TUBLA01

# Beam based calibration for beam position monitor

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# Contents

- Calibration at the beginning
  - Including mapping of BPM head, alignment, and gain calibration of electric circuit.
- Beam based alignment
  - BBA in next year beam commissioning of KEKB.
- Beam based gain calibration
  - Gain calibration of BPM in the KEKB
    - We have done BBGC in every 2-3 month since 2003.
  - New method for gain calibration of BPM in the J-PARC
    - Total least squares method is applied in J-PARC
- High-precision BPM system
  - Monitoring the consistency error and applying the beam-based gain calibration

# Calibration of BPM

**Systematic errors in BPM**

- Setting error of BPM to Q-mag.

  Measurement of $\Delta x=?$, $\Delta y=?$

  Offset error

- Imbalance error in 4-outputs

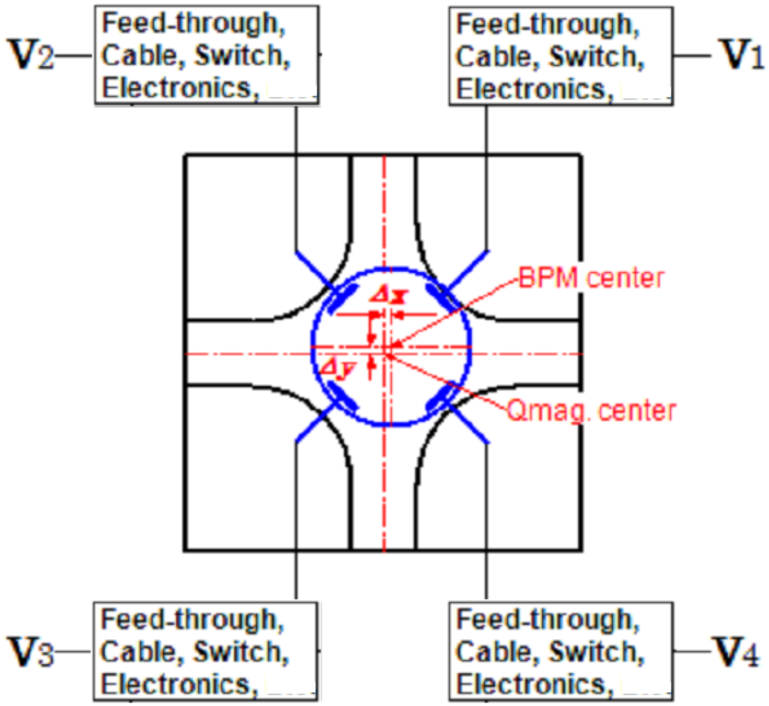
  Relation among $V_1$, $V_2$, $V_3$, $V_4$

  when the beam locates in the center

  Gain error

  – the output signals travel through 4 separate cables, connectors, attenuators, and switches

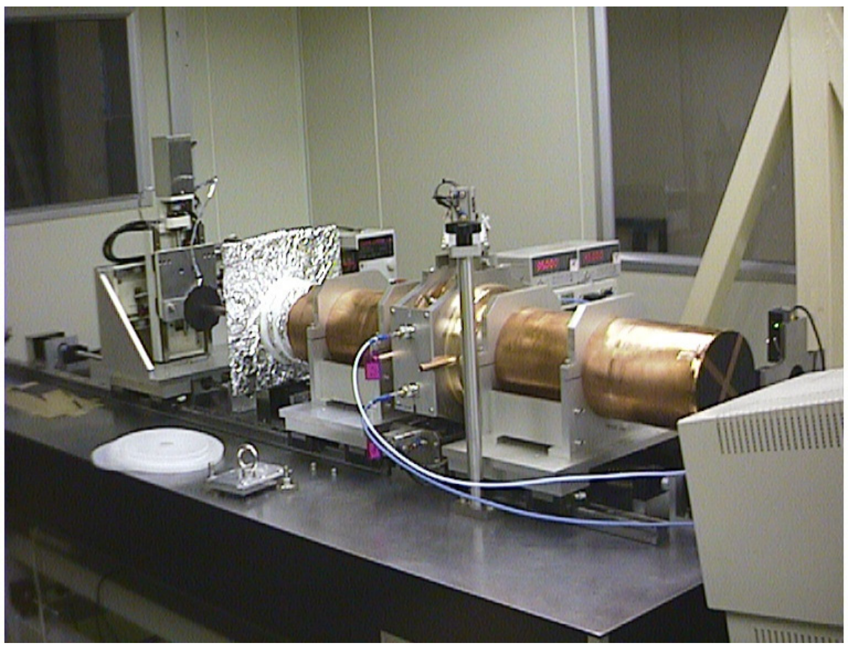
**BPM model**



# STEP 1, Mapping of BPM head

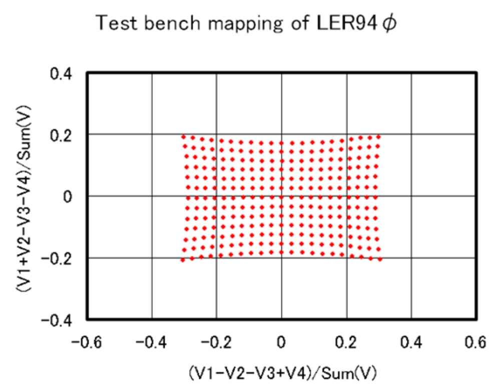
All BPMs were mapped at a test bench with a movable antenna .

