Commissioning of National Synchrotron Light Source-II (NSLS-II) Fast Orbit Feedback System

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Outline

• NSLS-II status and parameters overview
• NSLS-II orbit feedback system
  • Technical requirements and specifications
  • Hardware review
• Individual eigenmode compensation
  • NSLS-II FOFB algorithm with individual eigenmode compensation
• Implementation
  • FPGA
  • Latency
• Performance measurement
• Summary
**NSLS-II Key performance**

- **Beamline operation started Feb. 2015 with 150 mA**
- **Oct started 250 mA top-off operation**
  - 3 GeV, 500 mA beam current with 1 nm-rad horizontal and 8 pm-rad vertical emittance.
    - Beam sizes at source points are ~100 µm / 3 µm (x/y)
  - High beam stability in position (<10% of rms size) and angle (<10% of rms divergence)
  - 1080 bunches in 1320 RF buckets, 3 hrs lifetime
  - Top off injection for stable intensity (±0.5% variation)

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>3</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>500</td>
</tr>
<tr>
<td>Circumference [m]</td>
<td>792</td>
</tr>
<tr>
<td>Number of DBA cells</td>
<td>30</td>
</tr>
<tr>
<td>X/Y Emittance [nm-rad]</td>
<td>1/0.008</td>
</tr>
<tr>
<td>Relative energy Spread</td>
<td>0.1%</td>
</tr>
<tr>
<td>RF Voltage [MV]</td>
<td>4.9</td>
</tr>
<tr>
<td>Number of ID straights</td>
<td>15 SSS and 12 LSS</td>
</tr>
</tbody>
</table>

**One super-period SR Lattice function**

Long ID =9.3m  Short ID= 6.6m
**SR BPMs and Correctors Location**

- **Slow correctors (Qty=6)**
  - Slow response – 2 Hz
  - Strong strength – 800 μrad
  - Utilized for – Alignment
  - Slow orbit feedback

- **Fast correctors (Qty=3)**
  - Fast response – 2 kHz
  - Weak strength – 15 μrad
  - Utilized for – Fast orbit feedback

100 mm slow(8)
156 mm slow(4)

30 mm fast (air core)
System Specifications

- Number of CCs: 30 sets
- Minimize beam motion < 10%
- Feedback rate: 10 kHz
- Bandwidth: ~200 Hz
- Control algorithm: SVD, Individual Eigenmode with PID control
  - FPGA based parallel matrix calculation
- Number of BPMs: 180 ea + ID bpms (27)
  - NSLS-II in house designed high performance rf BPM
- Number of a fast correctors: 90 ea
  - 15 urad, 20 bit current output resolution, 1 ppm step response, 2 kHz small signal bandwidth
- Virtex-6 FPGA based hardware digital processor
  - Local cell installed own feedback processor which called Cell Controller unit
- Communication update rate is 10 kHz
  - 5 Gbps fiber optics communication for BPM and CC, 100 Mbps copper for PS
- All System’s (CC/BPM/AI/PS) synchronized with accelerator timing system
Diagnostics/PS Rack and Cell Controller Chassis

- 100 Mbit/s link for corrector setpoints
- IO signals (16 inputs, 12 outputs, 4 Vout) for fast machine protection
- 5 Gigabit/s SDI link for BPM and CC data
- Gigabit Ethernet to EPICS IOC
- Embedded Event Received
- BPMs
- CC and FOFOB
- EVR
- Serial console
- Power Supply Rack
- +/-0.1 degC temperature controller
- IOC
RF BPM Chassis

- **BPM install status (~270)**
  - Linac – 6
  - LTB – 5
  - BR - 36
  - BTS - 9
  - SR – 211, arc (180), ID (27), Injection(4)

- 60% fill pattern, beam current was limited to an administrative limit of 25 mA, which corresponds to almost full ADC scale.
  - TBT (378 KHz) Resolution at 15 mA ~ 700 nm
  - FA (10 KHz) Resolution at 15 mA ~ 200 nm
RF BPM Chassis

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NSLS-II Serial Device Interface (SDI)

- Ring topology method
- BPM and CC 5 Gbps, bidirectional (CW, CCW direction)
- Global 31 nodes
- bpm local nodes (6-13)
- PS 12 nodes (100 Mbps Ethernet PHY)
- Every 10 kHz transfer packets to neighbor cell
- Global packet size is 780 x 4byte (3120 bytes)
- Local packet size is 26 x 4byte (104 bytes)

