NSLS-II Fast Orbit Feedback System

Yuke Tian
On behalf of FOFB Team

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Outline

- NSLS-II fast orbit feedback (FOFB) system
  - Orbit stability requirement
  - System architecture
  - Hardware system
  - Algorithm and implementation
- FOFB system status
  - Short term performance
  - Long term performance
  - Beam stability operation case 1: local bump with FOFB running
  - Beam stability operation case 2: orbit recover after beam dump
  - Beam stability operation case 3: X-Ray stability: photon local feedback
  - Derivative instruments from BPM/FOFB development at NSLS-II
- FOFB system future plan
  - Electron beam stability
  - Photon beam stability
- Summary
NSLS-II Orbit Stability Requirements

Standard BPMs (2) on each multipole chambers

High stability BPMs (2/3) on ID straight chambers

Electron Beam Sizes & Divergences

<table>
<thead>
<tr>
<th>Types of source</th>
<th>Long ID</th>
<th>1-T 3-Pole wiggler</th>
<th>Bend magnet</th>
<th>Short ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_x$ (\mu m)</td>
<td>108</td>
<td>175</td>
<td>44.2</td>
<td>29.6</td>
</tr>
<tr>
<td>$\sigma_x$ (\mu rad)</td>
<td>4.6</td>
<td>14</td>
<td>63.1</td>
<td>16.9</td>
</tr>
<tr>
<td>$\sigma_y$ (\mu m)</td>
<td>4.8</td>
<td>12.4</td>
<td>15.7</td>
<td>3.1</td>
</tr>
<tr>
<td>$\sigma_y$ (\mu rad)</td>
<td>1.7</td>
<td>0.62</td>
<td>0.63</td>
<td>2.6</td>
</tr>
</tbody>
</table>
The ultimate goal for light source stability is the photon stability at the user end-station. Sometimes the 10% criterion can’t meet the user requirement.

NSLS-II, HXN (3-ID) beamline:
Front-end xBPM (16m away from ID source) long term drift is less than 1um.
This corresponds to 1/16 urad = 62.5nrad long term ID angle stability. → Beyond the resolution of RF BPMs.
FOFB system architecture: two tier structure

BPM data → Orbit feedback calculation → Corrector setpoint

Tx/Rx BPM data around the ring

BPM data → Orbit feedback calculation → Corrector setpoint

Tx/Rx BPM data around the ring
Common tasks for any global fast orbit feedback system:
1. Deliver BPM data to feedback calculation unit
2. Performance feedback calculation
3. Deliver corrector setpoint to power supply controller

Cell controller at NSLS-II:
- Receiver local BPM data
- Tx/Rx BPM data to/from other cell
- Carry out FOFB calculation
- Tx corrector setpoints to PS control system

FOFB system architecture
FOFB system architecture

100 Mbit/s link for corrector setpoints

IO signals (16 inputs, 12 outputs, 4 Vout) for fast machine protection

Embedded Event Received

Gigabit Ethernet to EPICS IOC

5 Gigabit/s SDI link for BPM and CC data
FOFB implementation: FPGA block diagram
FOFB system architecture: FOFB calculation in FPGA vs CPU/DSP

<table>
<thead>
<tr>
<th>Calculation power</th>
<th>Flexibility</th>
<th>Architect simplicity</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU, DSP-base FOFB calculation</td>
<td>Limited, due to series calculation nature.</td>
<td>Good. It is C/C++ based.</td>
<td>Need to build interface to other systems (BPM, power supplies)</td>
</tr>
<tr>
<td>FPGA-based FOFB calculation</td>
<td>Strong due to the parallel DSP resources.</td>
<td>Not good, unless have FPGA expertise.</td>
<td>Seamlessly integrate with other systems.</td>
</tr>
</tbody>
</table>
FOFB hardware: correctors

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

30 mm fast (air core)
### FOFB hardware: BPM

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Mode</th>
<th>Max Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC Data</td>
<td>On-demand</td>
<td>256Mbytes or 32M samples per channel simultaneously</td>
</tr>
<tr>
<td>TBT</td>
<td>On-demand</td>
<td>256Mbytes or 5M samples; Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd</td>
</tr>
<tr>
<td>FOFB 10KHz</td>
<td>Streaming via SDI Link and On-demand</td>
<td>Streaming - X,Y,SUM; For On-Demand: 256Mbytes or 5M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd</td>
</tr>
<tr>
<td>Slow Acquisition 10Hz</td>
<td>Streaming and On-demand</td>
<td>80hr circular buffer; Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd</td>
</tr>
<tr>
<td>System Health</td>
<td>On-demand</td>
<td>80hr circular buffer; AFE temp, DFE temp, FPGA Die temp, PLL lock status, SDI Link status</td>
</tr>
</tbody>
</table>
FOFB hardware in a cell
FOFB algorithm: spatial mode decomposition (MIMO problem to SISO problem)
FOFB algorithm: spatial mode decomposition