**Test bench for the mapping**

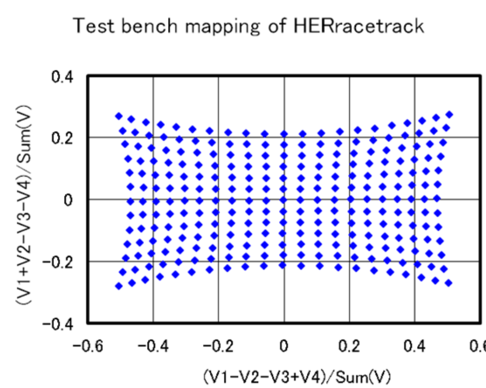


**result for mapping**

LER



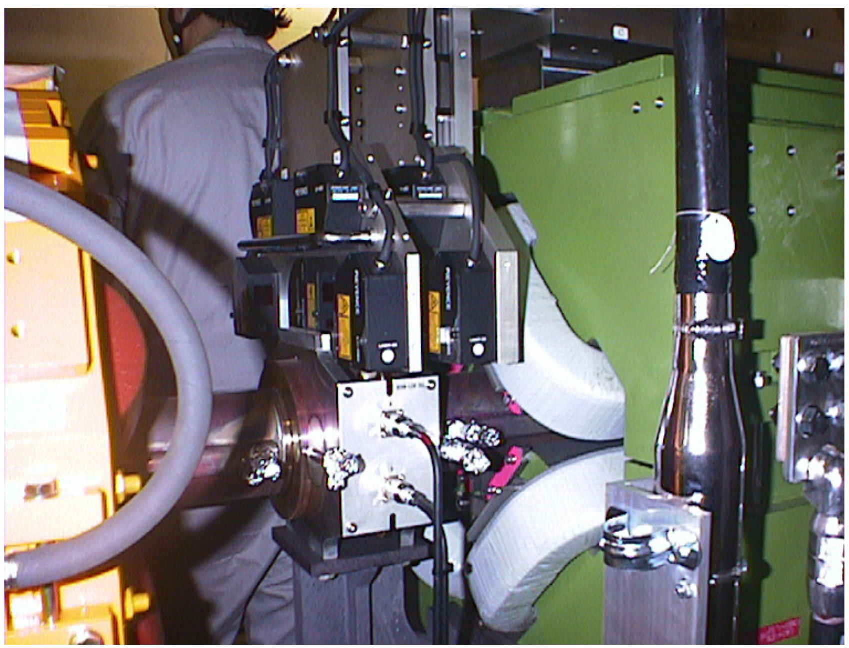

HER



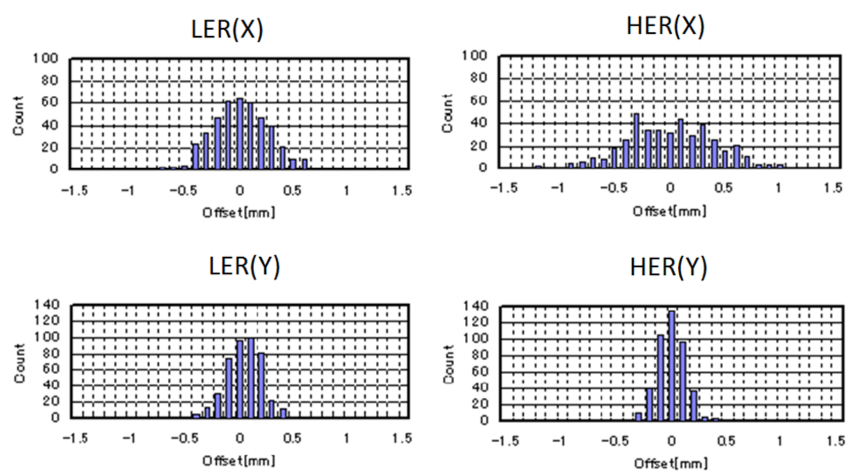
# STEP 2, Alignment of BPM heads against to the Q-magnets

Measurement of the mechanical offsets of the BPM heads to the Q-magnets.

**Photograph of Measurement tool**



**Results of alignment of BPM heads against to the reference plane of the Q-Magnets**

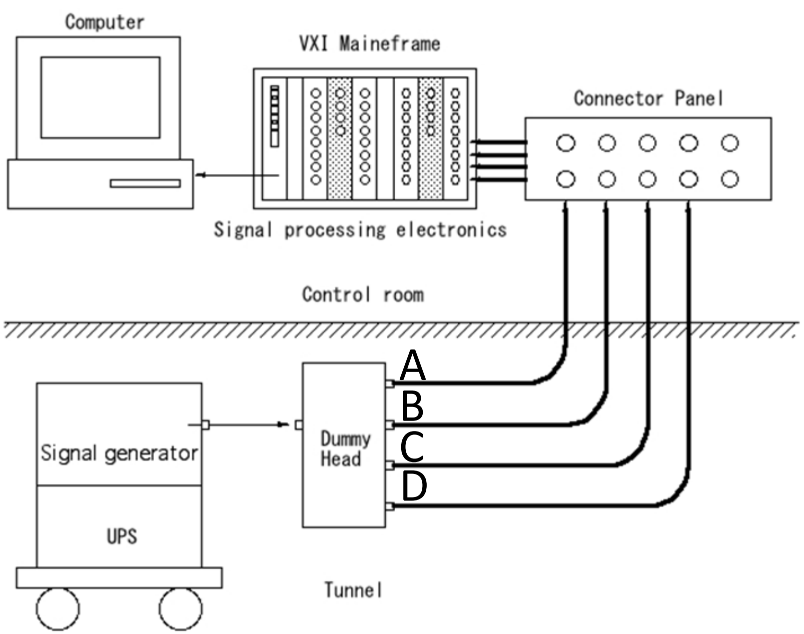


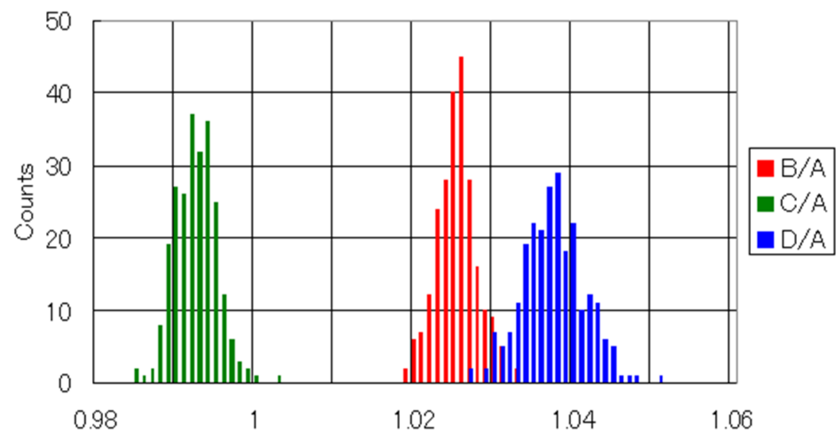
# STEP-3, Gain calibration of the electronics

## Attenuation of cable, switch, electronics, etc.

We measured the distribution of signal attenuation of the all electronics
We used a dummy head instead of BPM heads.