Lab test configuration before installation (2013.9)

- Tested total 32 nodes
- Confirmed:
  - Timing, communication protocol, IOC, ...
  - Firmware functionalities
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FOFB Calculation - Compensation for each eigenmode

\[ R = U \Sigma V^T \]

Accelerator

\[ d_{gold} \rightarrow e \rightarrow U^T \rightarrow Q(z) \rightarrow \Sigma^{-1} \rightarrow V \rightarrow \theta \]

\[ d \rightarrow e \rightarrow d \]
FOFB Calculation - Compensation for each eigenmode

\[ d_{gold} \rightarrow -e \rightarrow U^\top \rightarrow Q(z) \rightarrow \Sigma^{-1} \rightarrow V \rightarrow \theta \]

\[ c \]

\[ d \]

\[ e \]

\[ \Sigma^{-1} \]

\[ V \]

\[ R = U \Sigma V^\top \]

\[ Q(z) = \begin{bmatrix} Q_1(z) & 0 & 0 & 0 \\ 0 & Q_2(z) & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & Q_N(z) \end{bmatrix} \]

c_1, c_2, \ldots, c_N \text{ is the input projections in the eigenspace.}

Q_1(z), Q_2(z), \ldots, Q_N(z) \text{ is the compensator for each eigenmode.}

We want to prove that Q_1(z), \ldots, Q_N(z) only change the corresponding eigenmode in eigenspace without affecting other eigenmodes.
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Block diagram of the feedback calculation
Overall timing estimation

- **Local BPM data**: (2.2 us, 104 byte, 5 Gbps, @ 125 MHz)
- **Global BPM data transfer link**: (20 us, 3120 byte, 5 Gbps, @ 125 MHz)
- **Calculation**: (48 us @ 50 MHz, 180* 480 and 540 * 6 matrix calculation)
- **Corrector setting**: (7 us, 100 Mbps @ 25 MHz)
BPM/CC/PSI Hardware Latency measurement

- RF Signal Generator
- EVG RF in
- EVG/EVR Timing
- PLL
- EVR
- BPM
- 5 Gbps GTX
- Cell Controller
- 10 Gbps Ethernet
- PSC
- 16 Mbps Fiber
- PSI
- Corrector PS
- Analog reference +/− 10V

Signal Measurement Scope

1. RF
2. Tx trigger 100 us
3. CC DAC OUT
4. PSI DAC OUT

b_{RF} = 499.680 MHz
f_{rev} = 378 kHz

Trig (10 kHz)
BPM/CC/PSI Hardware Latency measurement

System Transfer function measurement (PS -> corrector M -> chamber -> bpm button)  H : 1 kHz, V : 800 Hz

RF
Tx trigger 100 us
CC DAC OUT
PSI DAC OUT
BPM/CC/PSI Hardware Latency measurement

System Transfer function measurement (PS -> corrector M -> chamber -> bpm button)  H : 1 kHz, V : 800 Hz

f_{RF} = 499.680 \text{ MHz}

EVR Timing

f_{rev} = 378 \text{ kHz}

4 way split

2.5 Gbps

RF Signal Generator
PSD/RMS beam motion measurement

Integrated RMS motion in frequency range 1-500Hz, plotted for 12 BPMs in one super-cell (C02 and C03).

180 BPMs, 16384 points of FFT
Average PSD excluding dispersive BPMs, 40 Eignemode, $K_i=0.25$, $K_p=0.5$

⇒ With FOFB on, RMS motions in both H and V plane meet the specifications (dashed lines).
Top-off injection mode test

Without feedback

< 1 %

With feedback

1 %

4 hours
Summary

- Run FOFB user operation since May 2015
- The long term drift was less than 4 um(H) / 1 um(V) during 15 hours.
- BPM SA data shows the orbit stability was improved a factor of 7 to 10.
- BPM FA data shows the noise suppression up to 400 Hz.
- The integrated orbit noise is less than 10 % of beam size.

- Measured open loop system transfer function and system latency
- Run top-off injection mode at 250 mA operation

- Continues study that optimization and operation procedure
Thank you for your attention!

Questions and comments are welcome.
Acknowledgments

• BPM/ Cell controller development:
  Kurt Vetter
  Joseph Mead
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  Joseph De Long
  Om Singh

• PSC and PS design:
  Wing Louie
  John Ricciardelli
  George Ganetis