Offset calibration of single pass BPM

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- Motivation
- 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.

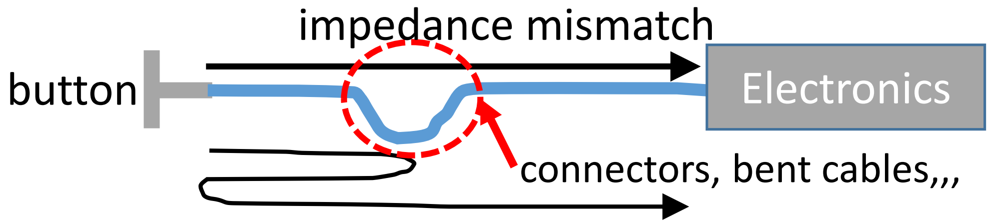
Major factor of the **BPM offset** is **gain imbalance** between BPM channels.

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?



V.S.W.R ≲ 1.2 typical
10 % is reflected signal!

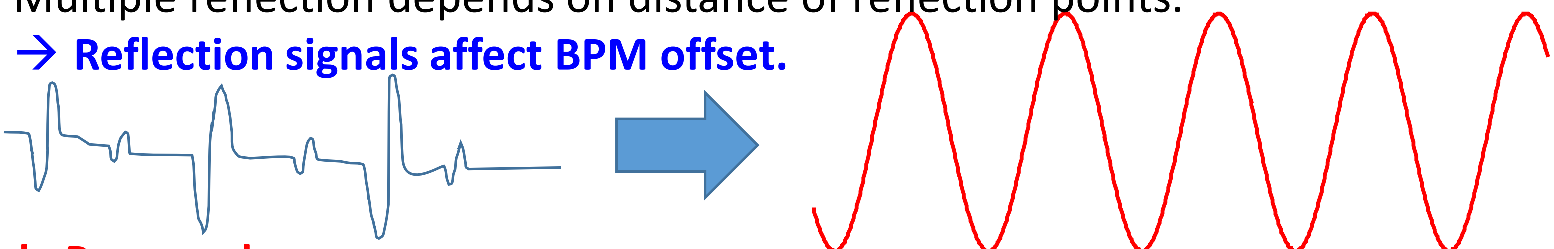
COD mode

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.

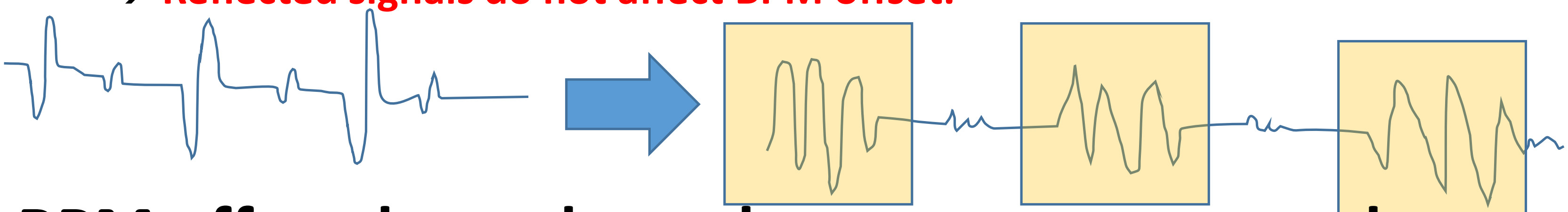
→ **Reflection signals affect BPM offset.**



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.

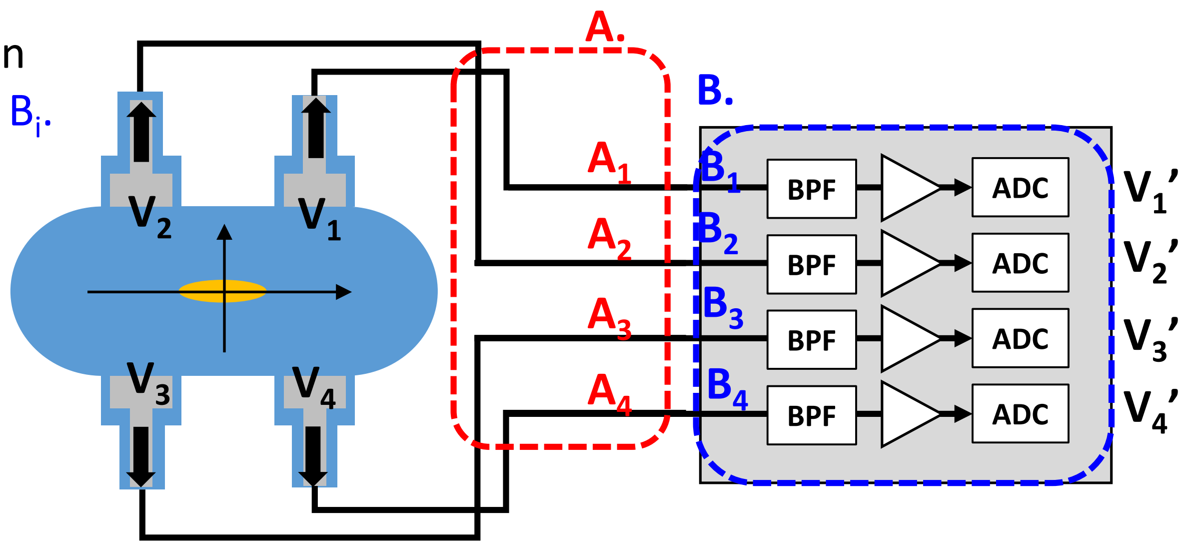
SP mode offset should be calibrated with pulsed RF signal.

