Orbit Stability Challenges for Storage Rings

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Advanced Photon Source
Beam Diagnostics
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Outline

- Beam stability requirements
- RF beam position monitor technology
- NSLS II developments
- Recent x-ray fluorescence-based photon beam position monitor results
Beam Stability Requirements

- The scales of interest are the electron beam size and photon beam angular divergence for diffraction limited beams. Typical stability requirements set at 5-10% of beam size / divergence.
- Electron beam size for ultimate storage rings approaching 10 μm, photon angular divergence $1 / (\gamma \sqrt{N})$ approaching 5 μrad.

<table>
<thead>
<tr>
<th>experiment parameters</th>
<th>beam orbit</th>
<th>beam size</th>
<th>beam energy/energy spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.1% intensity steering to small samples</td>
<td>$\Delta x, y &lt; 5% \sigma_{x,y}$</td>
<td>$\Delta \sigma_{x,y} &lt; 0.1% \sigma_{x,y}$</td>
<td>$\Delta E/E({\text{coher}}) &lt; 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta x', y' &lt; 5% \sigma'_{x,y}$</td>
<td>$\Delta \sigma'<em>{x,y} &lt; 0.1% \sigma'</em>{x,y}$</td>
<td>$\Delta E/E({\text{rms}}) &lt; 10^{-4}$</td>
</tr>
</tbody>
</table>

- < 10^{-4} photon energy resolution
  - $\Delta x' \sim 5$ μrad
  - $\Delta y' \sim 1$ μrad
  (undulator)

- timing, bunch length
  - $\Delta \sigma_t < 0.1\% \sigma_t$

$\Delta E/E({\text{coher}}) < 5 \times 10^{-5}$
$\Delta E/E({\text{rms}}) < 10^{-4}$
(und n = 7)

R. Hettel, USPAS 2003
## Beam Stability Requirements

<table>
<thead>
<tr>
<th></th>
<th>AC rms Motion 0.01-200 Hz</th>
<th>AC rms Motion 0.01-1000 Hz</th>
<th>Long-term drift (One Week)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μm rms μrad rms</td>
<td>μm rms μrad rms</td>
<td>μm rms μrad rms</td>
</tr>
<tr>
<td>Horizontal</td>
<td>3.0 0.57</td>
<td>6.0 1.14</td>
<td>5.0 1.0</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.42 0.22</td>
<td>0.82 0.44</td>
<td>1.0 0.5</td>
</tr>
</tbody>
</table>
APS Broadband RF BPM data acquisition upgrade

- Eight channels/board, 88 MS/sec sampling. Altera FPGA processing.
- One second (262144 samples) turn-by-turn beam history for machine studies / fault diagnosis.
- Demonstrated noise floor $< 5 \text{ nm} / \sqrt{\text{Hz}}$
- Eighteen sectors instrumented, more on the way.
State-of-the-art Commercial Solution

- Noise floor approaching 2 nm / √Hz.
- Long term drift 200 nm p-p / 24 hours*.
- Integrated User FPGA support

* Guenther Rehm, Diamond Light Source, EPAC 2008
APS BPM Electronics Performance

Libera Brilliance@APS

APS BSP-100 Module

- Integrated RMS Noise (nm) vs Frequency (Hz)
  - 100 nm / √Hz
  - 10 nm / √Hz
  - 1 nm / √Hz

Noise Floor
NSLS-II RF BPM / Feedback Development

BPM Laboratory Test Setup

AFE

PTC

NSLS II Digital Front End Cell Controller

RF Shield

Courtesy of Om Singh
NSLS-II RF BPM Features

- Long-Term Stability (200nm) based on thermal rack stability of +/- 0.1°C
- Active Pilot-Tone (calibration and system test)
- Sub-sampling coherent signal processing – Phase Locked to Frev
- Frequency domain position calculation via single Bin DFT
- Generic design – Parametric configuration for Single-Pass, Booster, SR
- Latest Xilinx Virtex-6 FPGA technology
- Up to 8M samples (ADC data, TbT, FOFB)
- Simultaneous EPICS and Matlab communication
NSLSII BPM Stability Test Data without Pilot-Tone

