NSLS-II Electron and X-Ray Beam Stability Review
Power Supply Stability & Electrical Noise

George Ganetis, Wing Louie, & David Bergman
January 18, 2018
Outline

• Overview Power Supply Systems
• Diagnostics & Measurements Used for Power Supplies
• Sample Stability Data
• Sample Noise Data
• Electrical Noise Reduction Design Features
• Challenges to Maintaining Stability in NSLS-II
• Summary
Power Supply Design Requirements

Main Dipole Power Supply Specifications

- AC input power
  - 3-phase 460 Vac ~635 Aac
- DC maximum output current – Imax
  - 400 Adc
- DC minimum output current – Imin
  - ~1 Adc
- DC output voltage
  - 1200 Vdc
- Operating quadrants
  - 1: (V+, I+)
  - 500 Hz
- Small-signal – 3 db bandwidth
  - 25 ppm
- Stability (8 h–10 s) – referred to Imax
  - 15 ppm
- Stability (10s–300 ms) – referred to Imax
  - 10 ppm
- Stability (300 ms–0 ms) – referred to Imax
  - 100 ppm
- Absolute accuracy – referred to Imax
  - 25 ppm
- Reproducibility long term – referred to Imax
  - 5 ppm 60 Hz and greater
- Current ripple – referred to Imax
  - 18 bit ±1 LSB
- Resolution of reference current
  - 16 bit ±1 LSB at 200 μsec
- Resolution of current measured – fast sampling
  - 22 bit ±1 LSB at 16.67 msec
- Resolution of current measured – slow sampling

Power supply stability specifications were developed from requirements from Accelerator Physics Group (With a engineering safety margin)

- Basic specifications have been developed for all power supplies

Power supply current stability is defined in peak ppm of the current maximum of the power supply. The stability value will have different valves depending on the length of given time period.
### Summary Table – Storage Ring Power Supplies

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Dipole</strong></td>
<td>1</td>
<td>1200 V</td>
<td>450 A</td>
<td>Unipolar Switch-Mode, Digital Regulator center point tied to GND</td>
<td>25 3.8</td>
<td>DC 1 Quadrant</td>
</tr>
<tr>
<td><strong>Quadrupole -A</strong></td>
<td>60</td>
<td>16 V</td>
<td>175 A</td>
<td>Unipolar Switch-Mode, Analog Curr. Regulator – 2 DCCTs</td>
<td>50 3.8</td>
<td>DC 1 Quadrant</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>22 V</td>
<td>175 A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>30 V</td>
<td>175 A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>30 V</td>
<td>200 A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sextupole -A</strong></td>
<td>40</td>
<td>40 V</td>
<td>120 A</td>
<td>Unipolar Switch-Mode, Analog Curr. Regulator- 2 DCCTs</td>
<td>100 15 (3.8)</td>
<td>DC 1 Quadrant</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>60 V</td>
<td>165 A</td>
<td>Model A &amp; B = 1 PS per 6 Magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>16 V</td>
<td>120 A</td>
<td>Model C = 1 PS per 2 Magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Global Horz. &amp; Vert. Correctors -A</strong></td>
<td>90</td>
<td>15 V</td>
<td>1.25 A</td>
<td>2 Channel Bipolar Linear, Analog Curr. Regulator - 4 Shunts</td>
<td>100 15 (3.8)</td>
<td>2000 Hz 4 Quadrant</td>
</tr>
<tr>
<td><strong>Insertion Horz. (Canting) Correctors –B</strong></td>
<td>15</td>
<td>30 V</td>
<td>30 A</td>
<td>Unipolar Switch-Mode, Analog Curr. Regulator – 2 DCCTs</td>
<td>50 3.8</td>
<td>DC 1 Quadrant</td>
</tr>
<tr>
<td><strong>Skew Quad Corrector-C</strong></td>
<td>30</td>
<td>20 V</td>
<td>20 A</td>
<td>Bipolar Linear, Analog Curr. Regulator – 2 DCCTs</td>
<td>100 15 (3.8)</td>
<td>DC 2 Quadrant</td>
</tr>
<tr>
<td><strong>Alignment Horz. &amp; Vert. Correctors -D</strong></td>
<td>180</td>
<td>25 V</td>
<td>20A</td>
<td>2 Channel Bipolar Linear / Pre-Regulator, Analog Curr. Regulator - 4 DCCTs</td>
<td>25 3.8</td>
<td>3 Hz 2 Quadrant</td>
</tr>
<tr>
<td><strong>Dipole Trim – Corrector -E</strong></td>
<td>27</td>
<td>15 V</td>
<td>1.25 A</td>
<td>2 Channel Bipolar Linear / Pre-Regulator, Analog Curr. Regulator – 4 Shunts</td>
<td>100 15 (3.8)</td>
<td>DC 4 Quadrant</td>
</tr>
<tr>
<td><strong>Dipole Trim – Corrector -F</strong></td>
<td>3</td>
<td>20 V</td>
<td>10 A</td>
<td>2 Channel Bipolar Linear / Pre-Regulator, Analog Curr. Regulator – 4 DCCTs</td>
<td>100 15 (3.8)</td>
<td>DC 2 Quadrant</td>
</tr>
</tbody>
</table>