Results for ration between output signal B,C and D against to A in all electronics




Output signals: A, B, C, D

# Beam based calibration

**Beam Based Alignment**

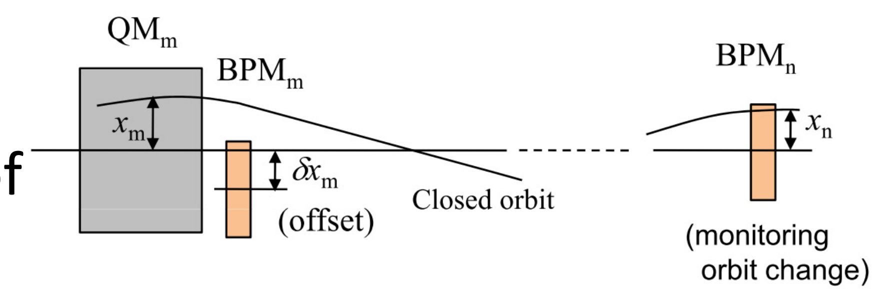
- Measurement of the offset of BPM to the field center of the adjacent Q-magnet using the beam.

**Beam Based Gain Calibration**

- Calibration of the gain imbalance among four outputs of a BPM using the beam.

# Beam based alignment(BBA)
# - Principal -

- BBA is searching the a beam orbit which is insensitive to the change of field strength of Q-magnet.
- This orbit must passing through the magnetic center of Q-magnet.
- The measured beam position for this orbit is corresponding to offset origin of BPM.

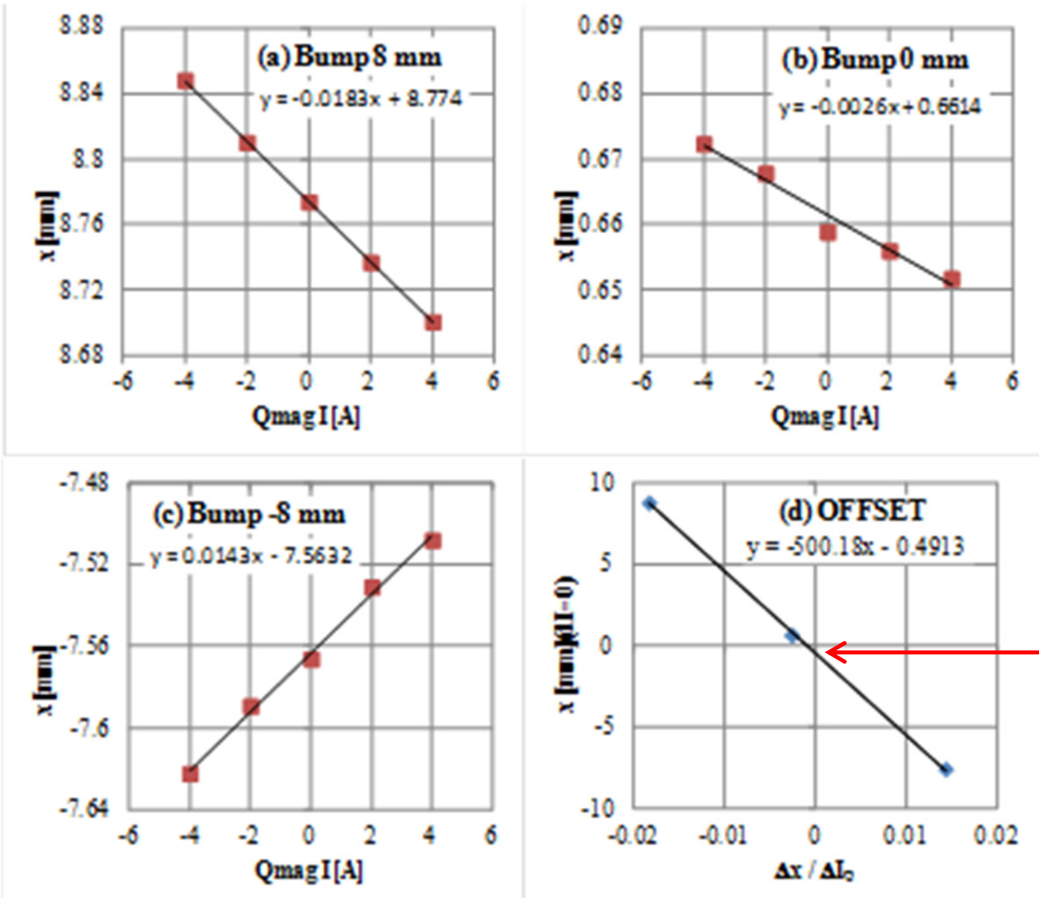



$$\Delta x_n = -a_{nm}(x_m - \delta x_m)\Delta K_m$$

$$a_{nm} = \frac{\sqrt{\beta_n \beta_m}}{2\sin \pi\nu}\cos(\pi\nu - |\phi_n - \phi_m|)$$

$\Delta Xm=0$ then $\delta xm$ offset

# Actual procedure for BBA




Bump orbits: -8, 0, 8[mm]

$I_Q$ : -4, -2, 0, 2, 4 [A]