(8) BPMs measured simultaneously in Thermal Test Rack, CW (8hrs), 1/17/12

Standard Deviation (um) – Horizontal Plane
BPM (1-8): 0.4012  0.1991  0.1362  0.1343
0.1511  0.1300  0.1437  0.1267

Temperature stability measured with AFE sensor

Temperature stability measured with AFE sensor

BROOKHAVEN SCIENCE ASSOCIATES

Courtesy of Om Singh
**ALS Pilot-Tone Experimentation**  
500mA, Top-off, Dual-cam User Beam

**Muti-Bunch,**  
PT frequency $RF + f_{\text{rev}}/64$

Study correlation of PT and signal as a function of frequency offset  
The fan above the BPM was turned off twice for about 10 minutes  
Pilot Tone set to: $RF + f_{\text{rev}}/64$

**Thermal Perturbation to BPM**

Turn off fan above BPM (BPM thermal sensors)

<table>
<thead>
<tr>
<th>Time of Day [Hours]</th>
<th>AE [°]</th>
<th>BE [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>11.0</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>11.5</td>
<td>50</td>
<td>42</td>
</tr>
</tbody>
</table>

Corrected Signal

**Raw and Corrected Position**

Courtesy of Greg Portmann, ALS
NSLSII BPM Measurements at ALS

**Single Bunch (ALS)**
A single 25mA bunch was injected at the ALS SR in decay mode. The ALS revolution period is 656ns or 1.52MHz corresponding to 77-samples per turn.

**User Operation (ALS) 500mA Double Cam Fill**
Button A was split to BPM channels A, B, C, D
RF = 499.641546 MHz

Measured Single-Bunch Resolution vs. Bunch Charge

- 2.5 nm /√Hz
- 11 nm /√Hz

Data Courtesy of Om Singh
APS Hard X-ray Beam Position Monitor Development

- Extensive studies have taken place at the APS investigating copper x-ray fluorescence vs. photoemission for photon beam position monitoring.
  - Soft bending magnet radiation background essentially eliminated.

- High-power, high power-density performance has been demonstrated.
  - 10 kW from two in-line APS undulator A magnets

IR camera image of copper GRID-XBPM intercepting approx. 5 kW of x-rays from two in-line undulator A sources with 102 mA of stored beam.
## X-ray BPM Performance Requirements

**APS upgrade beam stability goals (19 m from the source)**

<table>
<thead>
<tr>
<th>Plane</th>
<th>AC Motion (0.1-200 Hz)</th>
<th>Long Term (1-week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal (RMS)</td>
<td>10.5 µm</td>
<td>19.6 µm</td>
</tr>
<tr>
<td>Vertical (RMS)</td>
<td>4.2 µm</td>
<td>9.6 µm</td>
</tr>
</tbody>
</table>

**APS upgrade XBPM-1 performance specifications (19 m from the source)**

<table>
<thead>
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<th>Plane</th>
<th>AC Motion (0.1-200 Hz)</th>
<th>Long Term (1-week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal (RMS)</td>
<td>7.5 µm</td>
<td>14 µm</td>
</tr>
<tr>
<td>Vertical (RMS)</td>
<td>3.0 µm</td>
<td>6.8 µm</td>
</tr>
</tbody>
</table>
Conceptual Design (GRID-XBPM)

Plan View

Two Pin diode pairs -
above / below midplane

Concept courtesy of Bingxin Yang
GRID-XBPM First Production Article
Tests at 29-ID-A
Bend magnet radiation background

- Correctors have soft magnetic edges, generating mostly soft x-rays.
- Strong TEY near undulator axis
- A Cu-K XRF detector is insensitive to low-energy x-ray photons (< 9 keV).

Comparison of 2-D intensity distribution of BM radiation from corrector magnets: XRF map @ 20 m has a clean center.

