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Outline

1. Introduce NSLS-II BPMs and resolution in standard configuration
2. Motivate resolution improvements for single- and few bunch fills and the need to resolve a few bunches within a ring turn
3. Show how this is done and the best resolution achieved
4. Give examples of beam physics measurements that benefit from these new BPM capabilities
Introduction: NSLS-II BPM Types & Pickup Geometries

- NSLS-II: 30 cell DBA 3 GeV ring with 1 nm / 8 pm design x/y emittances (see WEPOY055 for more)
- NSLS-II BPMs differ in chamber and button geometry

<table>
<thead>
<tr>
<th>RF BPM Types</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Pole Chamber BPMs (LA)</td>
<td>6 per cell 180 Total</td>
</tr>
<tr>
<td>Large Aperture (25 mm vert.)</td>
<td></td>
</tr>
<tr>
<td>Insertion Device (ID) Chamber BPMs (SA)</td>
<td>2-3 per ID straight ~30 Total (now)</td>
</tr>
<tr>
<td>Small Aperture (8-11.5 mm vert.)</td>
<td></td>
</tr>
<tr>
<td>Special BPMs (injection, BxB fdbk, test, ...)</td>
<td>~10</td>
</tr>
</tbody>
</table>

- Different geometries result in different sensitivity/resolution by a factor of ~2
- Most sensitive (ID) BPMs are at the locations with small beam size

Real SA button assemblies are rotated around the vertical
Introduction: NSLS-II BPM Receivers

<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>Turn-by-Turn (TbT), Frev=379 kHz</td>
<td>On-demand</td>
<td>256Mbytes or 5 M samples</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Va, Vb, Vc, Vd, X, Y, SUM, Q, pt_va, pt_vb, pt_vc, pt_vd</td>
</tr>
<tr>
<td>Fast Acquisition (FA), 10KHz</td>
<td>Streaming via SDI Link &amp; on demand</td>
<td>Streaming - X, Y, SUM; For on demand: 256 Mbytes or 5 Msamples.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Va, Vb, Vc, Vd, X, Y, SUM, Q, pt_va, pt_vb, pt_vc, pt_vd</td>
</tr>
<tr>
<td>Slow Acquisition (SA), 10Hz</td>
<td>Streaming and On-demand</td>
<td>80hr circular buffer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Va, Vb, Vc, Vd, X, Y, SUM, Q, pt_va, pt_vb, pt_vc, pt_vd</td>
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</tbody>
</table>

- Original NSLS-II development (by Kurt Vetter et al.)
- Resolution specs of 1 μm turn-by-turn (TbT) and 200 nm in 10 kHz (FA) mode were verified with beam
- TbT used for injection & kicked beam studies, FA for fast orbit feedback & interlocks, SA for orbit measurements
- No bunch-by-bunch capability (cannot resolve bunches within a turn)
Introduction: BPM Signal Processing

ADC

TbT

FA

SA

ADC

F \text{rev} = 378.55 \text{ kHz}

9.96 \text{ kHz}

9.96 \text{ Hz}

F_{s} = 117.349 \text{ MHz}
Introduction: BPM Signal Processing

Analog 500 MHz BP filter, ~20 MHz BW

ADC

Fs = 117.349 MHz

1/310

Frev = 378.55 kHz

1/38

9.96 kHz

1/1000

9.96 Hz

Boris Podobedov, IPAC’16
Introduction: BPM Signal Processing

Analog 500 MHz BP filter, ~20 MHz BW
**Introduction: BPM Signal Processing**

- Analog 500 MHz BP filter, ~20 MHz BW

![Diagram of BPM signal processing](image)

- ADC
- Fs = 117.349 MHz
- TbT: Frev = 378.55 kHz
- FA: 9.96 kHz
- SA: 9.96 Hz

*3 Turns of Raw ADC Data; Single Bunch*

![Graph of ADC counts](image)

ADC Counts

0 200 400 600 800

ADC Sample
Introduction: BPM Signal Processing

Analog 500 MHz BP filter, ~20 MHz BW

Digital 30 MHz BP, ~6 MHz BW

“pilot tone filter”

ADC

TbT

FA

SA

ADC

\(F_s = 117.349\text{MHz}\)

\(F_{\text{rev}} = 378.55\text{kHz}\)

\(9.96\text{kHz}\)

\(9.96\text{Hz}\)

ADC Counts

ADC Sample

\(\times 10^4 3\text{ Turns of Raw ADC Data; Single Bunch}\)

\(3\text{ Turns of Raw ADC Data; Single Bunch}\)

ADC Counts

ADC Sample

~23 samples
Introduction: BPM Signal Processing

1 Turn = 310 ADC Samples =
= 1320 of 500 MHz RF buckets
Introduction: BPM Signal Processing

- TbT X, Y, and Σ are obtained (in FPGA) from ADC signals by coherent signal processing locked to revolution harmonic.