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,**

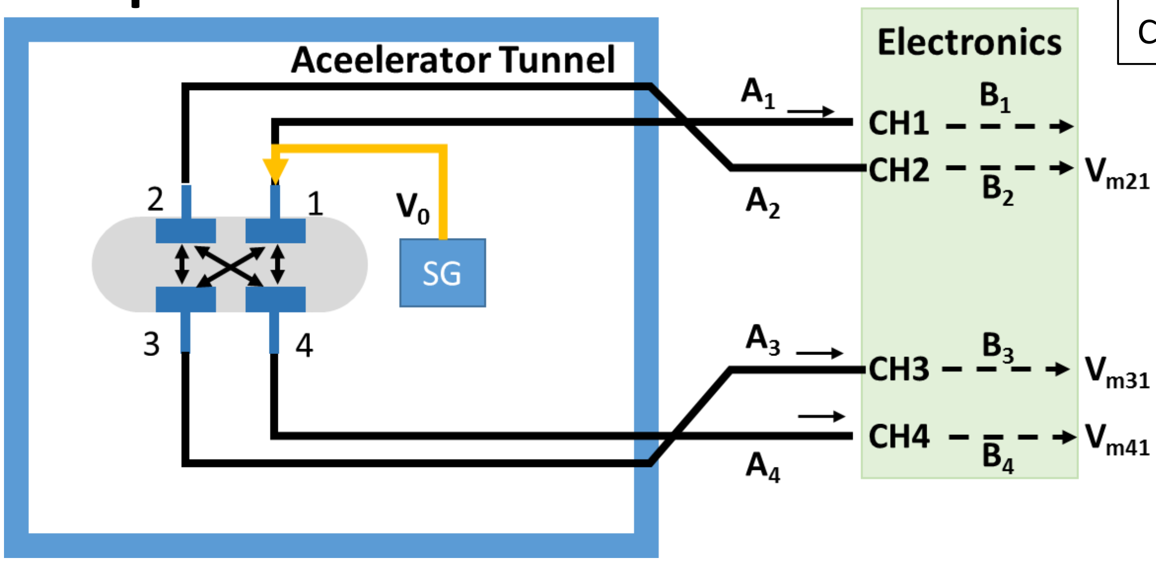
$$\mathbf{C_i = A_i \times B_i}$$

to calibrate the offset.

Calibration Method

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

Setup



B_i : cable gain
C_i : electronics gain

$$V_{m21} = V_0 \times S_{21} \times A_2 \times B_2$$

$$\cdot \quad \cdot \quad \cdot$$

$$V_{mji} = V_0 \times S_{ji} \times A_j \times B_j$$

correction coefficients

$$\mathbf{C_i = A_i \times B_i}$$

$$\mathbf{C_i = V_{mi1}/V_{m1i} \times S_{1i}/S_{i1}}$$

$$\mathbf{= V_{mi1}/V_{m1i}}$$

S parameters cancels

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.

Spec. of Calibration Signal

pulse signal

frequency	: 508.58MHz (=detection freq.)
peak power	: 10W
pulse width	: 100ns
repeatition	: revolution period (=4.8 μs)

CW signal

frequency	: 508.58MHz
power	: 10W

Applying the coefficients to beam signals, verify the calibration.

BPM used for the calibration

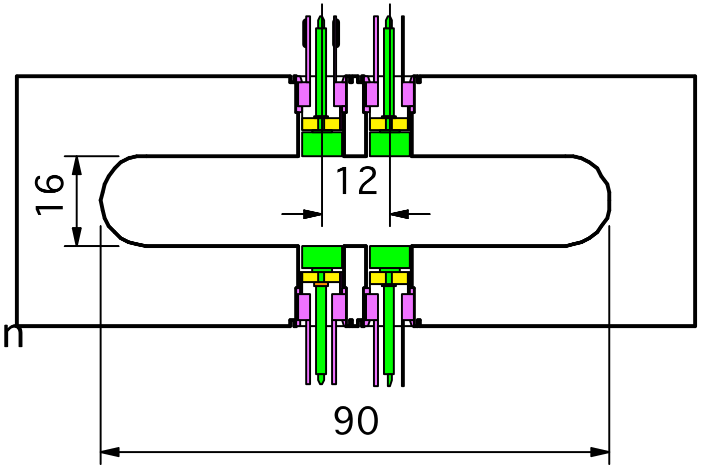
As a demonstration of the calibration,
proposed calibration was applied to
prototype of BPM system for SPring-8 upgrade.

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, SiO_2),
  corrugate cable (1/2'')
- Electronics : Libera brilliance+

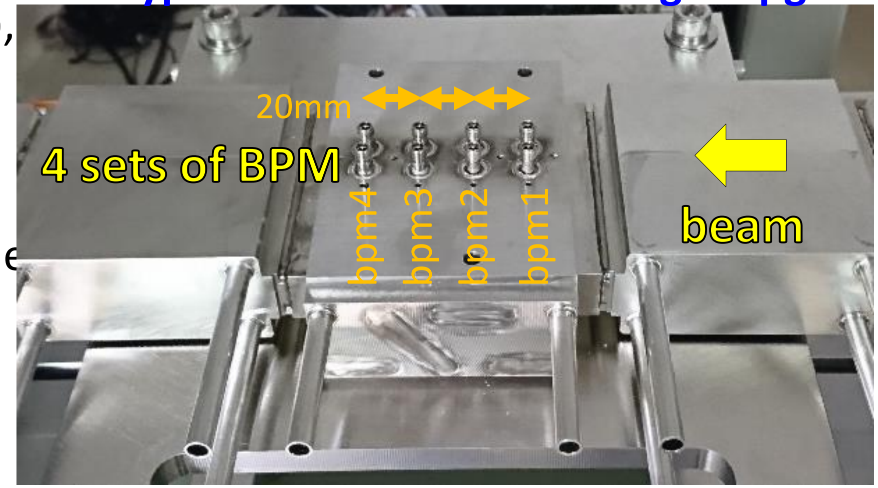
Measure beam signals for single pass and COD mode.
Apply correction coefficients to the data,
BPM offset after the calibration is obtained.
Verify which calibration is valid (pulse or CW)
from the BPM offsets.

