Offset calibration of single pass BPM

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- Gain balance and BPM offset
- Calibration method
- Verification of calibration
- Summary
Motivation

Offset calibration of single pass (SP) BPM prior to the machine commissioning is crucial for successful turns and storage of the first beam in the ring.

Major factor of the BPM offset is gain imbalance between BPM channels.

Reflection signals in BPM cables (~a few % typical) affect the balance of gains depending on the BPM measurement mode.

For accurate calibration of the SP BPM offset, proper signal processing procedure is required distinct from that for the COD mode.

In this presentation, gain imbalance of BPM and its calibration are discussed for both the SP and COD modes. The methods and results of offset calibration are also presented.
Why are the BPM offsets different between COD and single-pass modes?

COD mode
Since signals are filtered to narrow band-width, beam signals and reflection signals are “mixed”.

- Reflected signals result in multiple reflection.
- Multiple reflection depends on distance of reflection points.

→ Reflection signals affect BPM offset.

Single Pass mode
Since signals are processed with wide band-width, beam signal and reflection signals are separated in time.

→ Reflected signals do not affect BPM offset.

BPM offset depends on the measurement mode.
SP mode offset should be calibrated with pulsed RF signal.
Factors of Gain imbalance

A. uneven cable loss including impedance mismatch
   not only ohmic loss in cables but also reflections due to impedance mismatch

B. uneven gain of electronics
   gain of step attenuator, BPF, amplifier, ADC, etc.

Voltage readout $V_i'$ include the gain factors of cable $A_i$, and electronics $B_i$.

$$V_i' = V_i \times A_i \times B_i$$

We need to measure correction coefficients,

$$C_i = A_i \times B_i$$

to calibrate the offset.
Calibration Method

including **BPM head**, **cable** and **readout electronics**.

Setup

During the measurement of $V_{mij}$, buttons, cables and electronics were kept connected.

Calibration signal: **CW**, pulsed RF signal

**CW**: Calibration signal is **mixed** with reflected signal.

**Pulse**: Calibration signal and reflected signal are **separated** in time.

Applying the coefficients to beam signals, verify the calibration.

\[
V_{m21} = V_0 \times S_{21} \times A_2 \times B_2 \\
\vdots \\
V_{mji} = V_0 \times S_{ji} \times A_j \times B_j
\]

**correction coefficients**

\[
C_i = A_i \times B_i \\
C_i = \frac{V_{mi1}}{V_{m1i}} \times \frac{S_{1i}}{S_{i1}} = \frac{V_{mi1}}{V_{m1i}} \quad \text{S parameters cancels}
\]

**Spec. of Calibration Signal**

<table>
<thead>
<tr>
<th>pulse signal</th>
<th>frequency</th>
<th>508.58MHz (=detection freq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>peak power</td>
<td>10W</td>
<td></td>
</tr>
<tr>
<td>pulse width</td>
<td>100ns</td>
<td></td>
</tr>
<tr>
<td>repetition</td>
<td>revolution period (=4.8 μs)</td>
<td></td>
</tr>
</tbody>
</table>

**CW signal**

| frequency | 508.58MHz |
| power     | 10W       |
BPM used for the calibration

As a demonstration of the calibration, proposed calibration was applied to prototype of BPM system for SPring-8 upgrade.

Prototype BPM system

・4 sets of BPM in one block with 20mm separation
  → resolution evaluation by 3BPM method
  → offset evaluation
・installed in the present SPring-8 storage ring
・small mechanical tolerance
  BPM offset due to the tolerance is expected as tens of microns.
・BPM cable test: semi-rigid cable (PEEK, SiO2), corrugate cable (1/2’’)
・Electronics: Libera brilliance+

Measure beam signals for single pass and COD mode. Apply correction coefficients to the data, BPM offset after the calibration is obtained. Verify which calibration is valid (pulse or CW) from the BPM offsets.
Single pass offset measured with beam signal

If gain balances are properly corrected, 4 BPM readings come close to one point.

### Prototype of BPM head for SPring-8 upgrade

<table>
<thead>
<tr>
<th>Condition</th>
<th>BPM offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.47mA(=2.25 nC), single bunch</td>
<td></td>
</tr>
<tr>
<td>TBT data</td>
<td></td>
</tr>
<tr>
<td>No correction</td>
<td>scatter ~ 100 μm</td>
</tr>
<tr>
<td>CW correction</td>
<td>scatter ~ 100 μm</td>
</tr>
<tr>
<td>Pulse correction</td>
<td>scatter ~ 50 μm</td>
</tr>
</tbody>
</table>

Single pass BPM should be calibrated using **pulsed RF signal**. If CW signal is used, the correction does not work well.
COD offset measured with beam signal

- BPM4 had large offset without correction.
- The large offset was corrected by CW correction.