There is a total of 1000 power supply channels used for the storage ring.
## Summary Table – Insertion Device Power Supplies

<table>
<thead>
<tr>
<th>Power Supply - Model</th>
<th>Qty</th>
<th>Max. Voltage</th>
<th>Max Current</th>
<th>Configuration</th>
<th>Stability / Resolution</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion Device Correction Coils</td>
<td>17</td>
<td>30 V</td>
<td>10 A</td>
<td>6 Channel Bipolar Linear / Pre-Regulator</td>
<td></td>
<td>DC</td>
</tr>
<tr>
<td>Slow Interface</td>
<td>4</td>
<td>30 V</td>
<td>10 A</td>
<td>RS 232 Setpoint Interface</td>
<td></td>
<td>2 Quadrant</td>
</tr>
<tr>
<td>Fast Interface</td>
<td></td>
<td></td>
<td></td>
<td>NSLS-II PSC/PSI Interface</td>
<td></td>
<td>2 Quadrant</td>
</tr>
<tr>
<td>Insertion Device Beam Chamber Strip</td>
<td>5</td>
<td>15 V</td>
<td>5 A</td>
<td>8 Channel Bipolar Switch Mode</td>
<td>1000 ppm</td>
<td>3 Hz</td>
</tr>
<tr>
<td>BINP (23-ID)</td>
<td>8</td>
<td>15 V</td>
<td>5 A</td>
<td>6 Channel Bipolar Linear / Pre-Regulator</td>
<td>~ 200 ppm</td>
<td>3 Hz</td>
</tr>
<tr>
<td>Res. Rec. (2-ID &amp; 21-ID)</td>
<td>1</td>
<td>30 V</td>
<td>10 A</td>
<td>6 Channel Bipolar Linear / Pre-Regulator</td>
<td>~ 100 ppm</td>
<td>2 Quadrant</td>
</tr>
<tr>
<td>Danfysik (21-ID)</td>
<td></td>
<td></td>
<td></td>
<td>8 Channel Bipolar Switch Mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 Channel Bipolar Linear / Pre-Regulator</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Analog Curr. Regulator – 6 Hall CTs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 Channel Bipolar Linear / Pre-Regulator</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Analog Curr. Regulator - 6 DCCTs Readbacks</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 Channel Bipolar Linear / Pre-Regulator</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Analog Curr. Regulator - 6 DCCTs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- All Insertion device correction coils (mounted at the device) use a 6 channel Danfysik Power Supply
- Early installation use a simple RS 232 interface to set and readback the current
- Latest installations use the standard NSLS-II controls – PSC/PSI
- All EPU beam chamber current strip power supplies use NSLS-II controls – PSC/PSIs
- Res. Rec. = Resonance Research – power supply company name
Storage Ring Main Dipole Power Supply

- 2 - 600 V 450 A power Converters connected in series and center-taped to ground.
- Large energy storage to ride through AC power disturbances.
- Digital voltage and current loops using NI Compact RIO FPGA.
- Precision DMM used for long term stability.
- Linear output stage to minimize 60Hz harmonics.
- Dual DCCTs for output current sensors.
- Heavily instrumented for fast fault diagnoses.
- Air cooled – No water in power supply
Multipole Unipolar Power Supplies

This configuration is used for Quadrupole, Sextupole, & Transport Line magnet circuits.

Two DCCTs are used, one for feedback and the other for redundant monitoring.

Power Supply Controller – Performs all high level functions for the power supply – setpoint /ramp generation and diagnostic monitoring.

There are no local controls for the power supplies. Everything has to go through the control system.

Current loop is simple Analog PID.

All PS have an AC input line filter.

DMM is used to monitor Long term stability of Setpoint and DCCTs.

The design incorporates a large amount of monitoring instrumentation that is used for initial testing and operations.

Complete power supply is in temperature controlled rack that is maintained at 24 C ± 1.
SR Dipole PS 80-Day Stability

~ 4 ppm lpp for 80 days

Stability Requirement is ~ 25 ppm

Digital Setpoint

Current Signal

14 ppm

SR:C03-MG(PS:D-SP):Il:DMM2-I
SR:C03-MG(PS:D-SP):Il:Sp1-SP [AMP]
Dipole magnet B-field measurements are made in the C03G3 and C02G5 magnets.
- C03G3 (90 mm): Hall probe and NMR
- C02G5 (35 mm): Hall probe
- DMM used to measure DCCTs for SR main dipole and trim for cell 03 magnet
- Data is continuously captured on a standalone system.
- This system is “temporary” to supply an independent check of dipole current & field stability
Dipole Magnet B-Field 5-Day Stability

Dipole Current (5 ppm/div)

C03G3 NMR (5 ppm/div)

5 ppm

5 ppm

5 ppm
Twenty nine days stability plot of C01-QM2B using DMM data

Blue is analog setpoints.

Red straight line is digital setpoints.

Brown is DCCT1 current

Discontinued time when the power supply was shut off and current went to zero

All Data is from DMM Scanner located in each PS rack group.
Quadrupole Magnet PS Four Day Stability

Four days stability plot of C01-QM2B using DMM data

- Blue is analog setpoints.
- Red straight line is digital setpoints.
- Brown is DCCT1 current

This is typical current stability for quadrupole power supplies. Stability Requirement is ~ 50 ppm
**Sextupole Magnet PS Current Long Term Stability**

**Thirty one days stability plot of C07-SM1A-P3 using DMM data**

- **Red straight line is digital setpoints.**
- **Blue is analog setpoints.**
- **5.8 ppm (0.0007A) 55.3516A**
- **10 ppm (0.0012A) 55.3494A**
- **55.3506A**
- **55.3509A**
- **Brown is DCCT1 current**
- **Discontinued time when the power supply was shutoff and current went to zero**

All Data is from DMM Scanner located in each PS rack group.
Sextupole Magnet PS Four Day Stability

Four days stability plot of C07-SM1A-P3 using DMM data

Blue is analog setpoints.

Brown is DCCT1 current

Red straight line is digital setpoints.

This is typical current stability for sextupole power supplies. Stability Requirement is ~ 100 ppm
PS Diagnostics - Snapshot Features

- Ten seconds circular buffer, 5 seconds on pre-trigger and 5 seconds on post trigger.
- Sample rate is 100 us, total 100,000 data points per buffer and stored as one record.
- The ADCs used are 16 bit SARs.
- All records are saved in archiver, which can retrieve by Control System Studio (CSS) or BNL developed plotting software.
- Each single channel power supply has 9 buffers and Dual channel power supply has 18 buffers.
- Methods to trigger the snapshot:
  - Hardware faults
  - Software on demand
- The snapshot feature is used to find out which sub-system has caused the power supply to fail and cause a beam trip.
- The snapshot is also used to determine power supply noise levels.
- Can perform FFT on data to look for possible noise sources that match the beam data.
In both incidents, the ground current spikes happened first and caused the ps current to change.
Snapshot Features - Noise Analysis