cross sectional view

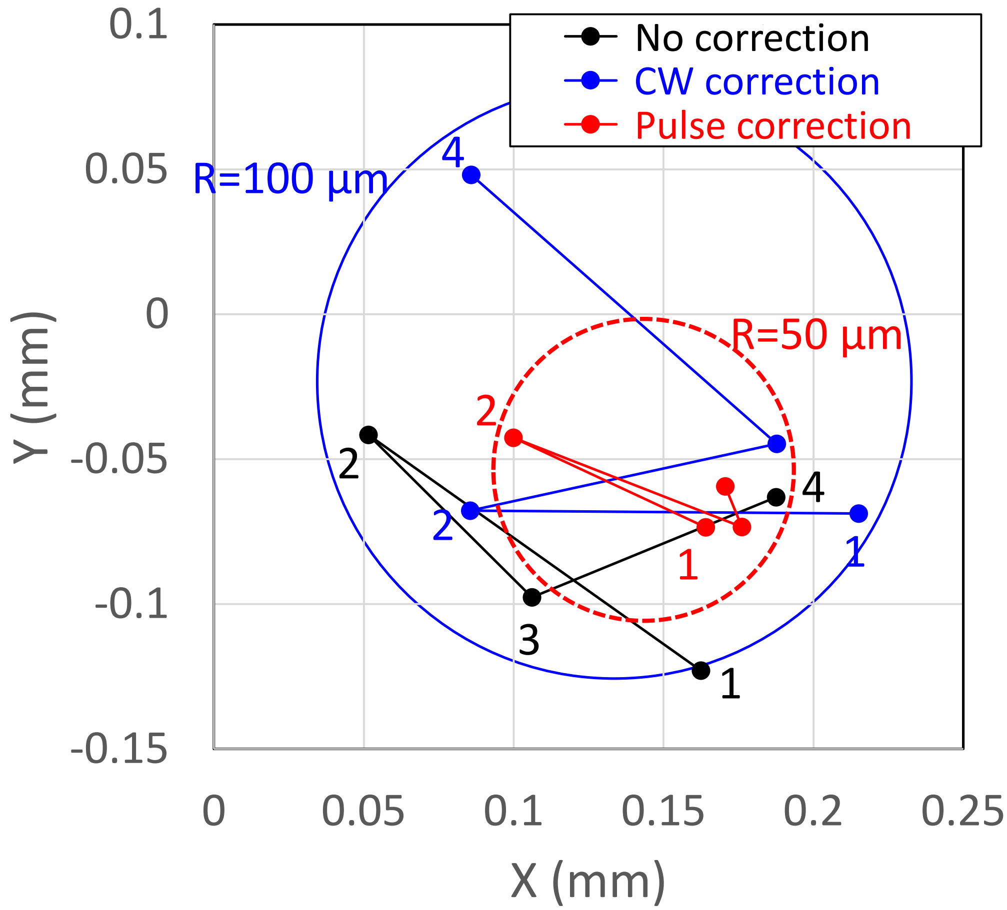


vertical aperture, button span
were same as SPring-8 upgrade

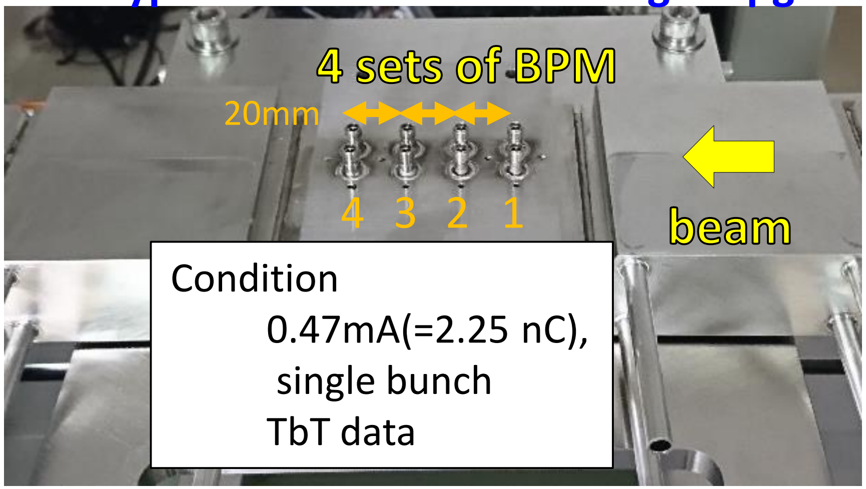
Prototype of BPM head for SPring-8 upgrade



Single pass offset measured with beam signal



Prototype of BPM head for SPring-8 upgrade

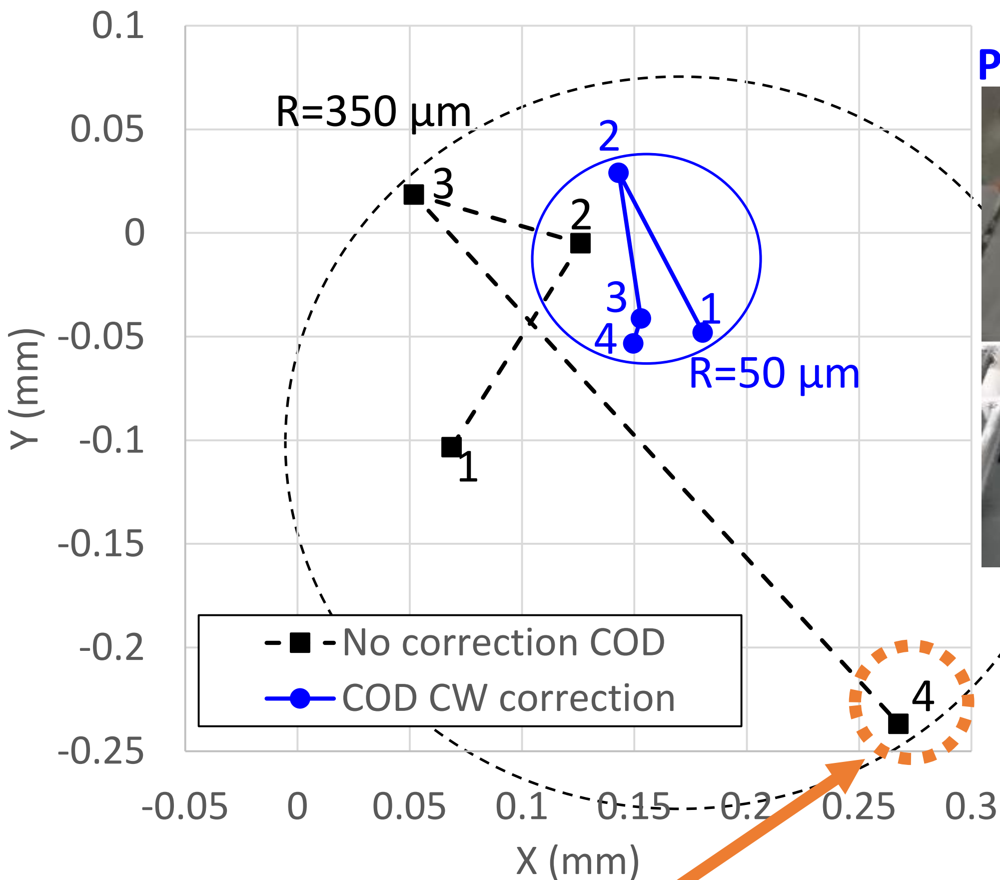


If gain balances are properly corrected,
4 BPM readings come close to one point.