If gain balances are properly corrected, 4 BPM readings come close to one point.

<table>
<thead>
<tr>
<th>Condition</th>
<th>BPM offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mA, multi-bunch SA data</td>
<td>scatter ~ 350 μm</td>
</tr>
<tr>
<td>CW correction</td>
<td>scatter ~ 50 μm</td>
</tr>
</tbody>
</table>

COD should be calibrated using CW RF signal.
Correction coefficients for single pass mode

Difference in coefficient $C_4$ of BPM4 is significant.
After this work, we found cable4 of BPM4 was damaged (deformation).
This difference was caused by the damage.

Correction coefficient of 0.01 corresponds to 15~20 μm of BPM offset.
Deformed cable of BPM4-4

TDR waveform

- TDR waveform and length of deformed part was agreed.
**Major factor of calibration error**

- Non-linearity of readout electronics?
  
  Max ADC during pulse calibration were 2000~6000. (Variation is due to coupling direction of BPM head.)

- Beam signals measured for demonstration
  
  2.25nC, single bunch → 12,000~19,000 count

  
  \[
  \text{ADC range : } \pm 32767
  \]

  \[
  \begin{array}{|c|c|c|}
  \hline
  \text{coupling direction} & \text{Ex.} & \text{coupling (voltage ratio)} \\
  \hline
  \text{vertical} & 1 \rightarrow 4, 2 \rightarrow 4,,, & \sim -64 \text{dB (1)} \\
  \hline
  \text{horizontal} & 1 \rightarrow 2, 3 \rightarrow 4,,, & \sim -67 \text{dB (0.7)} \\
  \hline
  \text{diagonal} & 1 \rightarrow 3, 2 \rightarrow 4,,, & \sim -74 \text{dB (0.3)} \\
  \hline
  \end{array}
  \]

- Beam signal : 0.4~0.6 of ADC range
- Calibration signal : 0.06~0.2 of ADC range

Difference in signal level for calibration and non-linearity of readout electronics is one of possibility of calibration error. Non-linearity is not measured yet.
Summary

• Calibration method of SP BPM offset using pulsed RF signal is proposed and demonstrated.

• This method is free from errors by signal reflections in cables and properly corrects overall gain imbalance for the SP mode due to BPM head, cables and readout electronics.

• Calibration of the prototype BPM system successfully demonstrated
  • by using the pulsed signal, offset correction for SP measurement with an accuracy of 50 μm,
  • by using CW single, offset correction for COD measurement with an accuracy of 50 μm.

• Factors that limit the accuracy to ~50 μm are currently under investigation.

• One of possible cause of the error is a non-linearity of the BPM electronics.
Thank you for your attention!
Backup slides
BPM offset by Lambertson Method

Calculate BPM offset from S-parameter

S-parameter is only for BPM head.

Prototype BPM

C21T BPM offset due to gain imbalance
by Lambertson method

This offset
One of possibilities of this offset is
damage of Network Analyzer port4.

correction coeff.

\[ c_1 = 1 \]
\[ c_2 = \frac{g_2}{g_1} = \left\{ \frac{v_{42}}{v_{41}}, \frac{v_{32}}{v_{31}} \right\}^{1/2} \]
\[ c_3 = \frac{g_3}{g_1} = \left\{ \frac{v_{32}}{v_{42}}, \frac{v_{43}}{v_{21}} \right\}^{1/2} \]
\[ c_4 = \frac{g_4}{g_1} = \left\{ \frac{v_{43}}{v_{42}}, \frac{v_{31}}{v_{21}} \right\}^{1/2} \]

\( v_i \): detected voltage via readout electronics
\( v_i' = v_i / c_i \)
\( \Delta' = \)
\( x_{\text{offset}} = k_x \times \Delta_x' / \Sigma' \)
\( y_{\text{offset}} = k_y \times \Delta_y' / \Sigma' \)

2019/June/3,4,5 DEELS2019 T. Fujita
BPM voltage measured using libera bri+

2018/04/27 during machine tuning
single bunch
0.47mA (=2.25nC)

Libera bri+
DSC:off
Switching:off
coeff:unity
Level:-60dB

average of 880 turn (maximum ADC count in one-turn )