(A) Power  (B) Total Electron Yield (Au)  (C) Cu-K fluorescence
Background Reduced a Factor of 1000 Compared to Photoemission-Based X-Photon BPM

~10 microAmps

Gaps Open To 180 mm

~10 nA

2.4 milliradians

7-ID

9-ID

23-ID Canted

32-ID

29-ID GRID xbmp

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Linear XBPM Vertical Response for Greater than 3 Decades of Signal Intensity

Vertical XBPM Readback (mm)

Fit Residual (mm)

Intensity (μA)

(at 27 meters from source)
Horizontal Response (Uncalibrated)

(data collected by sddsexperiment at 2.5 meters from source)
Storage Ring Orbit Stability Summary

- Instrumentation supporting electron beam stability is well in hand.
- High-power photon bpm technology has arrived.
Backup Slides
Insertion Device Field Integrals

\[ \int B_y \, dZ \]  
\[ \text{Gap} = 10.0 \, \text{mm} \]

\[ x_{\text{Prime}} \]  
\[ \text{Z (mm)} \]  
\[ \text{Gap} = 10.0 \, \text{mm} \]
Insertion Device Field Integrals

$\frac{\int By \, dZ}{(\text{Tesla})}$

$Z (\text{mm})$
$\text{Gap} = 11.0 \text{ mm}$

$x'_{\text{offset}} (\text{mrad mm})$
$\int x'_{\text{offset}} \, dZ (\text{mrad mm})$

$Z (\text{mm})$
$\text{Gap} = 11.0 \text{ mm}$

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Insertion Device Field Integrals

By (Tesla)

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 13.0 \text{ mm} \]

\[ \int By \, dZ \text{ (Tesla mm)} \]

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 13.0 \text{ mm} \]

xPrime (mrad)

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 13.0 \text{ mm} \]

\[ \int x\text{PrimeOffset} \, dZ \text{ (mrad mm)} \]

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 13.0 \text{ mm} \]
Insertion Device Field Integrals

![Graph 1]

- By (Tesla)
- Z (mm)
- Gap = 15.0 mm

![Graph 2]

- J By dZ (Tesla mm)
- Z (mm)
- Gap = 15.0 mm

![Graph 3]

- xPrime (mrad)
- Z (mm)
- Gap = 15.0 mm

![Graph 4]

- J xPrimeOffset dZ (mrad mm)
- Z (mm)
- Gap = 15.0 mm
Insertion Device Field Integrals

By (Tesla)

\[ Z \text{ (mm)} \]

\[ \text{Gap} = 18.0 \text{ mm} \]

\[ f \text{ By} \ dz \text{ (Tesla mm)} \]

\[ Z \text{ (mm)} \]

\[ \text{Gap} = 18.0 \text{ mm} \]

xPrime (mrad)

\[ Z \text{ (mm)} \]

\[ \text{Gap} = 18.0 \text{ mm} \]

f xPrimeOffset dz (mrad mm)

\[ Z \text{ (mm)} \]

\[ \text{Gap} = 18.0 \text{ mm} \]
Insertion Device Field Integrals

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 24.0 \text{ mm} \]

\[ B_y \text{ (Tesla)} \]

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 24.0 \text{ mm} \]

\[ x' \text{ (mrad)} \]

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 24.0 \text{ mm} \]

\[ \int B_y \, dz \text{ (Tesla mm)} \]

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 24.0 \text{ mm} \]

\[ \int x' \text{ (mrad mm)} \]

\[ Z \text{ (mm)} \]
\[ \text{Gap} = 24.0 \text{ mm} \]
Insertion Device Field Integrals

![Graph 1](image1.png)

**By (Tesla)**
- Z (mm)
- Gap = 30.0 mm

![Graph 2](image2.png)

**\int B_y \, dz (Tesla mm)**
- Z (mm)
- Gap = 30.0 mm

![Graph 3](image3.png)

**xPrime (mrad)**
- Z (mm)
- Gap = 30.0 mm

![Graph 4](image4.png)

**\int xPrimeOffset \, dz (mrad mm)**
- Z (mm)
- Gap = 30.0 mm