-current of correction coil

from figure (a),(b),(c), $\Delta x/\Delta I_Q$ and $x\ (I_Q=0)$, *where* $x=x_m$

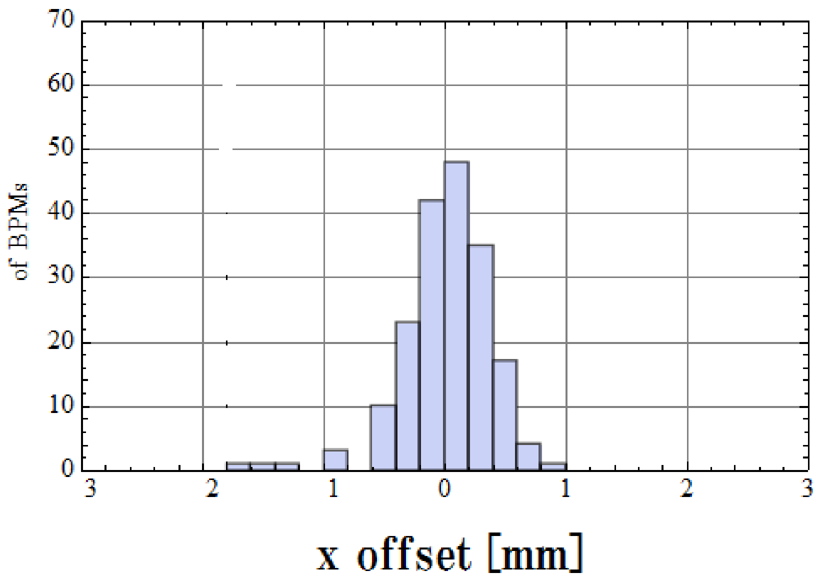
$\Delta x / \Delta I_Q = 0$

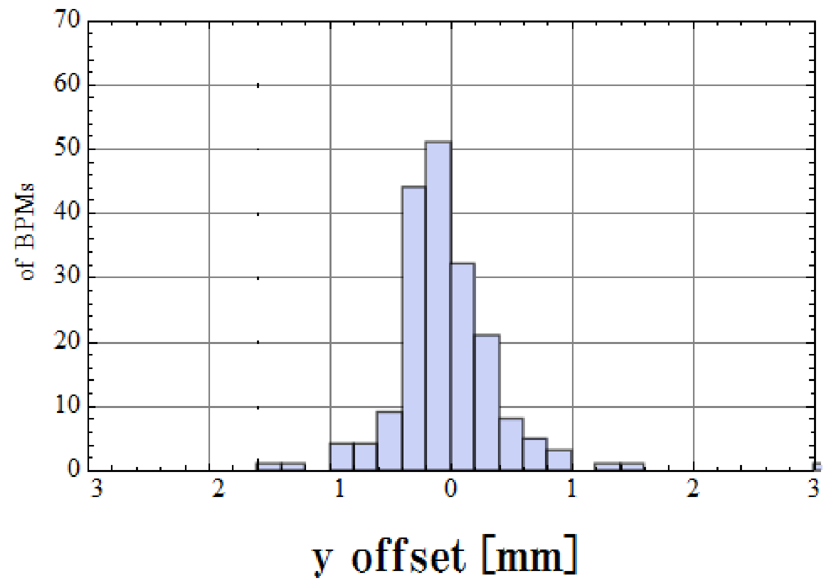
*Offset*

$X=0.4913$[mm]

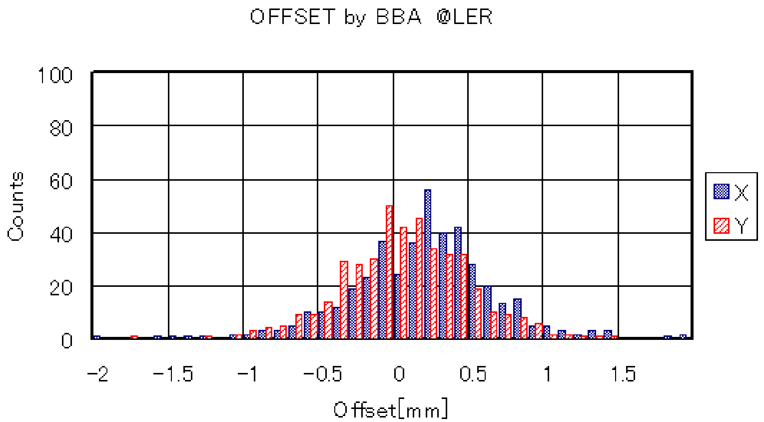
The orbital change due to $\Delta I_Q$ can be monitored not only the BPM but by any other BPMs in the ring.

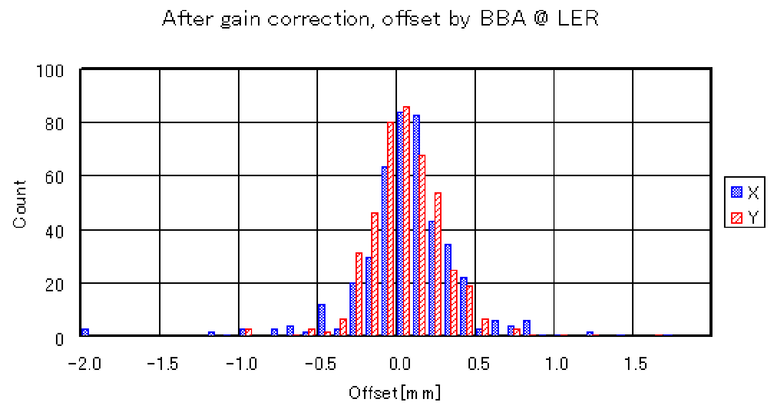
# Distribution of offsets with BBA in J-PARC MR