<table>
<thead>
<tr>
<th></th>
<th>電極1</th>
<th>電極2</th>
<th>電極3</th>
<th>電極4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM1</td>
<td>14912</td>
<td>13955</td>
<td>12838</td>
<td>13857</td>
</tr>
<tr>
<td>BPM2</td>
<td>18258</td>
<td>18976</td>
<td>19029</td>
<td>19500</td>
</tr>
<tr>
<td>BPM3</td>
<td>18104</td>
<td>16987</td>
<td>17996</td>
<td>19234</td>
</tr>
<tr>
<td>BPM4</td>
<td>15429</td>
<td>16148</td>
<td>14346</td>
<td>17340</td>
</tr>
</tbody>
</table>

12,000~19,000 count
=533 ~ 844 count / 100 pC
Measurement error of S parameter

Statistical error when calibration w/ S parameter is applied.

<table>
<thead>
<tr>
<th></th>
<th>(dB) p-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>reproducibility w/o reconnect</td>
<td>0.007</td>
</tr>
<tr>
<td>connector reconnect</td>
<td>0.011</td>
</tr>
<tr>
<td>character of RP-SMA adapter</td>
<td>0.031</td>
</tr>
<tr>
<td>freq. characterictic</td>
<td>0.01</td>
</tr>
<tr>
<td>calibration error of NetworkAnalyzer</td>
<td>0.03/(2)^0.5</td>
</tr>
<tr>
<td><strong>Total (r.m.s.)</strong></td>
<td><strong>0.041 dB p-p</strong></td>
</tr>
</tbody>
</table>

⇒ less than 0.1 dB (target)

measurement of 0.041 dB p-p correspond to (dx, dy) = (13 um p-p, 15 um p-p) error in BPM offset.
button-to-button coupling

BPM1
-0.083 -67.280 -73.943 -64.098
-67.283 -0.084 -64.221 -73.788
-73.957 -64.230 -0.091 -67.112
-64.070 -73.759 -67.082 -0.081

BPM2
-0.098 -67.326 -73.88 -64.171
-67.326 -0.081 -64.163 -73.857
-73.893 -64.171 -0.101 -67.0
-64.143 -73.831 -67.034 -0.085

BPM3
-0.066 -67.923 -74.498 -64.859
-67.921 -0.065 -64.835 -74.617
-74.497 -64.842 -0.068 -67.870
-64.826 -74.591 -67.845 -0.066

BPM4
-0.064 -67.832 -74.368 -64.647
-67.827 -0.065 -64.815 -74.497
-74.369 -64.820 -0.068 -67.690
-64.613 -74.476 -67.666 -0.066
BPM offset calibration for COD mode

Similar calibration is also possible for **COD mode** using **CW** signal.

- no correction
  - balance error was more than 100 μm
- gain calibration using CW RF
  - balance error decreased ~50 μm
- beam based correction
  - From voltage response when beam positions are intentionally changed, correction coefficients can be obtained by minimizing the balance error. BPM readings shrank to one position ± 30 μm.
BPM offset calibration for COD mode

Similar calibration is also possible for **COD mode** using **CW** signal.

Below, calibration results are shown.

- no correction: cross-bar switch turned off
- DSC correction: only DSC correction is applied
- DSC + beam based correction
- gain calibration:

![Graph showing calibration results](image-url)
**Correction Result (Single Pass mode)**

**Single Pass**

Before the calibration, \((x,y)\) of single pass was within \(R=75\mu m\).

Applying CW correction to the COD data, \((x,y)\) shrank within \(R=50\mu m\).

- COD \((x,y)\) of BPM4 without correction had large offset due to deformed cable.
- The large offset was corrected by CW correction.

Both single pass and COD were calibrated within \(~50\mu m\).
Correction Result (Single Pass, COD mode)

COD

COD \((x,y)\) without correction scattered \(R=350\mu m\).

Applying CW correction to the COD data, \((x,y)\) shrank within \(R=50 \mu m\).

- No correction Single pass
- No correction COD
- COD CW correction
- Pulse, w/ S-parameter

Both single pass and COD were calibrated within \(~50\mu m\).

Single Pass

Before the calibration, \((x,y)\) of single pass was within \(R=75\mu m\).

Applying CW correction to the COD data, \((x,y)\) shrank within \(R=50 \mu m\).

COD \((x,y)\) of BPM4 without correction had large offset due to deformed cable.

The large offset was corrected by CW correction.