	BPM offset
No correction	**scatter ~ 100 µm**
CW correction	**scatter ~ 100 µm**
Pulse correction	**scatter ~ 50 µm**

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



Prototype of BPM head for SPring-8 upgrade

Condition
100 mA, multi-bunch
SA data

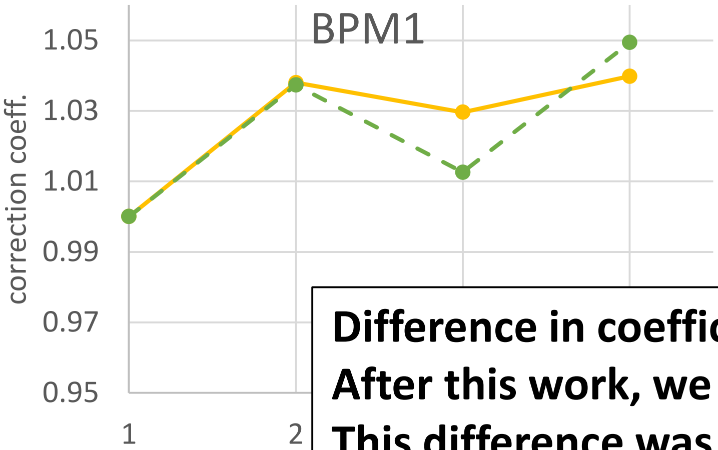
If gain balances are properly corrected,
4 BPM readings come close to one point.

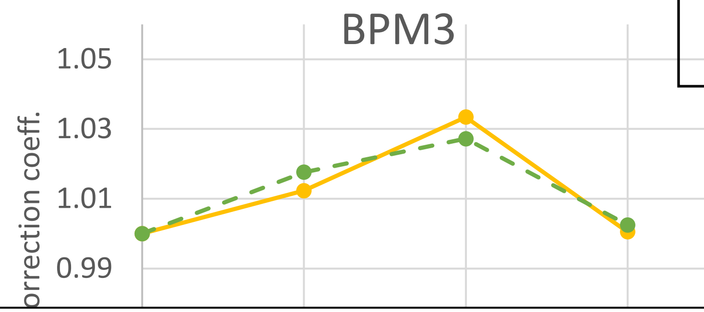
	BPM offset
No correction	**scatter ~ 350 µm**
CW correction	**scatter ~ 50 µm**

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

COD should be calibrated using **CW RF signal**.