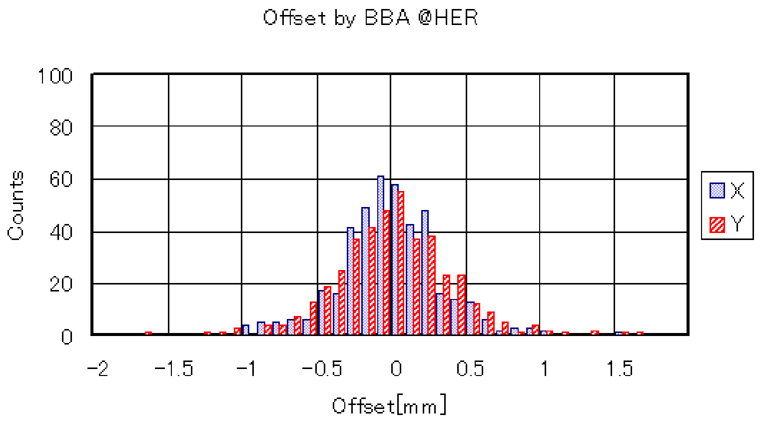


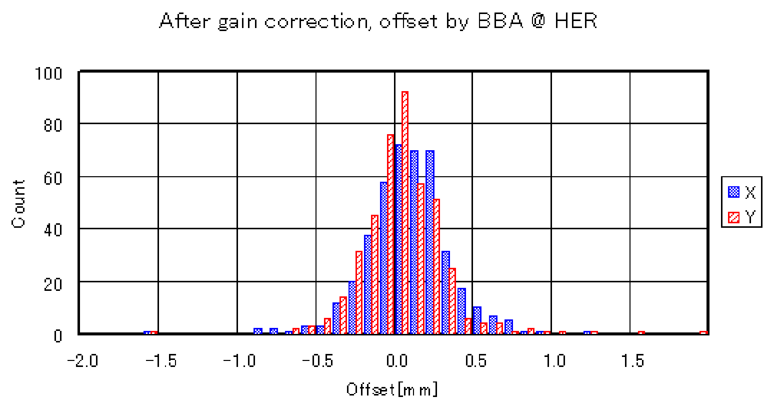



# Distributions of offsets with BBA In KEKB



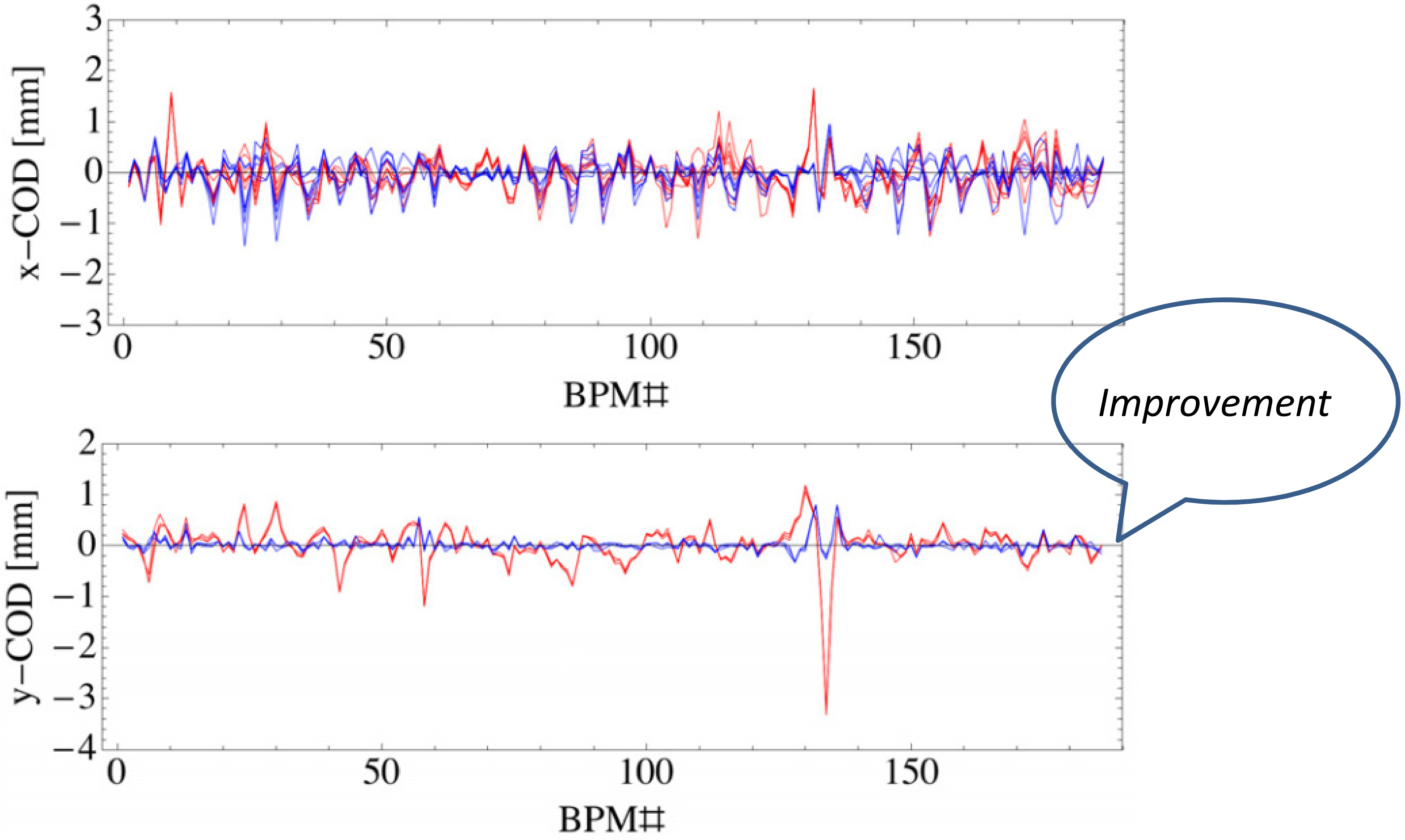



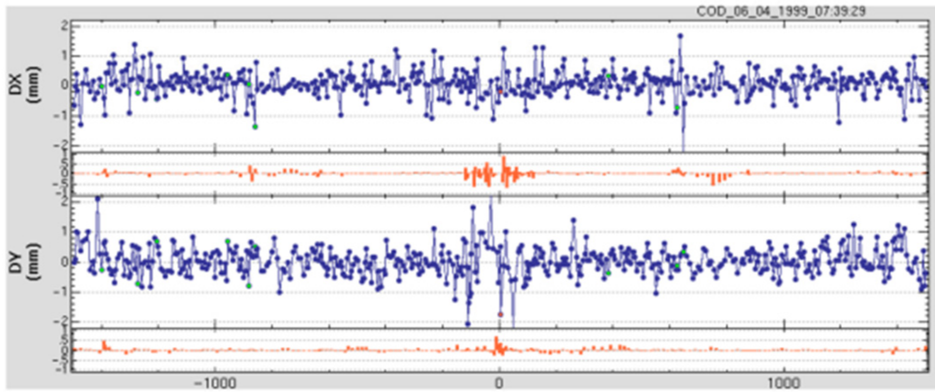
The BPM offsets measured by BBA were set in the data base for BPM system

