High Precision Beam Position Monitors

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High Brightness Synchrotron Light Source Workshop
Upton, NY, USA, Apr. 26-28, 2017
Outline

• Button BPM design
  – Sensitivity
  – Mechanical support
• BPM in-house developed electronics
• BPM performance
  – Resolution
  – RF attenuator dependency and calibration
  – Current and fill pattern dependency
  – Timing alignment for pure turn by turn data
• Beam measurements
  – TbT data applications
  – Orbit stability, short term and long term
  – Compare with xBPM
• Derivative products and future plans
• Summary
NSLS-II storage ring main parameters

Beam sizes in one super period calculated using $\varepsilon_x = 0.9 \text{ nm.rad}$, $\varepsilon_y = 8 \text{ pm.rad}$; $\Delta E/E = 0.09\%$

<table>
<thead>
<tr>
<th>Source point</th>
<th>Long ID</th>
<th>Short ID</th>
<th>3PW</th>
<th>BMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_x [\text{um}]$</td>
<td>135.0</td>
<td>40.3</td>
<td>153.0</td>
<td>133.1</td>
</tr>
<tr>
<td>$\sigma_y [\text{um}]$</td>
<td>5.2</td>
<td>3.0</td>
<td>12.4</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Orbit stability requirements: 
< 10% of beam size and divergence
**Button BPM pickups**

- **Types of NSLS2 button BPM:**
  - SR Large Aperture BPM
  - SR Large Aperture BPM, 64-deg rotated
  - SR Large Aperture BPM, 45-deg rotated
  - SR Small Aperture BPM - DW, 60-deg rotated
  - SR Small Aperture BPM - EPU, 60-deg rotated
  - Special BPMs in injection straight
  - 5 other types button BPM used in LINAC/LtB/BtS/Booster

- **Button BPM sensitivity nonlinearity** – 1D fitting
- **Button BPM sensitivity nonlinearity** – 2D fitting
- **BPM SUM signal nonlinearity** calculated for machine studies

- Button diameter – 7mm
- Button center distance – 16mm
- Gap between button and body – 250µm
- Button thickness – 2mm

**Button BPM pickups images**

- **LA-BPM**
  - Button diameter = 7mm
  - Button center distance = 16mm
  - Gap between button and body = 250µm
  - Button thickness = 2mm

- **SA-BPM**
  - Button diameter = 4.7mm
  - Button gap = 250µm
  - Button thickness = 2mm
BPM mechanical support and RF shielding

High stability BPM support (Invar, ground mounting, isolation bellows)

Normal BPM support (Carbon fiber plate, girder mount)

RF shielding to move the cutoff frequency ~900MHz

BeCu shield, 114mm from beam
BPM data acquisition and processing

PTC - pilot tone controller

BPM electronics includes AFE + DFE
- AFE: BPF + Amplifier + Var. Att + ADC
- DFE: Xilinx Virtex 6, integrated uBlaze, SRAM

Local SDI and global SDI network share the 10kHz data around the ring
30 cell controllers for FOFB calculation, corrector settings send to PS
Same SDI 10kHz data is used for Active Interlock

BPM IOC for 10Hz streaming data and on-demand ADC/TbT/FA waveform data
Digital BPM data type (NSLS-II storage ring)

Fr = 499.68 MHz, h = 1320, Frev = 378.55 kHz

F_{adc} = 117.349MHz = 310 \times Frev

F_{if} = Fr - 4 \times F_{adc} = 1320 \times Frev - 4 \times 310 \times Frev = 80 \times Frev. The 499.68MHz beam signal is in the 9th Nyquist zone with sampling rate of 117.349MHz.
BPM Resolution vs. ADC counts (after BPF)

Use C30 SBPM4
20 bunches, orbit was not stable

Resolution ~ 1/\sqrt{38}
~ 200 nm resolution achieved

Blue – PT, C30 BPM1
Red – single bunch, C30 BPM1
Green – 20 bunches, C30 BPM4
Magenta – 1000 bunches, C28 SBPM1

Beam was unstable at high single bunch current of 0.7mA

Sub-um resolution for TbT data

ADC count average = \sum(|adc|)/N
With the new static gain calibration LUT, most of the BPMs has RF attenuator dependency less than 10um, while attenuator varied from 0 to 20dB in 1 dB steps. Note that the LUT was generated in Nov 2014 and it’s working fine with different current and fill pattern.
Glitches while change the BPM attenuator settings

Vary Att 0 to 3 dB during the period. It’s clear that when Att was changed, there was a glitch on FA position readings. The glitch last for ~32 FA samples.

Note the position reading is not changing at 0dB and 3dB, which is because of good RF attenuator calibration.

Don’t change the BPM attenuator during user operation, especially when FOFB was turned ON.