Quadrupole PS Spectral Output

**PS Output Voltage**

**PS Current**

- The FFT vertical axis is scaled to the same time domain vertical axis in Amps or Volts.
- The time domain noise level are very low, but the FFT can extract some frequency data.
Snapshot Features - Noise Analysis

Sextupole PS Spectral Output

PS Output Voltage

- The FFT vertical axis is scaled to the same time domain vertical axis in Amps or Volts.
The FFT vertical axis is scaled to the same time domain vertical axis in Amps or Volts.
Electrical Noise Reduction Design Features at NSLS II

• PS Output cables use twisted pairs minimize loops. Reduces pickup of external noise.
• Ring wide ps circuits cables are folded back to eliminate large loops.
• Most Power Supplies have some energy storage which will allow ride through of AC power disturbances. Booster PS have energy storage to minimize AC line disturbances due to pulsing.
• PS use AC input line filters to minimize switch mode converter noise on AC power lines.
• All power supplies have a soft ground which is also used to monitor ground current & noise.
• Controls (Regulator & PSI) AC power separate from power converter – AC power is from UPS which also serves as a AC line conditioner.
• Grounding is isolated between pentants. Derived from sub-station ground system. No loops
• Fast Orbit Feedback corrector PS uses Linear Amplifier output stage in minimize noise.
• Sleep Mode for Booster Dipole PS places current at low current level between Top Off injection requests. This minimizes Booster Dipole field disturbances into the SR.
• Temperature Controlled Racks- Low stability $\pm 1$ C, high stability $\pm 0.1$ C.
SR Dipole Magnet Circuit – Folded Bus Configuration

NSLS II Dipole Magnet Electrical Circuits

54 - 35mm Aperture Dipole Magnets Connected to Small Dipole Bus
6 - 90mm Aperture Dipole Magnets Connected to Large Dipole Bus
60 Dipole Trim Power Supplies

600 V 400 A Power Converter

600 V 400 A Power Converter
SR Dipole PS – AC Disturbance Ride Through

3-Phase 480 VAC (Time = 10/27/2016 18:44:46.54)

- BO
- OY
- YB

SP Readback, DCCT1, DCCT2

Current (A)

Current Regulators 1 and 2

Output (V)

Current Loop Error and Gnd Current

Loop Error
Gnd Current

Time (s)
Challenges to Maintaining Stability and Reducing Electrical Noise in NSLS-II

- Large ground currents through the water isolators have been a cause of large errors in some power supplies. (Greater than 1000 ppm) Task force addressing water quality and other solutions being investigated.
- Small Offset changes in DCCTs when control power is cycled – 10 to 100 ppm has been seen. The system has provisions to correct for this but a process to do this correction needs to be developed.
- Large number of power supplies with a large data set to analyze. We still need to develop software that can create simple reports for engineering to review.
- Presently we rely on Accelerator Physics to identify a power supply stability and or noise problems and then we can look at archived data to analyze the problem. (We continuously monitor ground currents because they cause the biggest stability problems to date.)
- We have recently had problems with the Process Chilled Water supply temperature. When we had fast temperature swings of + 5 F (nominal is ± 0.5 F) the high stability rack temperatures had problems maintaining ± 0.1
Due to the ps controls design, the output current is susceptible to large ground current.

**Ground current variation:**
\[ (-.26V) - (-.86V)/100\text{ ohm} = 6 \text{ mA} \]

**Power supply current variation:**
\[ (85.8A - 85.57A) = 0.23A = 2684 \text{ ppm} \]
Summary

• Diagnostics plays a critical role in confirming the stability and noise performance of the NSLS-II power supplies.
• Overall the power supplies have met the required stability for operations.
• Having the power supplies located in temperature controlled enclosures contribute greatly to the power supply stability.
• When Accelerator Physics is looking for noise or stability issues we are able to determine if the power supplies are the cause by using the built in diagnostics.
• Electrical design features built into NSLS II minimizes electrical noise through out the facility.
• Ground current and PCW temperature stability are our current issues.