Correction coefficients for single pass mode



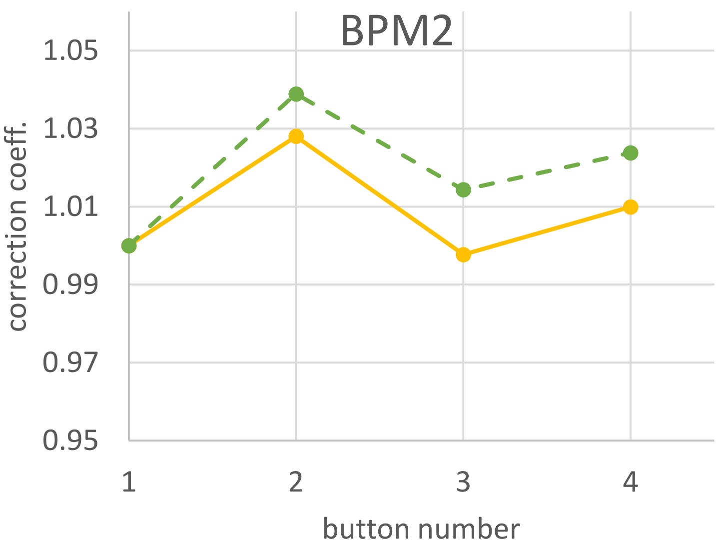


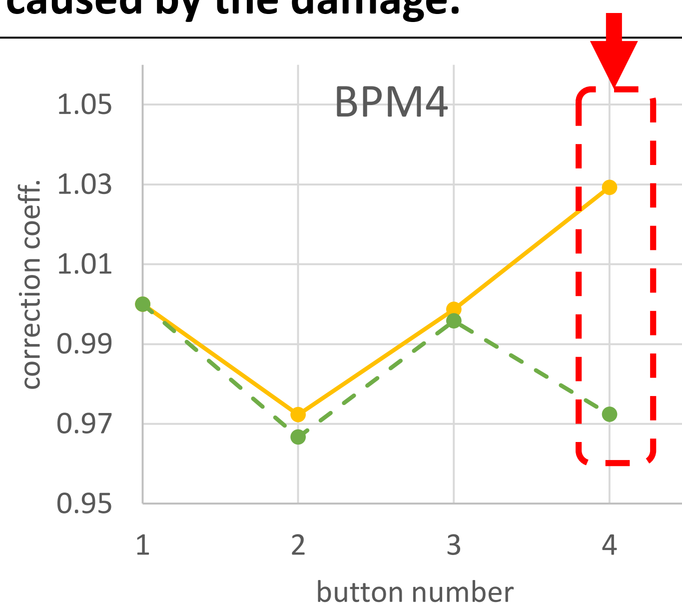
$V_i' = V_i \times A_i \times B_i$

correction coefficients

$\mathbf{C_i = A_i \times B_i}$

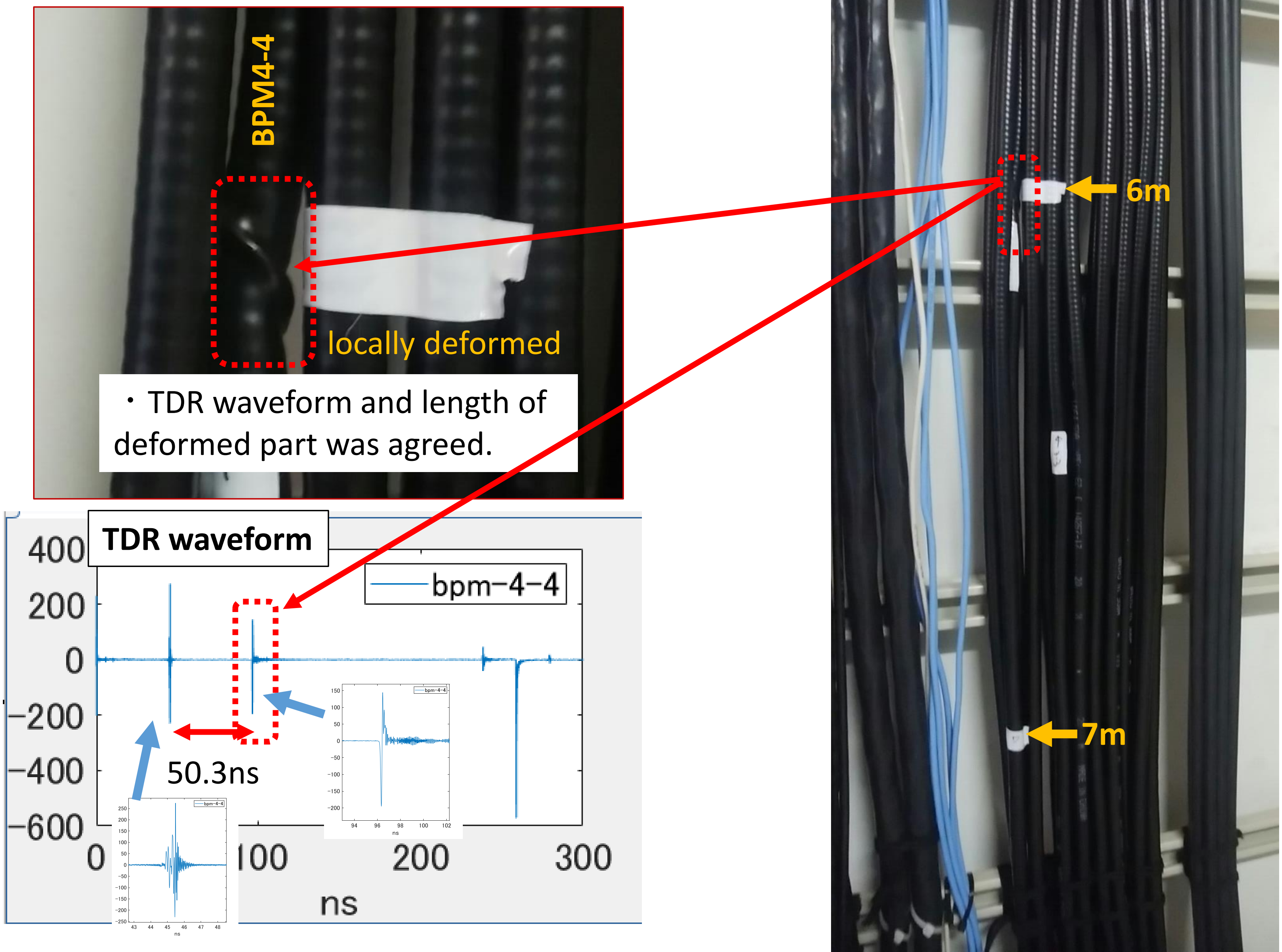
Difference in coefficient C_4 of BPM4 is significant.
After this work, we found cable4 of BPM4 was damaged (deformation).
This difference was caused by the damage.



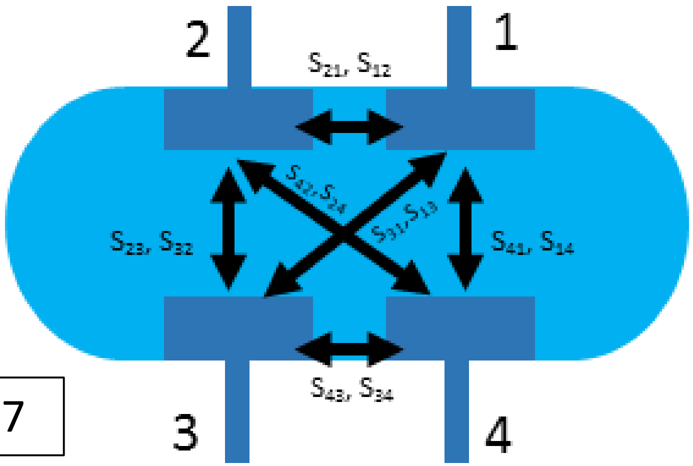


Correction coefficient of 0.01 corresponds to 15~20 µm of BPM offset.

Deformed cable of BPM4-4



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.)

ADC range : ±32767

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

coupling direction	Ex.	coupling (voltage ratio)
vertical	1→4, 2→4,,,	~-64dB (1)
horizontal	1→2, 3→4,,,	~-67dB (0.7)
diagonal	1→3, 2→4,,,	~-74dB (0.3)

beam signal : 0.4~0.6 of ADC range
calibration signal : 0.06~0.2 of ADC range

	calibration	beam signal
maxadc	2,000~6,000	12,000~19,000

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 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**.

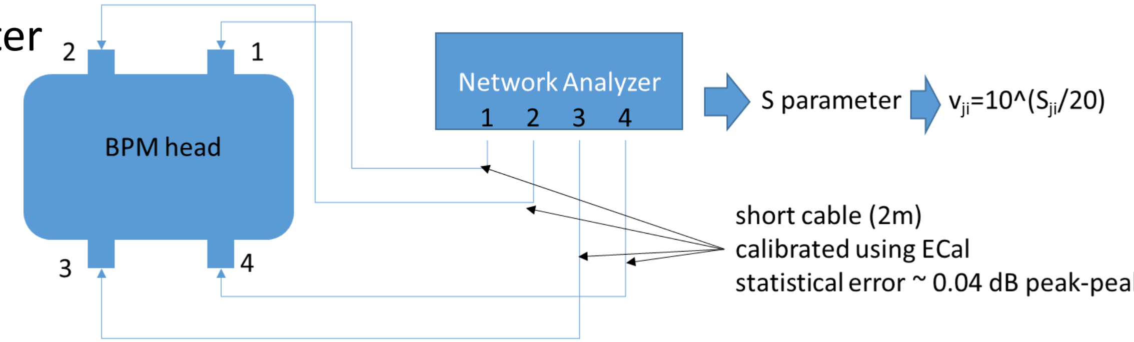
Thank you for your attention!

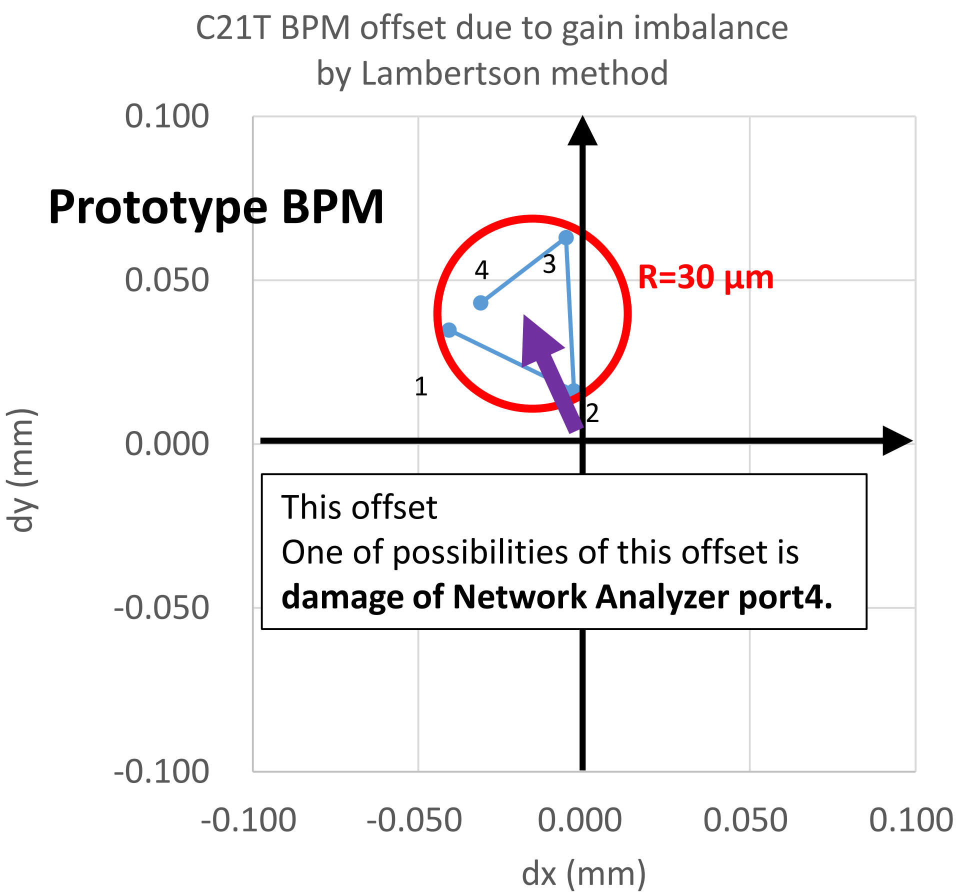
Backup slides

BPM offset by Lambertson Method

Calculate BPM offset from S-parameter

S-parameter is only for BPM head.





correction coeff.

$c_1=1$

$c_2=g_2/g_1=\{v_{42}\ v_{32}/v_{41}\ v_{31}\}^{1/2}$

$c_3=g_3/g_1=\{v_{32}\ v_{43}/v_{21}\ v_{41}\}^{1/2}$

$c_4=g_4/g_1=\{v_{43}\ v_{42}/v_{31}\ v_{21}\}^{1/2}$

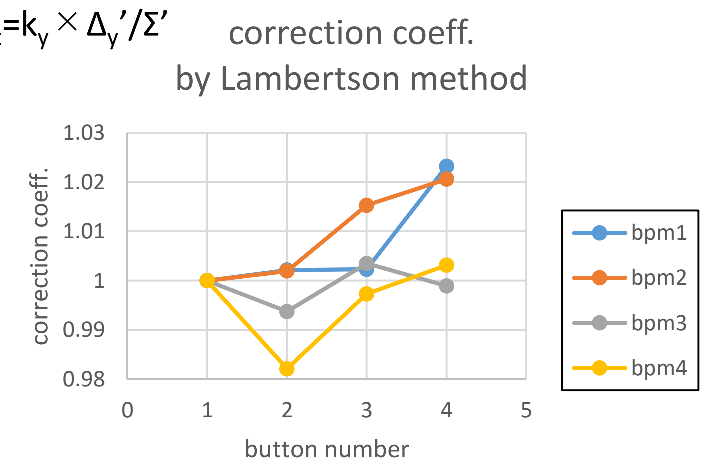
v_i : detected voltage via readout electronics

$v_i'=v_i/c_i$

$\Delta'=$

$x_{offset}=k_x \times \Delta_x'/\Sigma'$

$y_{offset}=k_y \times \Delta_y'/\Sigma'$



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

094923 average of 880 turn (maximum ADC count in one-turn)

	電極1	電極2	電極3	電極4
BPM1	14912	13955	12838	13857
BPM2	18258	18976	19029	19500
BPM3	18104	16987	17996	19234
BPM4	15429	16148	14346	17340

12,000~19,000 count
=533 ~ 844 count / 100 pC

Measurement error of S parameter

Statistical error when calibration w/ S parameter is applied.

	(dB) p-p
reproducibility w/o reconnect	0.007
connector reconnect	0.011
character of RP-SMA adapter	0.031
freq. characterictic	0.01
calibration error of NetworkAnalyzer	$0.03/(2)^{0.5}$
Total (r.m.s.)	**0.041 dB p-p**

⇒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

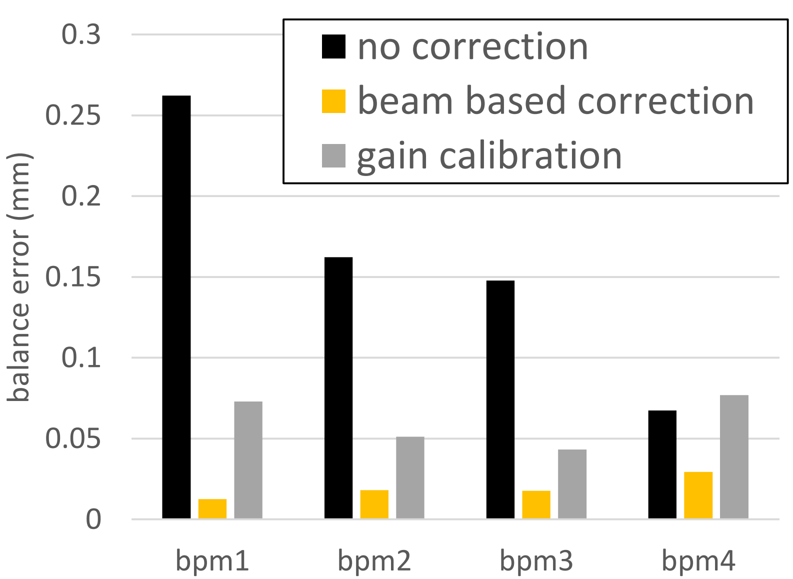
BPM4

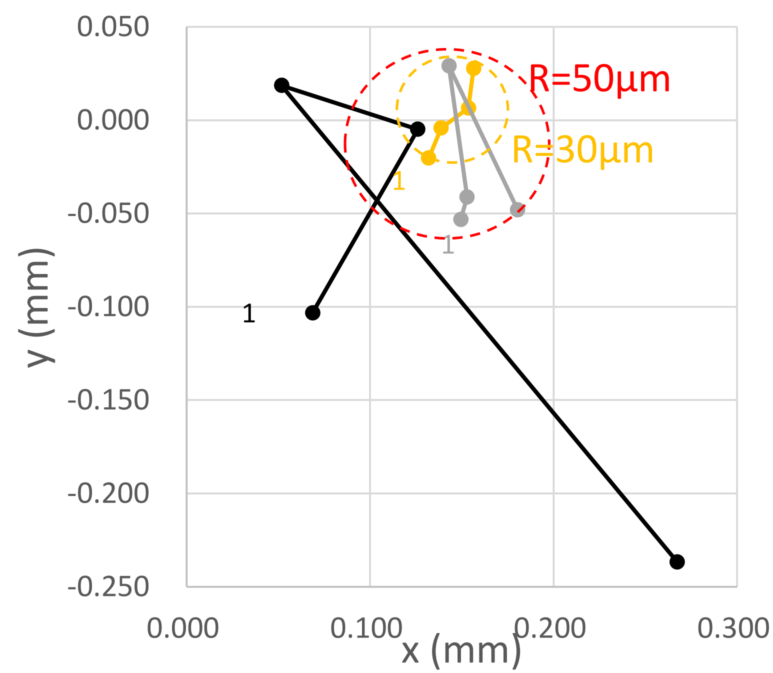
-0.064	-67.832	-74.368	-64.647
-67.827	-0.065	-64.815	-74.497
-74.369	-64.820	-0.068	-67.690
-64.613	-74.476	-67.666	-0.066

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.



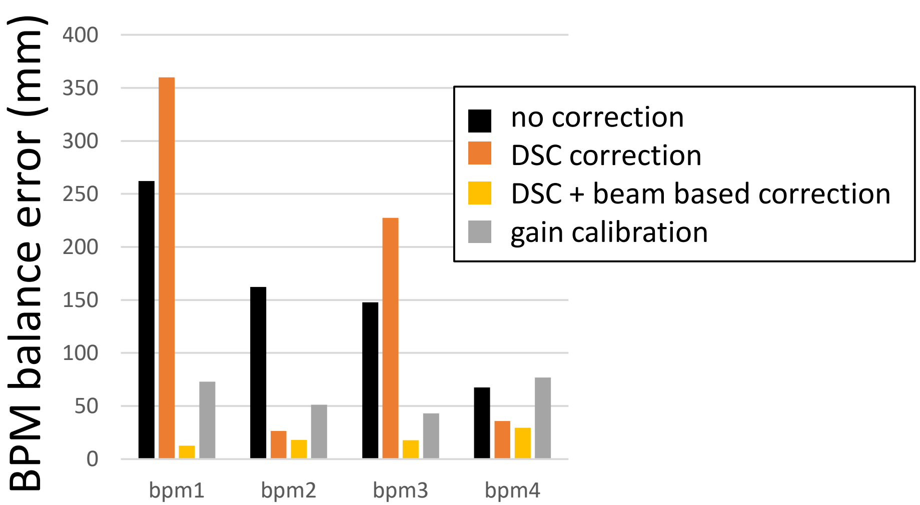


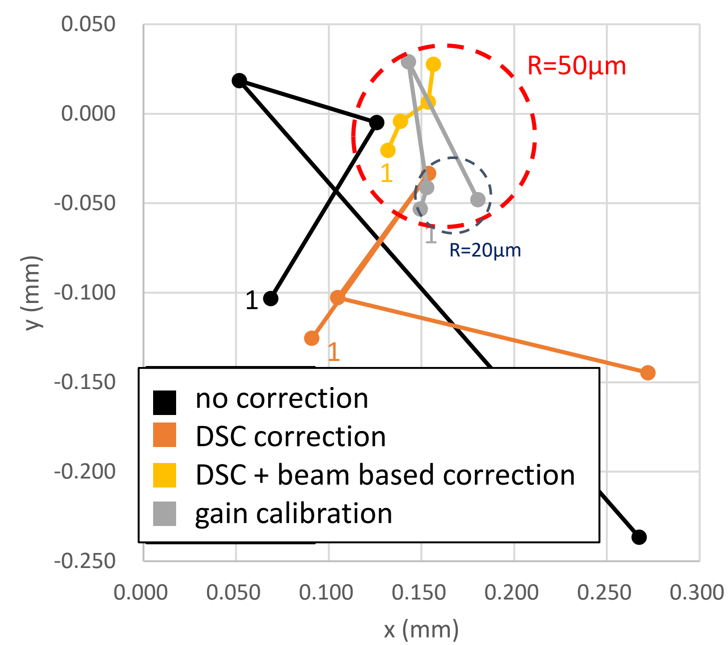
BPM offset calibration for COD mode

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 :



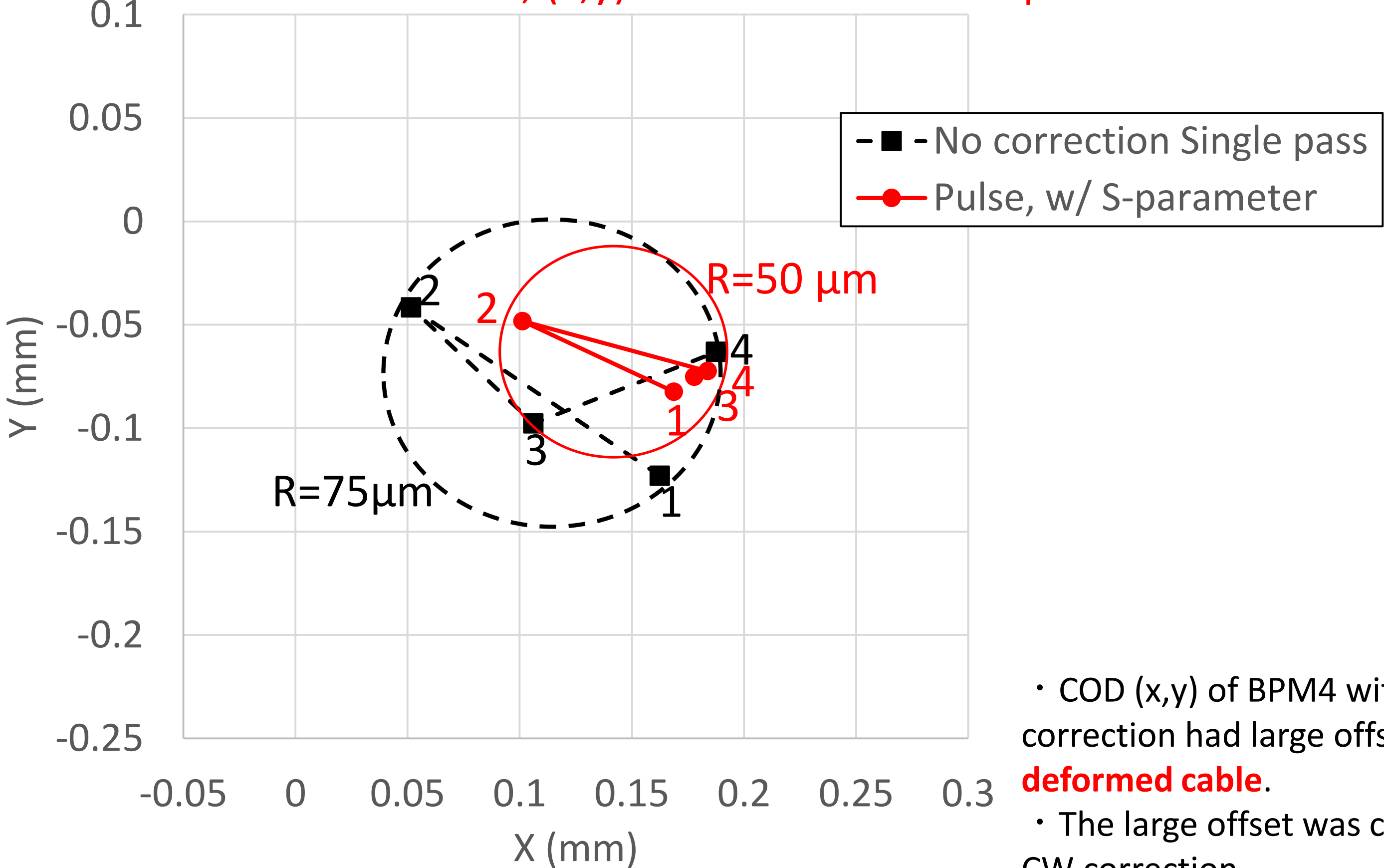


Correction Result (Single Pass mode)

Single Pass

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

Appling CW correction to the COD data, (x,y) shrank within R=50 μm.



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

・The large offset was corrected by CW correction.

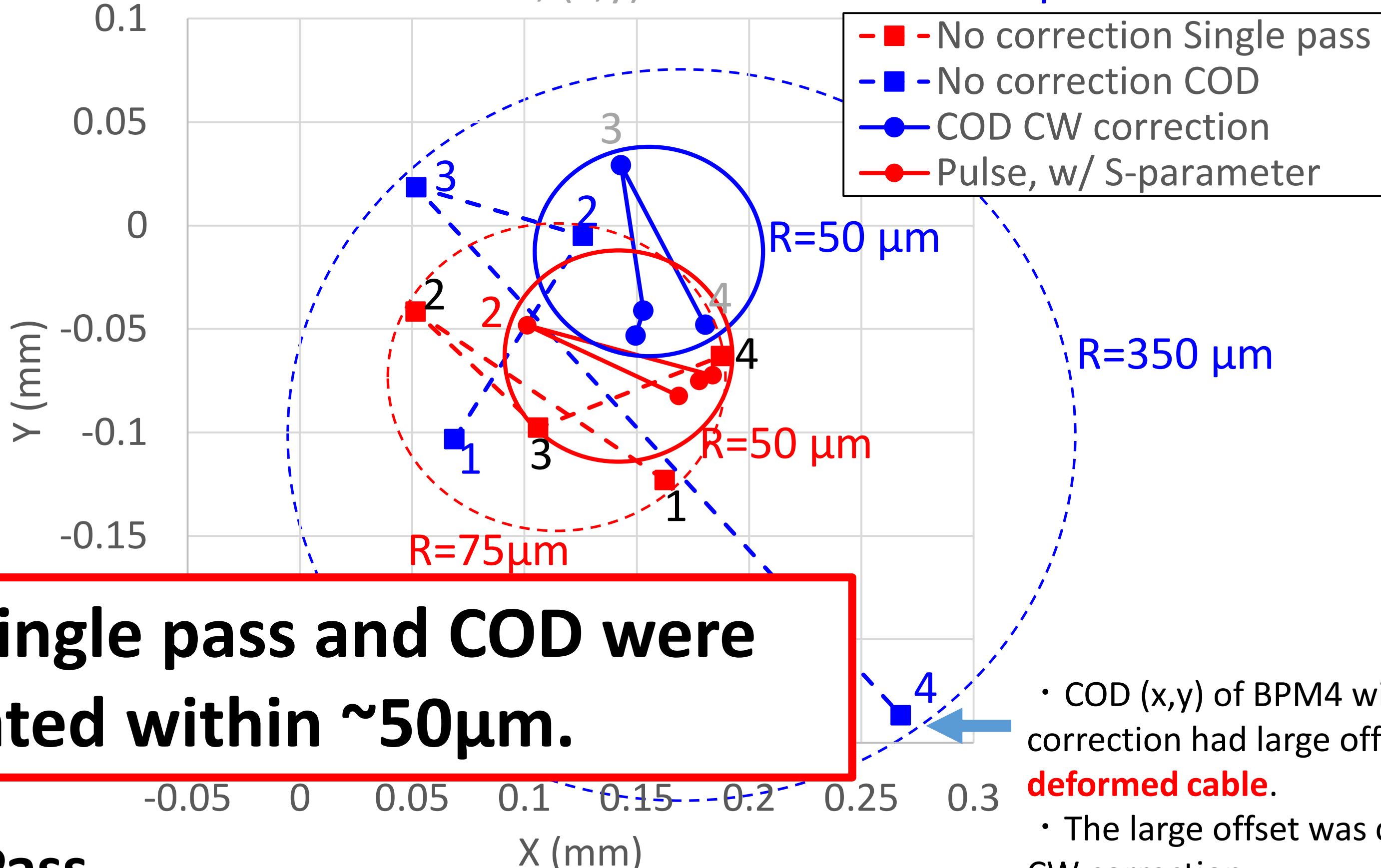
Both single pass and COD were calibrated within ~50μm.

Correction Result (Single Pass, COD mode)

COD

COD (x,y) without correction scattered R=350um.

Appling CW correction to the COD data, (x,y) shrank within R=50 μm.



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