First observed on BPM TbT data, verified with FA data.
Current and Fill Pattern Dependency

Three different fills to the same total beam current of 10mA distributed in 100, 200 and 350 bunches. Pretty small fill pattern dependency.

Knock out the bunches in steps to have different fill patterns.

BPMs near RF cavity section see larger current dependency, due to RF leaked signals at 500MHz. The issue is dominant for low current studies (I < 0.2mA). Not a problem when the beam current goes higher.

Recent study with different # of train fills shows small current and fill pattern dependency. < 5um at low current; very small (<1um p-p above 100mA)
Timing alignment

BPM timing has been well aligned since commissioning

Pure turn by turn data with beam in the bucket #0 - #1000

Recent development of BPM Gated function allows us to measure the beam position from partial bunches. Precisely aligned gated BPM TbT/FA data can be used to “transparent” lattice measurement and collective effect studies.
SR BPMs – TbT spectrum
(2015-Jul-11, 17:44:21, 23mA store beam, BxB feedback OFF)

Wide range of applications from synchronized TbT data, including beam instability, lattice, tune measurement, injection optimization, collective effect studies and many more.
### BPM TbT applications – more examples

- Beta-beat
- Phase advance
- Coupling etc.

- Injection transient
- TbT SUM signal monitor (beam loss localization)

0.42% increase, 1.05mA injected
Exclude dispersive BPMs from the averaged spectrum calculation
RMS Motions Along the ring from FA spectrum

RMS motion in frequency range [1 500] Hz

NSLS2 BPM FA Data RMS, I = 37.3447 mA

BPM index

BPM index
xBPM electronics has less noise, especially for >1kHz range (electrometer bandwidth).
BPM electronics long term stability

Splitter/combiner of 4-button signal to characterize BPM electronics stability

\(~150\text{nm RMS}\) electronics drift for 60-hours of top-off user beam

Real BPM position stability may be affected by:
- Mechanical stability of the BPM pickup and supports (temperature, flow rate etc.)
- Beam induced heating
- Earth tide and seasonal effect (mainly at dispersive BPMs)
- Earthquake, nearby traffic, local installation activities etc.

C30 six BPMs X/Y positions. Vertical offset adjusted for better view.

~ 50 um drift at BPM #3 ($\eta_x \sim 0.424$ m) => $\Delta E/E = 1.18 \times 10^{-4}$ => $\Delta L = 34$ um ($\Delta Frf = 21$ Hz)

Averaged COD drift, take first COD as reference, check the COD drifting for the period.

$X/Y$ are vectors including all BPMs readings.
Long term stability at ID source point

Beam position/angle at ID03

X RMS = 0.613 um
Y RMS = 0.145 um

X' RMS = 0.317 urad
Y' RMS = 0.056 urad
Long term stability @ C03 pBPM

C03 ID gap fixed at 5.92mm

150mA user operation, beam current in 110 – 150mA range. Refill every 3 hours

xBPM position can be calculated from two ID BPMs on ends of the IVU, compared to xBPM direct measurement.
NSLS-II BPM digital receiver derivative instruments

1. Cell Controller
   - FOFB
   - Active Interlock
   - PS AC excitation

2. xBPM electronics
   - Zynq XC7Z045 FPGA
   - ARM A9 processor
   - Linux OS
   - Embedded IOC

3. LBNL BPM
   - Pilot tone calibration

4. Sydor xBPM
Future plans

DFE with Zynq FPGA
- ARM A9 processor
- Linux OS
- Embedded IOC

Improve AFE stability
- Peltier cooling

New AFE electronics with bunch by bunch capability
- 500MHz 14-bit ADC
- External synchronization
- Integrate with new DFE
- Evaluation boards under test

Further improve the BPM/orbit stability
- Mechanical/thermal stability

Advanced beam measurements with expanded capabilities, e.g. BPM gate function.
Summary

• Various types of **BPM button pickups** have been designed, constructed, installed and commissioned, together with the in-house developed electronics.

• The NSLS-II **BPM electronics** has been developed and commissioned in ~5 years (2009-2014). Continuous improvement/development are only possible with experts around.
  – High resolution achieved (200nm@10kHz rate, <1um@TbT rate)
  – Short term orbit stability (~1% beam size horizontally; ~5% vertically)
  – Long term BPM electronics stability < 200nm RMS
  – Derivative instruments have been developed
    • Cell Controller (FOFB and Active Interlock)
    • X-ray BPM electronics (xBPM), Sydor xBPM
    • LBNL EBPM

• New DFE and other developments underway to continuously improve the overall system performance.

**Acknowledgements:**
Original BPM electronics team (**K. Vetter**, A. Dellapenna, K. Ha, M. Maggipinto, J. Mead, Y. Tian etc.)
NSLS-II BPM related paper/presentation:
