0.38	10	**0.0**	**0.0**
11	**0.05**	**0.05**	0.00	**-0.05**	**-0.05**	-0.08	11	**-0.1**	**0.0**
12	**0.00**	**0.00**	0.02	**0.08**	**0.08**	0.04	12	**0.0**	**0.0**
13	**0.14**	**0.14**	0.15	**-0.01**	**-0.01**	0.01	13	**0.0**	**0.0**
14	**0.02**	**0.02**	0.00	**0.04**	**0.04**	0.07	14	**0.0**	**0.0**
15	**0.21**	**0.21**	0.19	**-0.02**	**-0.02**	0.02	15	**0.0**	**0.0**

Note: ***The BNL analog and digital bucking measurements were performed simultaneously.***

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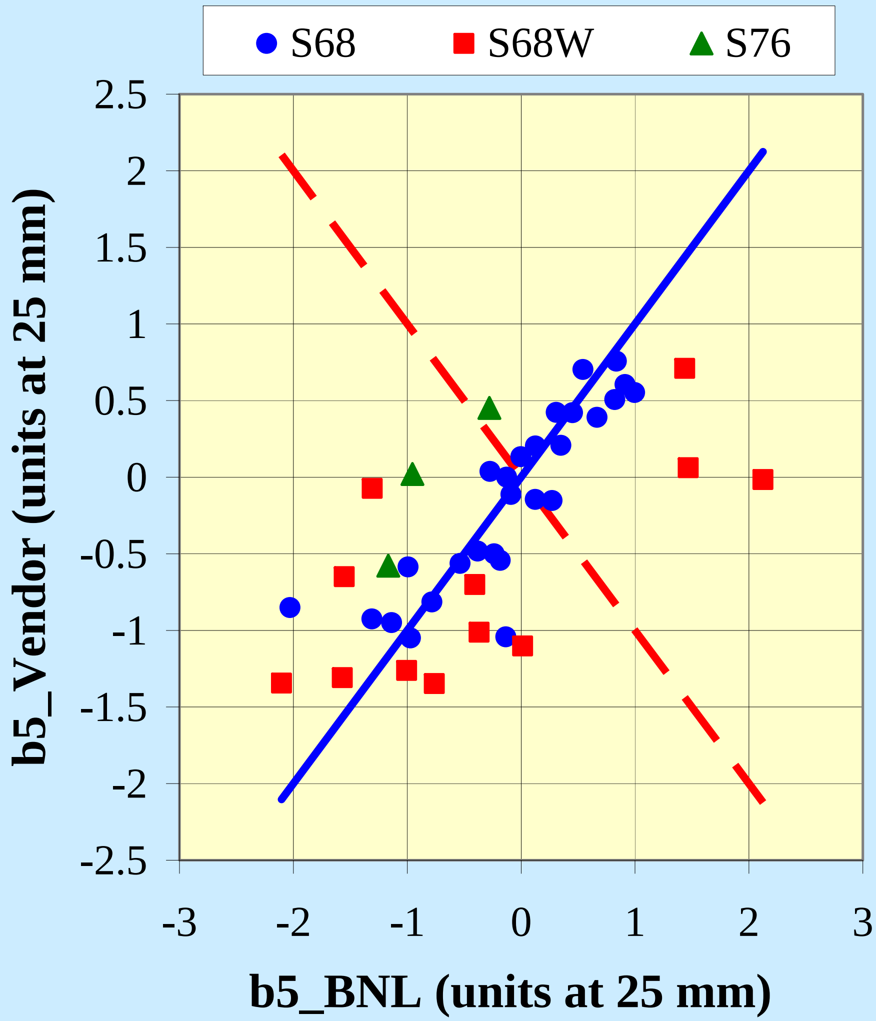
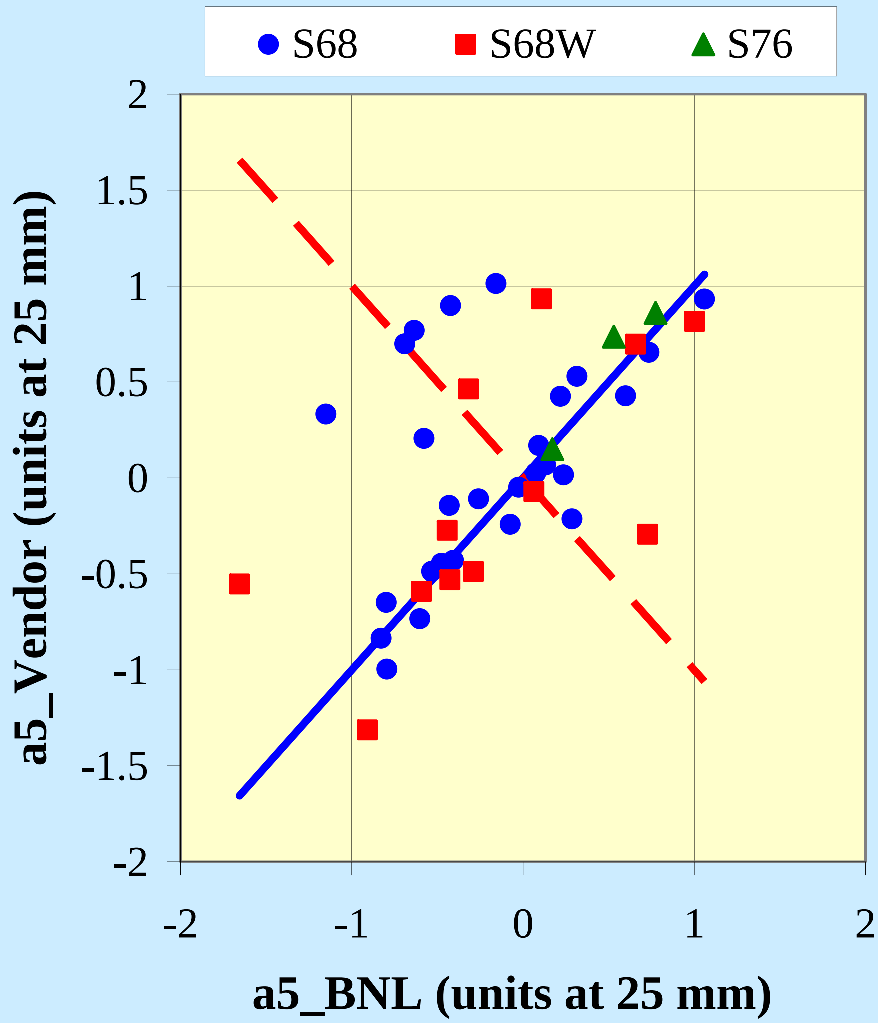
Vendors Vs. BNL Measurements in Sextupoles for NSLS-II





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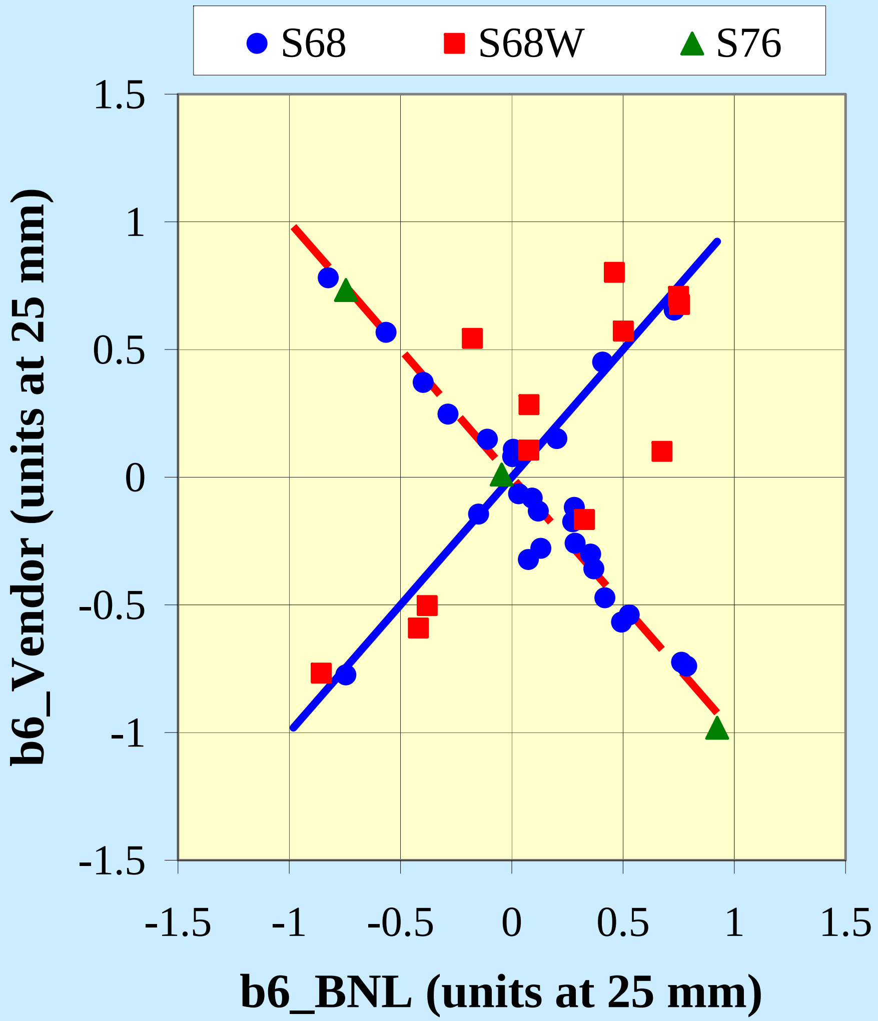
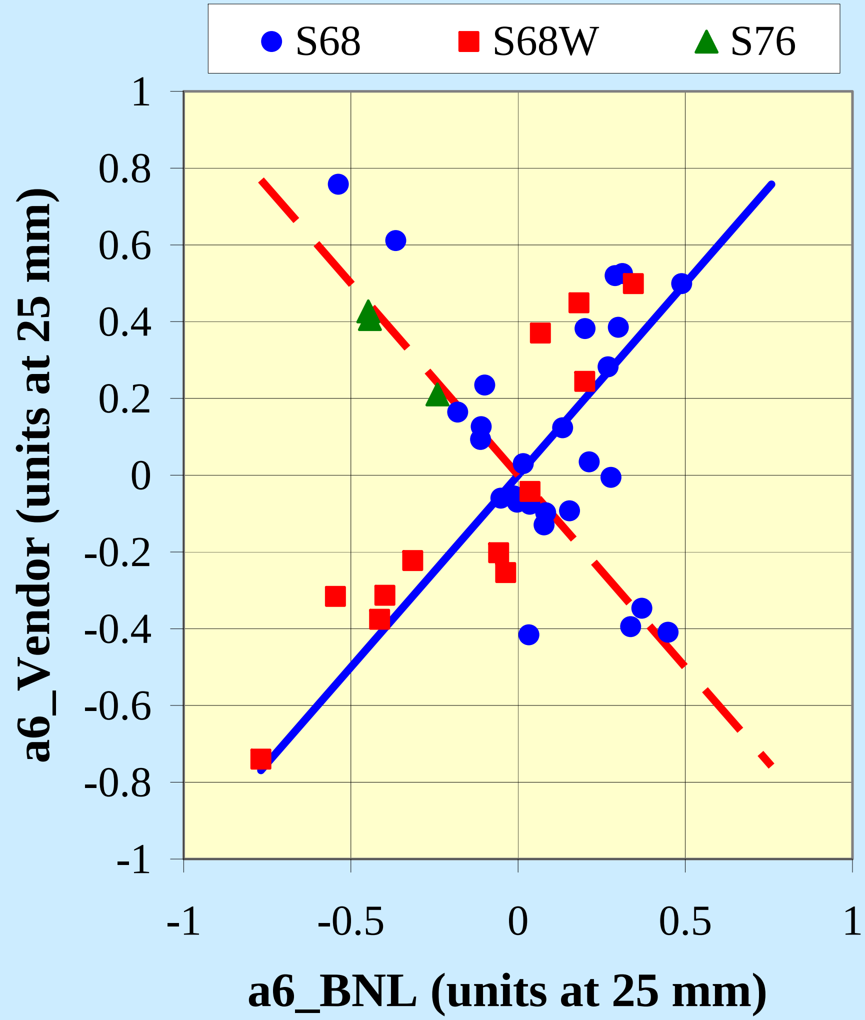
Vendors Vs. BNL Measurements in Sextupoles for NSLS-II





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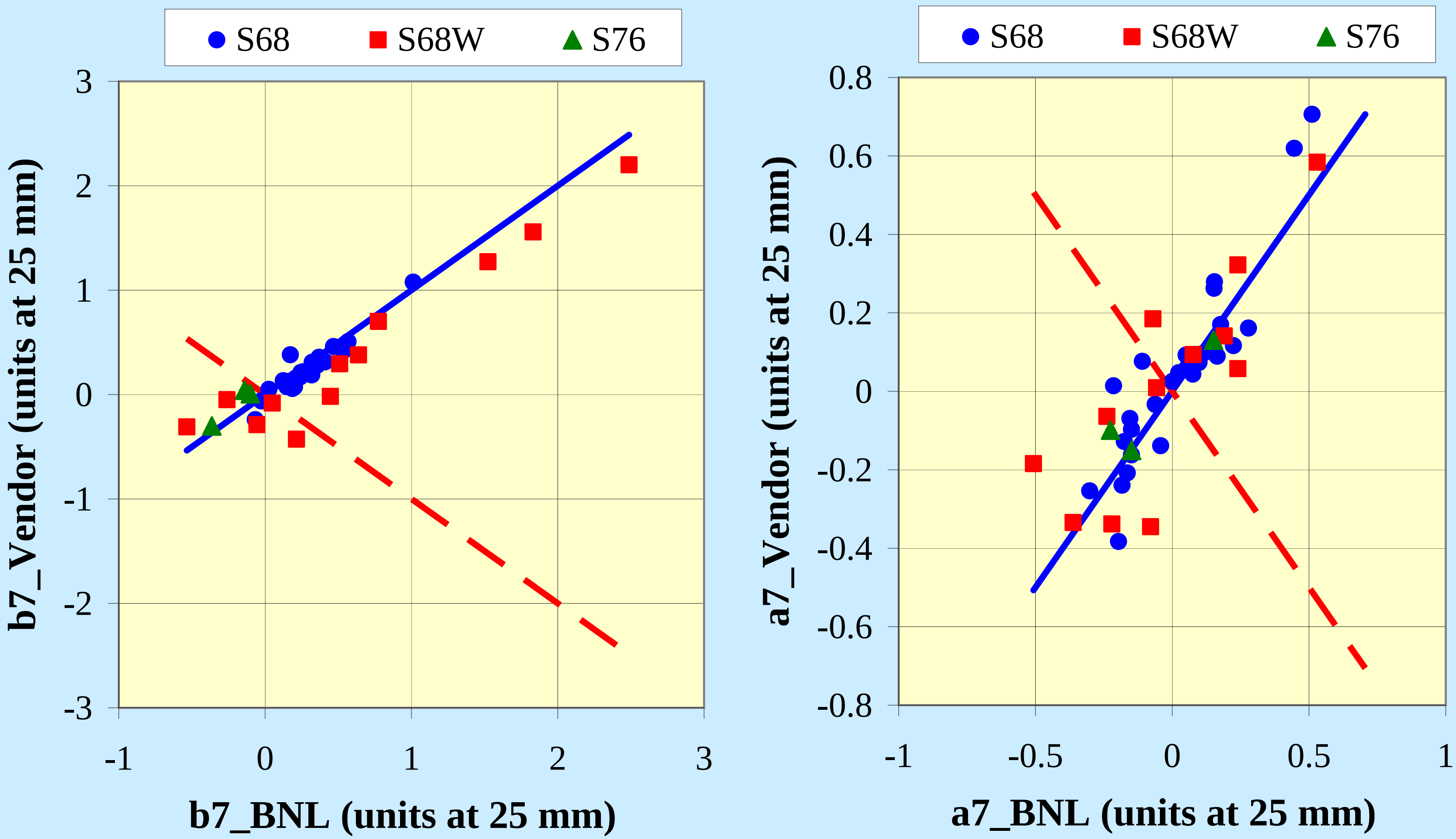

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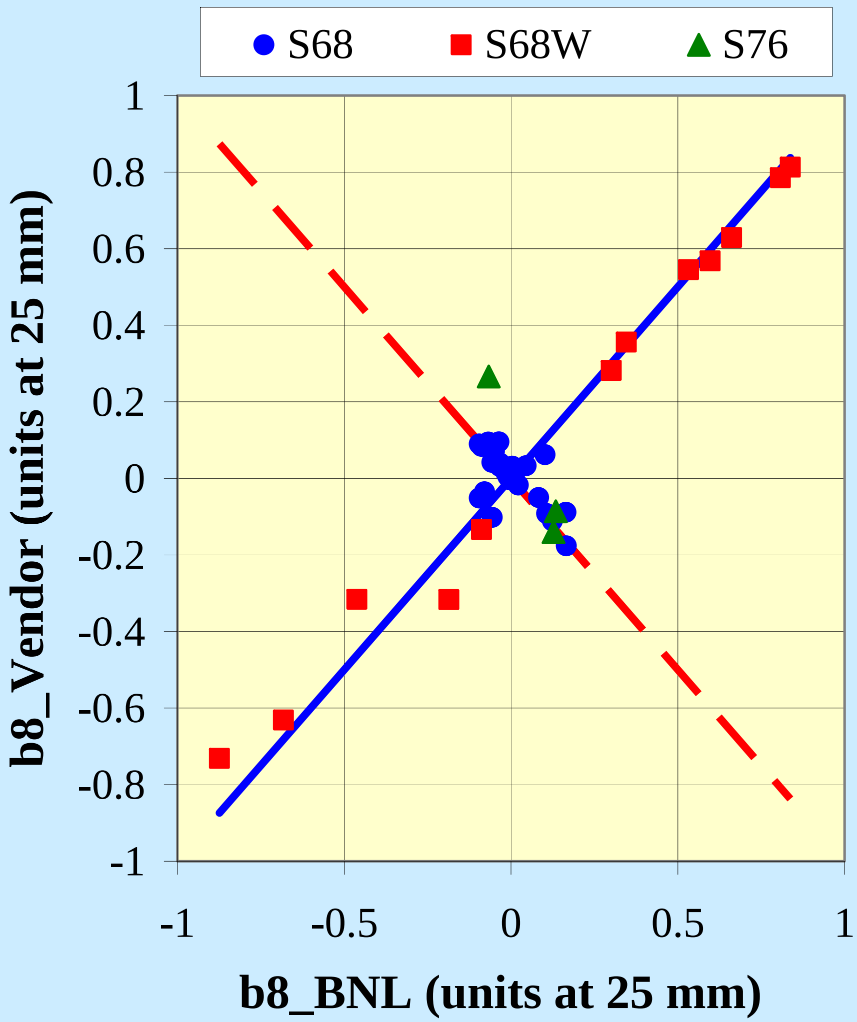

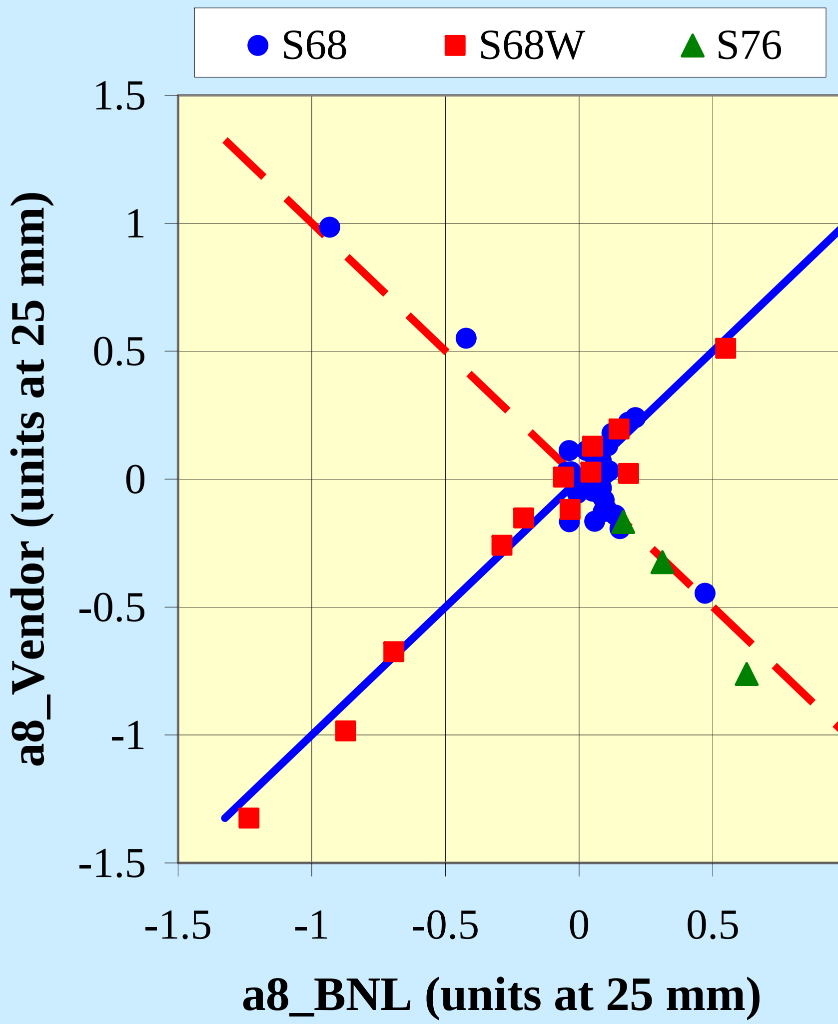