1 Turn = 310 ADC Samples = 1320 of 500 MHz RF buckets

Analog 500 MHz BP filter, ~20 MHz BW

Digital 30 MHz BP, ~6 MHz BW "pilot tone filter"

ADC

ADC Counts

ADC Sample

ADC

ADC Counts

ADC Sample

1 Turn = 310 ADC Samples = 1320 of 500 MHz RF buckets
• Sub-micron TbT resolution is routinely available for long bunch trains
• However, single bunch resolution is 1-2 magnitude orders worse
• The goal of present work is to improve it, and enhance BPM capabilities for single and few-bunch fills
Motivation

• Why single- or few bunch fills?

  For various beam dynamics studies, especially

    1) single bunch collective effects, incl. impedance measurement
    2) single particle non-linear dynamics
    3) beam lifetime

• Why resolution improvement is beneficial for these?

  Measurements are very sensitive (effects are small, and could be masked by machine drifts)

  Need to be done at low currents

• Apart from resolution why special BPM signal processing?

  To provide “bunch-by-bunch capability”* for overcoming the machine drifts

  * For at least a few, well separated, bunches
Motivation Example: Transverse Impedance Measurement

• What is the impedance (or kick factor) of an accelerator component, i.e. an undulator or a wiggler?
• By design, these are small.
• Impedance is not directly measured, but Z-related effects $\sim Q_b$ are.
• Take $Q_b=1$ nC, $\beta_y=3$ m, $k_y=500$ V/pC/m
  • Tune shift $\sim 4 \times 10^{-5}$
  • Closed orbit shift $\sim 0.7 \mu$m rms per $\Delta y=1$ mm
  • Local betatron phase jump of $\sim 4 \times 10^{-5}$
• These are hard to measure!
• The standard approach, via multiple injections or time-decay, is virtually impossible due to machine drifts
• Can be overcome by the relative measurements, with high-$Q_b$ and low-$Q_b$ bunches
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Need good resolution at low current, and many BPMs capable of resolving the orbits of at least two bunches
BPM Resolution Defined

- TbT resolution is defined as the beam position standard deviation over a few thousand turns (typically 2-3 k)
- Example: resolution at 0.1 mA single bunch is ~60 microns in X or Y

- Problem: this includes true beam motion, esp. at higher current
- Solution: splitter-combiner test BPM config on BPM28-9
Combiner-Splitter Test BPM Setup in Cell 28

- Dedicated LA BPM in Cell 28 with two BPM receivers
- True beam motion is excluded for 28-9, but not 28-10

- Power splitters introduce 3 dB loss => measured resolution is $\sqrt{2}$ higher than that for a regular LA BPM
Resolution Improvement: Time-Domain

- Standard BPM processing looks at all 310 ADC channels (i.e. entire turn)
- Let’s use only the ADC channels that contain most of the single bunch signal (i.e. apply a boxcar window on every turn)

- This results in resolution improvement by factor of 3 to 4.
Resolution Improvement: Frequency Domain

- Standard processing looks at a single revolution harmonic, \( f = 1320 \text{ Frev} \), which is fine for long trains used in user operations.
- Single bunch fills have BPM signals at every multiple of Frev (before filters).

Let’s include multiple harmonics to increase the signal and resolution.
- Resolution improvement of \(~4\) (for 23 rev. harmonics).

\[
\text{Resolution Improvement} = \frac{1}{n} \times \frac{1}{\text{Frev}} 
\]

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![Diagram showing resolution improvement for different numbers of revolution harmonics.](image)
Including Multiple Harmonics We Approach single micron @ 0.5 mA on ID BPMs

- Without pilot tone filter the number of in-band harmonics is higher => resolution improvement of about factor of 7.
- On ID BPMs directly measured resolution reaches 1.7 μm, or 1.3 μm when scaled from combiner-splitter BPM.
This Works on Few Bunch Fills as Well

- Blank-out signals from all but one bunch (on every turn)
- Include enough harmonics of Frev
- Use standard processing to extract $X$, $Y$, $\Sigma$ from these modified ADC data
- Repeat for each bunch
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As long as bunches are well separated (up to 8 for equally spaced)
Several measurements have been tried with promising results:

- Tune shift with current
- Probing impedance of a scraper
- Synchrotron tune shift with current with “RF-ping”
- Instability studies
- Beam lifetime studies
- Tune shift with amplitude

