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

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

**Total number of magnets in storage ring = 870**

<sup>(1)</sup> Integrated strength is defined as Int(B.dl) for dipoles, Int(B’.dl) for quads, and Int(B".dl) for sextupoles

<sup>(2)</sup> Strength listed is of the skew quadrupole; the dipole correctors have the same strengths as in C100
Magnets on Girders in NSLS-II

G6-Even Cell

Beam Direction

3.893 m

Fast Corrector

S68

Q66D

Q66C'

C100

S68W

Q66E

S68

C100

3.893 m
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!

NSLS-II Production Measurements: Lessons Learned; Animesh Jain, BNL
IMMW18: June 3-7, 2013
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.

⇒ 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

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

Consistently large discrepancies in a₄ for first 3 magnets.

from IMMW-17

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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.
Reassembly tests in LT-S68_0005

Spec = ±1 unit

Early modifications
With Cutoff Clamps
Cutoff Clamps No Center Pins
No Clamps

Measurement Number:

As-received. Clamp Removed Keys drilled out 1st Reassembly 2nd Reassembly 3rd Reassembly Clamps Cut Off 1st Reassembly 2nd Reassembly Re-Torqued 3rd Reassembly No Center Pins Magnet lifted 5 mm. 1st Reassembly 2nd Reassembly No Clamps or Pins 1st Reassembly 2nd Reassembly

a4 (units at 25 mm)
Reassembly tests in LT-S68_0005

Spec = ±1 unit

Early modifications

With Cutoff Clamps

Cutoff Clamps No Center Pins

No Clamps

Measurement Numbers:

- As-received
- Clamp Removed
- Keys drilled out
- 1st Reassembly
- 2nd Reassembly
- 3rd Reassembly
- Clamps Cut Off
- 1st Reassembly
- 2nd Reassembly
- Re-Torqued
- 3rd Reassembly
- No Center Pins
- Magnet lifted 5 min
- 1st Reassembly
- 2nd Reassembly
- No Clamps or Pins
- 1st Reassembly
- 2nd Reassembly

b5 (units at 25 mm)
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

The coil temperature sensor was later moved to midplane spacer on left side due to observed L-R asymmetry in some magnets.
Example: Full Excitation Curve Measurements

STP-9816-0022: 0.49 GPM on 02-Jan-2013 (Run 3)

Water temperature profile during 3 AC cycles prior to measurements

Measurements start when magnet is still cooling off after AC cycles.

Clock Time

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IMMW18: June 3-7, 2013
3 Currents at Planned Flow in STP-9816-1006

STP-9816-1006: 0.18 GPM on 28-Dec-2012 (Run 8)

Currents at Planned Flow in STP-9816-1006

- Current
- Temp Rise (Water)
- Temp Rise (Poles Avg)
- Temp Rise (Side Block NLE R)
- Temp Rise (Side Block NLE L)

Left-Right Asymmetry

Clock Time

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Harmonics Changes at Planned Nominal Flow

STP-9816-1006: 0.18 GPM on 28-Dec-2012 (Run 8)

Normal octupole is generated by temperature difference between the left and the right side spacers and poles. The effect could be as much as 1.1 unit difference from standard measurements.
3 Currents at Planned Flow in STP-9816-0022

STP-9816-0022: 0.18 GPM on 07-Jan-2013 (Run 6)

Very little yoke temperature rise, and no left-right asymmetry in this version 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

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Unexpected Variation of Field Readings

LT-D35_0005: Radial Pos. #2 (11-Apr-2012)

Position errors cannot explain the large variations

Vertical Field, $B_y$ (T)

$Y=0$ mm
$Y=+10$ mm
$Y=−10.5$ mm

$Y=0$ is out of phase with $Y = ±10$ mm
Radial Variation of Field
LT-D35_0005: Axial Pos. #170 (11-Apr-2012)

<table>
<thead>
<tr>
<th>Transverse Position, X (mm)</th>
<th>0</th>
<th>-10</th>
<th>-20</th>
<th>-30</th>
<th>-40</th>
<th>-50</th>
<th>-60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.20%</td>
<td>-0.15%</td>
<td>-0.10%</td>
<td>-0.05%</td>
<td>0.00%</td>
<td>0.05%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

Axial Position = 953.84 mm
Unexpected Variation of Field Readings

LT-D35_0005: Radial Pos. #2 (19-Apr-2012)

Variation with each point even with 1 mm scan step

Y=0 mm
Y=+10 mm
Y=−10.5 mm

Y=0 is out of phase with Y = ±10 mm

Axial Position (mm)
Axial Profile away from Edges

LT-D35_0005: Radial Pos. #3 (19-Apr-2012)

Large fluctuations disappear at radial positions away from the pole edges
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:

\[ F(\text{new}) = F(\text{old}) + \frac{F - F(\text{old})}{J} \]

where
- \( F(\text{old}) \) is the previous field reading display
- \( F(\text{new}) \) 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:

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

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)

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

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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.