# The effect of BBA correction in J-Parc MR

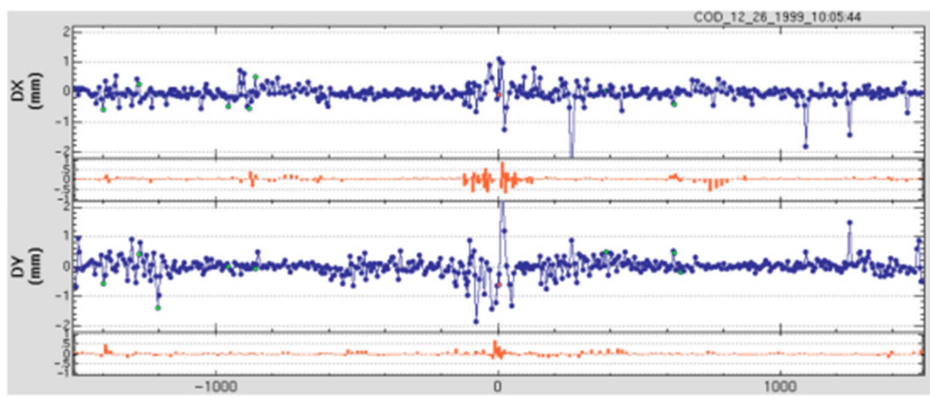



COD without / with the BBA offset data (red / blue lines)

# The effect of BBA correction in KEKB MR




before BBA

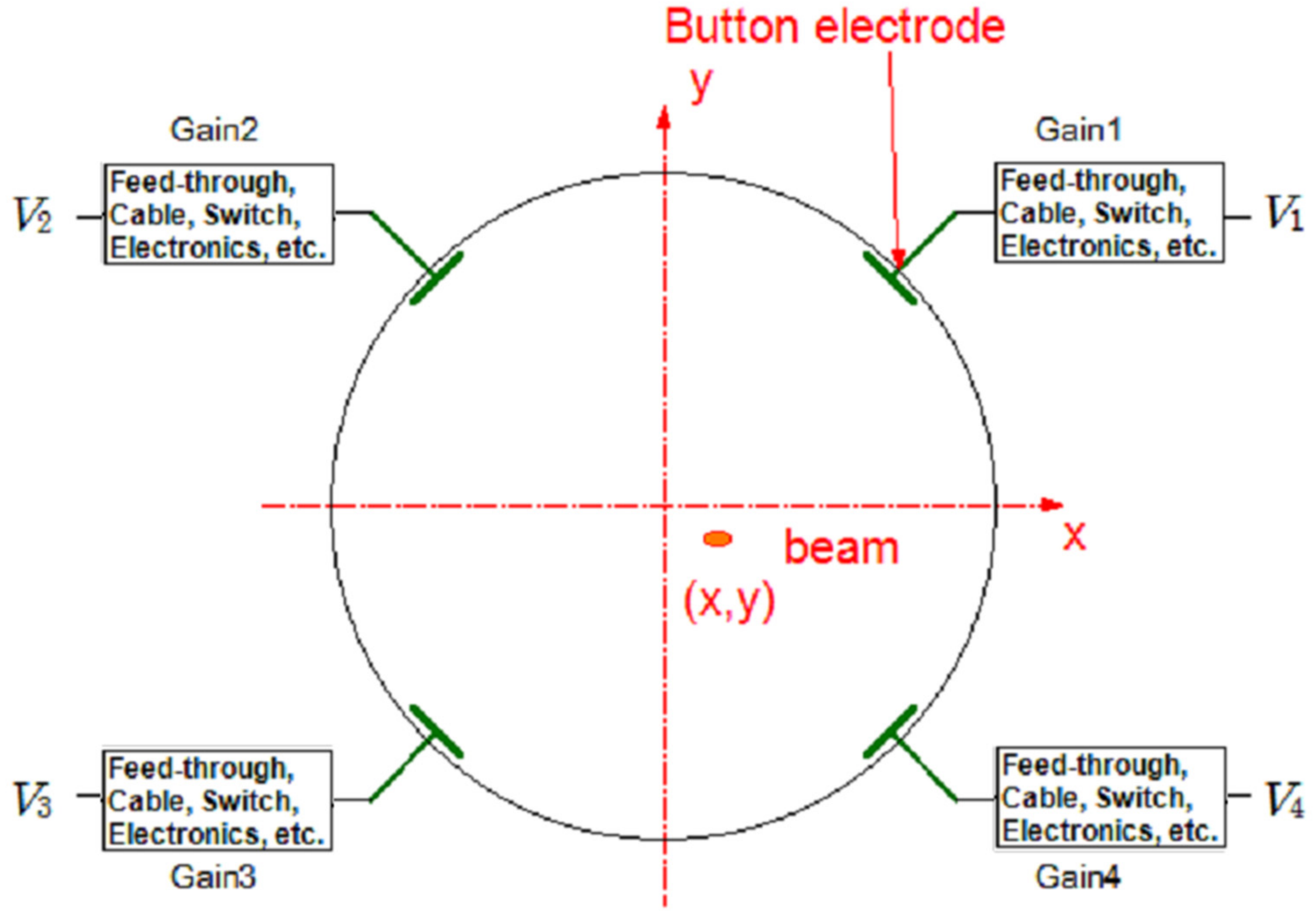



after BBA

# Beam Based Gain Calibration BPM with four button

- The relative gain of the output data may drift due to unpredictable imbalance among output signals from the pickup electrodes.
- The output signals(Vi) must travel through separate paths, such as feed-through, cables, connectors, attenuators, switches, and then are measured by the signal detectors.
- The most probable source of the gain drift is the change in the electrical characteristics of the transmission line of the signal by temperature fluctuation.
- Such as reason , the calibration of the gains of every BPMs are need.

# Gain conception of BPM model



# The output voltage model ($V_i$) for beam based calibration

$$V_i = q g_i F_i(x, y)$$

- $i$-$th$ electrode ($i=1,2,3,4$)
- $(x,y)$: beam position
- $q$: proportional factor to the beam current
- $g_i$: relative gain factor
- $F_i(x,y)$: response function normalized to $F_i(0,0)=1$

# Response function of 4 outputs

$$
\begin{aligned}
F_1(x, y) = 1 &+ a_1 x + b_1 y \\
&+ a_2\left(x^2 - y^2\right) + b_2(2xy) \\
&+ a_3\left(x^3 - 3x^2 y\right) + b_3\left(3xy^2 - y^3\right) \\
&+ a_4\left(x^4 - 6x^2 y^2 + y^4\right) + b_4\left(x^3 y - xy^3\right)
\end{aligned}
$$

$$
F_2(x, y) = F_1(-x, y), \quad F_3(x, y) = F_1(-x, -y),
$$
$$
F_4(x, y) = F_1(x, -y)
$$

These coefficients ($a_1$,,,$a_4$), ($b_1$,,,$b_4$) were determined by fitting the calculated mapping by the finite boundary element method.

# Beam mapping & Gain analysis

Measurement of m times beam positions by changing beam orbit .

$$V_{i,j} = g_i q_j F_i\left(x_j, y_j\right)$$

$$i = 1,,,4,\ j = 1,,,m$$

Analysis by non-linear least square method

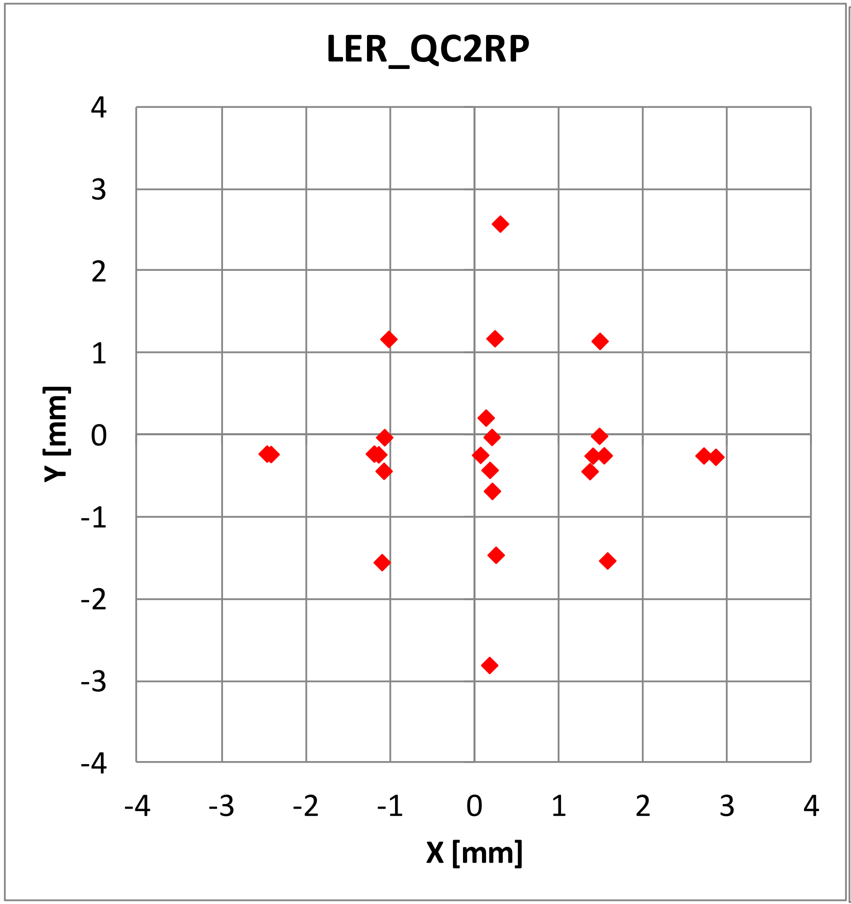
$$J(a) = \sum_{i=1}^{4} \sum_{j=1}^{m} \left[V_{i,j} - g_i q_j F_i\left(x_j, y_j\right)\right]^2$$

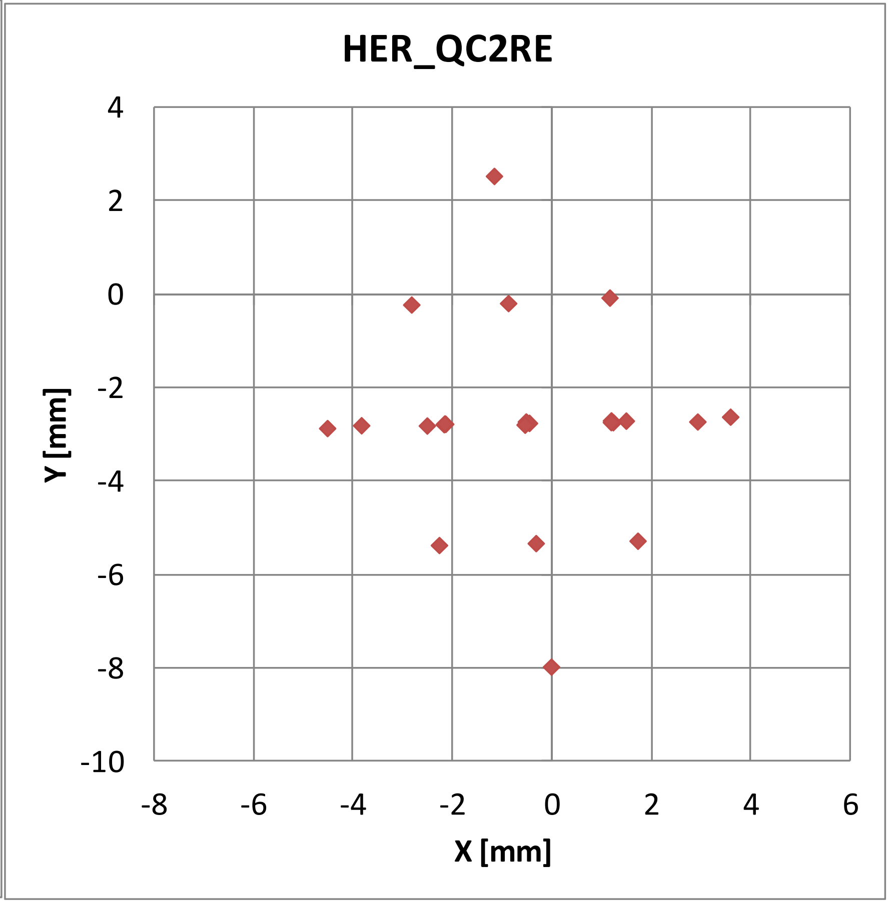
$$a = \left(g_2, g_3, g_4, q_1, x_1, y_1, \cdots, q_m, x_m, y_m\right)$$ fitting parameters

but $g_1 = 1,\ g_2 = g_2 / g_1,\ g_3 = g_3 / g_1,\ g_4 = g_4 / g_1$

To minimize the sum of the squares of residuals.
the software technique is a **Marquardt method**.