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Unequal Charge Bunches Kicked with a Pinger

- Two bunch fill with unequal bunches
- Pinger timing adjusted for equal vertical kick
- ADC data processed to get separate TbTs for each bunch
Unequal Charge Bunches Kicked with a Pinger

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Turn-by-Turn Signals

- Each bunch decays a long time, but the combined shows beating
- Also instability for high current bunch before the ping
Tunes are Distinctly Different

• Single BPM FFT shows tunes are clearly unequal
• Detailed analysis with interp’d DFT for 180 BPMs gives
  \( \nu_y = 0.26833 \pm 1.93 \times 10^{-5} \) (bunch 1) and \( \nu_y = 0.26334 \pm 6.90 \times 10^{-6} \) (bunch 2)
• Tune difference of 5e-3/(0.5 mA) is consistent with other measurements
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• Tune difference of 5e-3/(0.5 mA) is consistent with other measurements
Same Measurement in the Horizontal

- Same two bunches, 0.25 mA (1) and 0.75 mA (2), use hor. pinger
- ADC data processed to get separate TbTs for each bunch

\[ \Delta v_{21} = (6.0 \pm 3.8) \times 10^{-5} \]
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- Single harmonic # 1320 used for TbT
- Same data but 25 rev. harmonics used for TbT

\[ \nu_x = 0.22729 \pm 1.71 \times 10^{-5} \text{ (1)} \]
\[ \nu_x = 0.22735 \pm 9.06 \times 10^{-5} \text{ (2)} \]
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Single harmonic # 1320 used for TbT

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\[ v_x = 0.22735 \pm 1.79 \times 10^{-5} \text{ (2)} \]

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\[ v_x = 0.22729 \pm 1.71 \times 10^{-5} \text{ (1)} \]
\[ v_x = 0.22735 \pm 9.06 \times 10^{-6} \text{ (2)} \]

- Resolution improvement (est. x4) has helped; now convincingly show that hor. tune goes up with current.

\[ \Delta \nu_{21} = (6.0 \pm 0.9) \times 10^{-5} \]
Measurement of Tune Shift with Amplitude

Conventional measurement:
• Use short bunch train at low current
• Vary pinger voltage
• Record multiple TBT data sets

Issues: kicker jitter, machine drifts

Tune jumps without anyone touching the pinger or anything else in the machine

5 shots with the same pinger voltage
Single Shot Measurement of Tune Shift With Amplitude

Conventional measurement

New option

Alternative new option

Kicker jitter, machine drifts

Max. # of trains / turn

?
Single Shot Measurement of Tune Shift With Amplitude

Conventional measurement

New option

Alternative new option

Kicker jitter, machine drifts

Max. # of trains / turn

? The rest of this talk
Measurement Setup

- Fairly uniform fill pattern at low current (no collective effects!)

- Adjust pinger timing to center maximum kick in the middle
- 11 sample wide ADC window (~47 RF buckets); slide over the turn
- Results independent of window width when it’s << kicker rise time
• Fairly uniform fill pattern at low current (no collective effects !)

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TbT Signals from Selected ADC Bins

- Induced amplitudes vary according to bin position wrt. pinger
- Short chunks of the bunch train can be resolved!
Amplitudes for All ADC Bins Together

- Recover the shape of pinger pulse

- Except at the head (there is no kick) and near the ion gap
Tune Shift with Amplitude: 6 BPMs

- Smooth curves except at very low amplitudes
- Other cells look very similar
- From here: scale to injection point; error-bars from all 180 BPMs
Final Results: Horizontal

- Final result for 5mA/1000 bunches, single pulse of 2 kV
- Conventional measurement: 2 mA/100 bunches; 20 separate “pings”; clear pulse-to-pulse jitter, longer term drifts are likely
- Further optimization of new technique possible
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Conclusions and Future Plans

- Single-bunch resolution of NSLS-II BPMs was improved by an order of magnitude to about one micron TbT at ~1 nC/bunch.
- This improvement was achieved through special processing of ADC signals which additionally provides the new capability of resolving TbT signals from up to 8 bunches stored in the ring.
- Having this capability on all NSLS-II RF BPMs is extremely valuable for sensitive collective effect or single particle dynamics measurements. It allows us to simultaneously measure bunches with different charges (or kick amplitudes) thus eliminating harmful effects of machine drifts.
- ADC processing is presently done off-line but will be implemented in FPGA, so that improved resolution will be available through EPICS.
- Novel accelerator physics measurements enabled by improved resolution and new BPM capabilities will continue.
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Thank you