**Orbit changes for different compensation**

- Compensate the first 30 eigenmodes when feedback on
- Compensate the first 60 eigenmodes when feedback on
- Compensate all 90 eigenmodes when feedback on

**Error in mode space for different compensation**

- Compensate the first 30 eigenmodes when feedback on
- Compensate the first 60 eigenmodes when feedback on
- Compensate all 90 eigenmodes when feedback on
FOFB algorithm: spatial mode decomposition

One by one close loop in mode space

BPM errors when close loop in mode space
FOFB status: short term performance (power spectrum density)
FOFB short term stability:

- H and V plane noises suppression up to 200Hz.
- Integrated PSD (500Hz) in H plane (about 800nm), is within 1% of beamsize
- Integrated PSD (500Hz) in V plane (about 550nm), is within 10% of beamsize
RMS Motions Along the ring

RMS motion in frequency range [1 500] Hz

NSLS2 BPM FA Data RMS, I = 37.3447 mA
FOFB status: long term performance

H plane ID angles long term drift

=2μrad
FOFB status: long term performance

V plane ID angles long term drift
Beam stability operation case 1: local bump with FOFB running

Motivation: during user operations with FOFB running, occasionally some individual beamlines need to adjust the ID angle and offset by large values. FOFB alone can’t achieve this since fast correctors are not strong enough. Slow correctors settings need to adjust with local bump program to get large ID angle/offset adjustment. We want to achieve this without turn on/off FOFB and without any disturbances to other beamlines.

Procedure: run local bump program with FOFB running. To prevent fast correctors from saturation, a procedure is developed to shift fast corrector strength to slow correctors with FOFB and local bump program running.

Result: we can run local bump program to adjust the ID angle larger than 10urad and ID offset larger than 10um without stopping FOFB and without global disturbances.
Beam stability operation case 1: local bump with FOFB running

At 2.8 minute, C05 H needs a 30urad change:
→ Local bump runs
→ During local bump, fast corrector’s strength gets larger
→ Shift fast corrector strength to slow ones (at 3 & 3.3 minute)
→ No large disturbance for this large local bump

At 1 minute, C05 Y needs a 100um offset:
→ Local bump runs
→ During local bump, fast corrector’s strength gets larger
→ Shift fast corrector strength to slow corrector (at 1.6 minute)
→ No large disturbance for this large local bump
Beam stability operation case 2: orbit recover after beam dump

Motivation: after beam dump, the old procedure is to use orbit correction and local bump to recover the beam orbit. Some beamlines noticed differences before and after beam dump. It is desirable to recovery the orbit with less than 1um error.

Procedure: for beam dumps not caused by power supply system, after initial refill, turn on FOFB without orbit correction and local bump adjustment. The FOFB will bring the orbit to the previous saved target reference orbit. This procedure recovers the orbit with less then 1um error and reduces the recovery time by eliminate orbit correction and local bump adjustment steps.

Result: FOFB will recover the orbit with less than 1um error.
Beam stability operation case 2: orbit recover after beam dump

1. Refill beam to 2mA

2. Turn on FOFB

3. Drive orbit to golden orbit using FOFB
Beam stability operation case 2: orbit recover after beam dump

Orbit/Fast Corrector Compare Using FOFB To Recover Orbit at Beam Dump (Y plane)

Before Dump
After Orbit Recovery

Orbit/Fast Corrector Compare Using FOFB To Recover Orbit at Beam Dump (X plane)

Before Dump
After Orbit Recovery
Beam stability operation case 3: photon local feedback

Motivation: some beamlines request much more stringent photon stability (for example, HXN needs ID angle long term stability: 50nrad). This request is beyond the resolution of our RF BPM. We can use the xBPM (front-end xBPM or beamline xBPM) as sensors, and use ID corrector coil as actuators to make photon local feedback to achieve the stringent long term stability requirement.

Procedure: with FOFB running, measure the response between xBPM and the ID corrector coil current. Design a photon feedback system to stable the xBPM readings. The response could be gap dependent.

Result: we have released the photon local feedback system for the four beamlines which have front-end xBPM installed. We have also tried to use beamline xBPM as sensors, but didn't release it because the beamline xBPM reading dependent many factors of beamline settings.
Beam stability operation case 3: photon local feedback (optical)

HXN photon stability with photon local feedback (H plane)
Beam stability operation case 3: photon local feedback

HXN photon stability with photon local feedback (V plane)
Other applications from BPM/FOFB developments

- The BPM/FOFB development at NSLS-II provide a common FPGA-based digital platform with many useful features:

**Features:**
- Virtex-6 FPGA (LX240T)
- Embedded MicroBlaze soft core μP
  - Xilkernel OS and lwIP TCP/IP stack
- Gigabit Ethernet
- 2Gbyte DDR3 SO-DIMM
  - Memory throughput = 6.4 GBytes/sec
- Six 6.6Gbps SFP modules
  - Embedded Event Receiver
- Fast Orbit Feedback
- Fixed Point DSP Engine
- 1Gbit FLASH memory
Derivative instruments from BPM/FOFB developments: active interlock master

Cell Controller

CELL CONTROLLER (CC)

EVR

FOUT

CELL PLC Interface

PLC

#10

#11

#21

#22

#23

#31

NSLS-II SR

AI Master

AL System

KSU & LLRF

BOX64-1, HLA

AI-DB Server

Linux-IOC

RF Trip signal

RF Trip status

RF SYSTEM

Moxa: 10.0.133.83 4011

Beam current status
0.2 mA, 2 mA, 50 mA

Beam current status

0.2 mA, 2 mA, 50 mA

One Cell BPM

AI-DB

Cell Controller

U.S. DEPARTMENT OF
ENERGY

BROOKHAVEN SCIENCE ASSOCIATES
Derivative instruments from BPM/FOFB developments: Encoder timestamp module

Beamline Encoder Timestamp Module: To provide NSLS-II timing system timestamp for beamline encoder signals.
General DAQ Timestamp Module: To provide NSLS-II timing system timestamp for 8 analog inputs, 8 analog outputs, 16 digital inputs/outputs signals.
BPM update stage 1: Zynq-based DFE

- New Zynq DFE will provide many new features for the overall performance of BPM, cell controller and other derivative instruments.

- The new Zynq DFE’s connector is pin-to-pin compatible with the Virtex6 DFE board. All the derivative instruments can be updated without any hardware redesign effort.

- RF switch circuit is tested with new DFE board. It improves BPM stability and removes the dependences of temperature-controlled rack.

Zynq DFE
BPM update stage 1: testing Zynq-based DFE

Existing BPM

PT 500 MHz

RF SWITCH box

Splitter

Combiner

Beam signal 400 mA
BPM update stage 1: Zynq-based DFE stability

Existing V6 BPM: installed in temperature-controlled rack (+/- 0.1 C): (Red curve)

→ Stability (RMS): 130 nm (H plane), 126 nm (V plane)

zBPM with RF switch: installed in open rack (+/-0.5 C)

→ Stability (RMS): 11 nm (H plane), 20 nm (V plane)

Conclusions: RF switch reduce the BPM’s temperature dependence.
BPM update stage 1: Zynq-based DFE stability

BPM PSD plot

Red: V6 BPM in temperature-controlled rack
Blue: zBPM with RF switch in open rack
BPM update stage 2: AFE upgrade with RF switch and board temperature control

Key improvements:

- New PCB design.
- Incorporates RF switch circuit.
- New RF shield box.
- Bottom side only has GND copper plane and vias.
- Board temperature is controlled by Peltier cooling plate.
- New type monoblock ceramic BFP.
- Improved voltage regulators.

New BPM under testing (Nov. 1, 2018)
FOFB future plan: electron beam orbit stability

- Based on the existing hardware:
  - We have done PI control in spatial mode. More SISO feedback control algorithm (internal model control etc.) will help to find the optimized noise suppression in each spatial mode.
  - Combine slow orbit feedback system (SOFB) with FOFB. Need to separate in either frequency domain or spatial domain. Since our FOFB has gain in low frequency, we will try to separate the two feedback systems in spatial domain.

- Performance improvement from hardware update:
  - With the improvement of BPM resolution and power supply control system, we should be able to improve the FOFB performance.
  - In the long term, with the updated DFE for BPMs and cell controllers, we can send the BPM data with 10Gbit/second rate. The new DFE also provides much more resource to do different FOFB calculations. With some update of power supply control system, we can increase the feedback sampling rate from 10kHz to 20kHz or higher. The higher sampling rate is helpful to improve the FOFB performance.
  - Study the possibility to include xBPM into the FOFB loop. This needs to enable the xBPM fast data link into the FOFB SDI.
  - Introduce FPGA-based machine learning to make adaptive feedback control.
FOFB future plan: photon beam orbit stability

The photon beam stability is the ultimate goal

- Photon beam stability should include xBPM from beamlines
  - FOFB in accelerator can’t suppress the noises from beamline optics
  - Some beamlines might need photon beam stability beyond the limits of RF BPM or fast corrector in accelerator

- Universal hardware platforms for beamline feedback system. Deliver stable photon beam to the experiment end station.
  - Sensor: xBPM or beamline user signals
  - Actuators: piezoelectric to control mirror (bandwidth limited), fast ID correctors
Summary

- NSLS-II FOFB system meets the design requirements with 240 BPMs and 90 fast correctors.

- The system can be used for orbit controls during user operations for different scenarios.

- Large calculation resources from FPGA enable us to do more complicated FOFB algorithm.

- Some derivative instruments have been developed and used at NSLS-II facility, both in accelerator and beamlines. All these instruments will benefit from the efforts of Zynq DFE development with minimum hard redesign. Hardware design reuse and code sharing have proven working very well at NSLS-II.

- Approach beam stability from feedback systems from both accelerator and beamlines.