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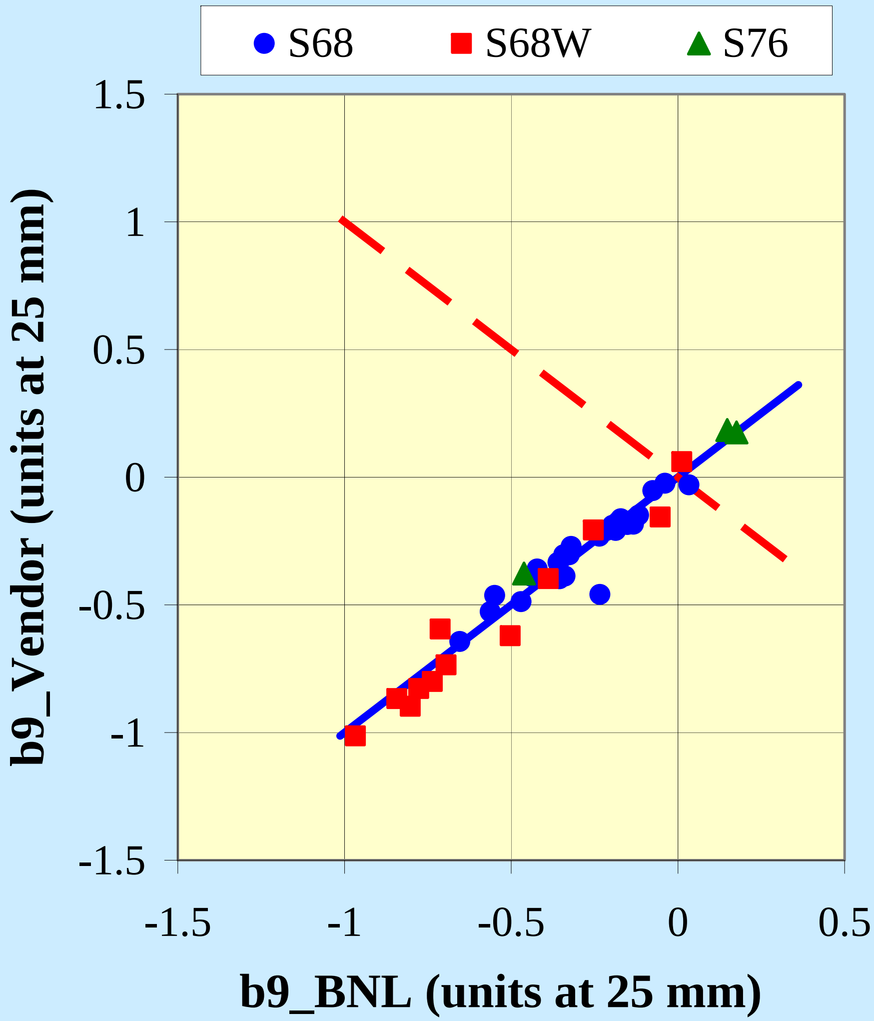

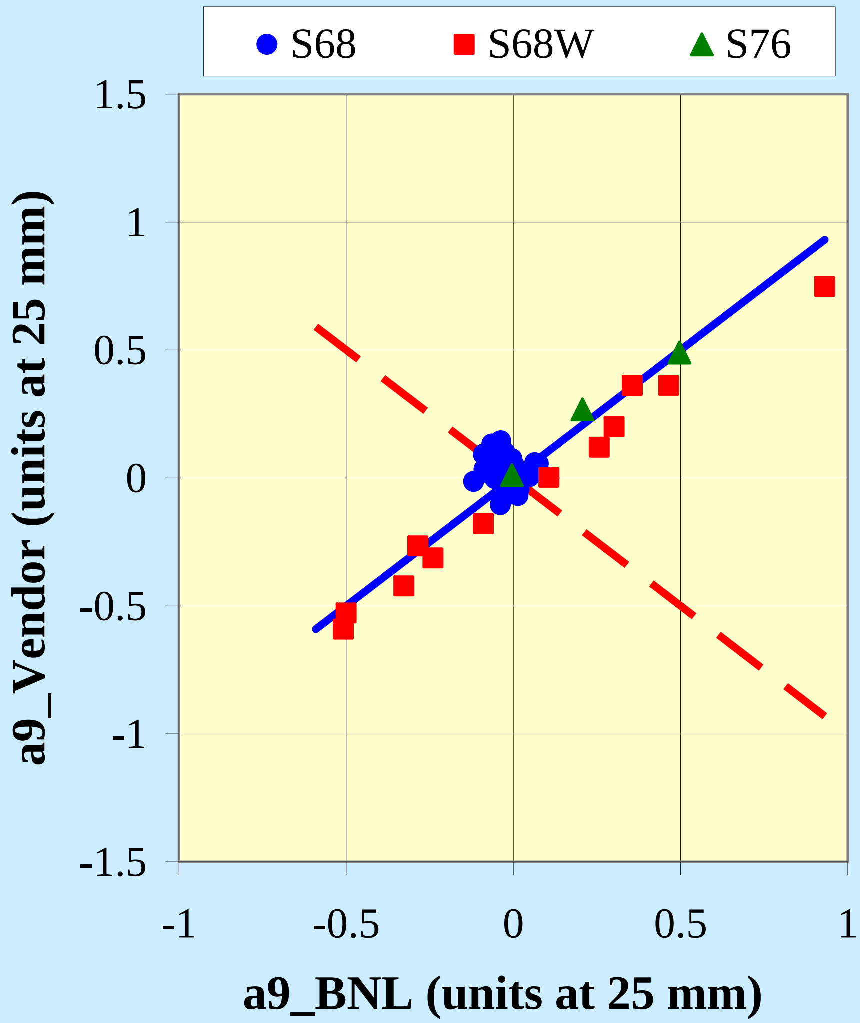

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Summary

- The production of magnets for NSLS-II storage ring is in full swing.
- After some initial difficulties, a steady stream of magnets is now being delivered from most manufacturers.
- All magnets are measured by the manufacturers before shipping.
- Not all manufacturers have the capability to measure roll angle.
- Initial plan was to measure only a small sample at BNL.
- Uncertainties in the vendors' data may necessitate measurements of a bigger fraction of magnets (possibly all multipoles) at BNL.
- New measurement systems are being commissioned at BNL to cope with increased testing requirements.
- The magnet production and measurements program is expected to last until early 2013.