# Mapping data by steering magnets for the gain calibration



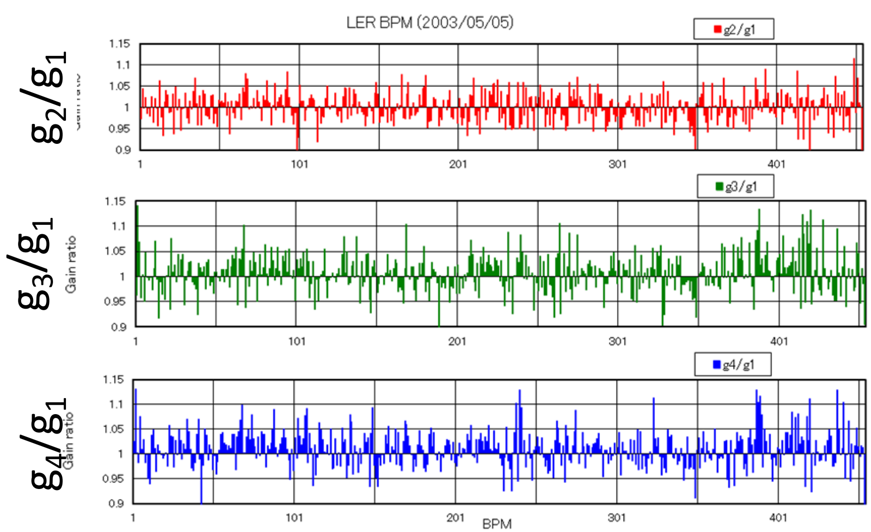




m=25

# Result of calibration in KEKB

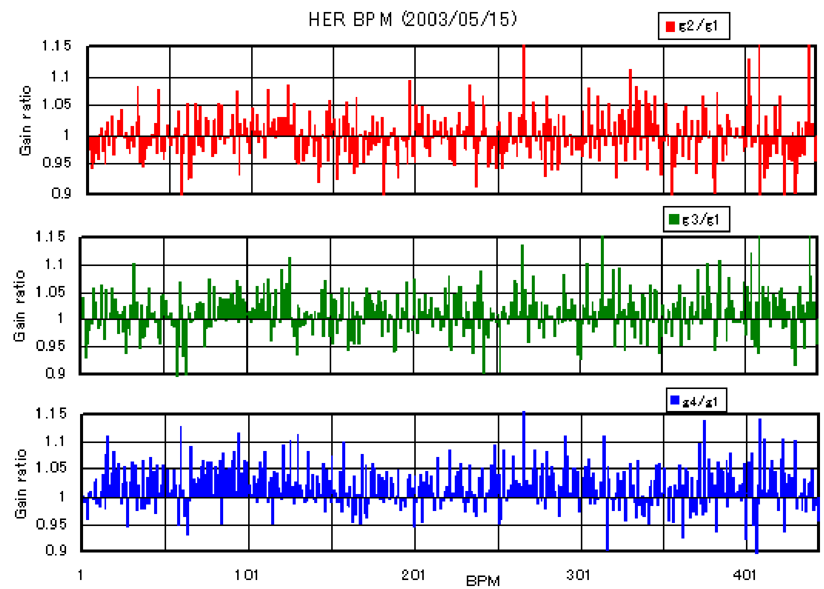
These data are first measurements by beam based gain calibration

**LER**




BPM No.

**HER**




BPM No.

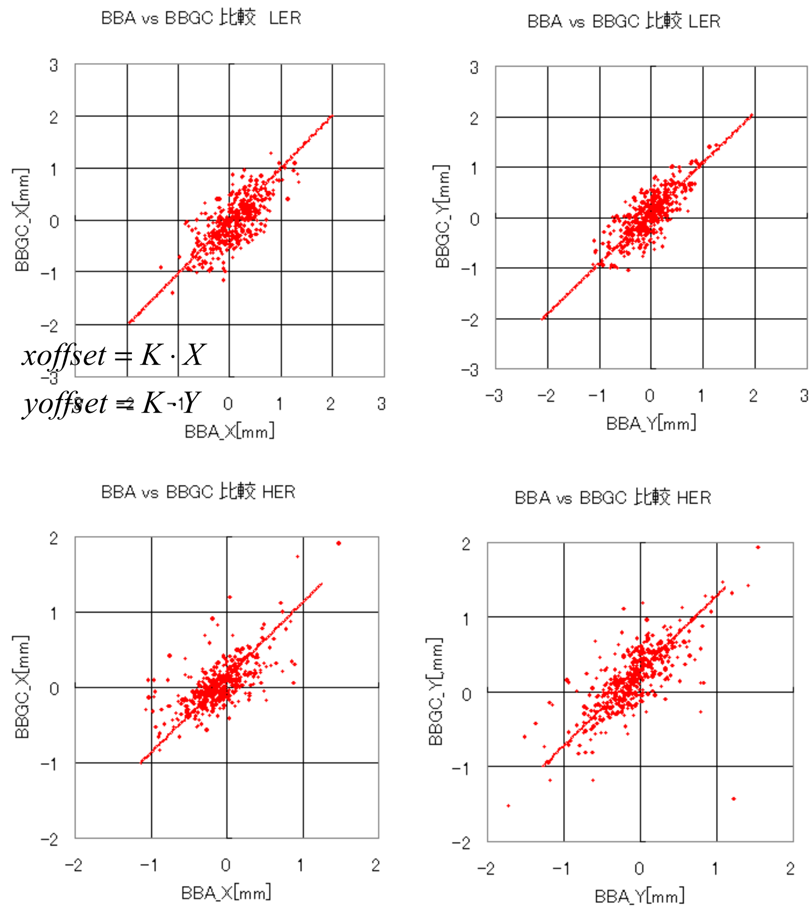
The BPM gains measured by BBGC were also set in the data base for BPM system

# Correlation in the offset between BBA and BBGC

$$x_{offset} = K \cdot \frac{1 - 1/g_2 - 1/g_3 + 1/g_4}{1 + 1/g_2 + 1/g_3 + 1/g_4}$$

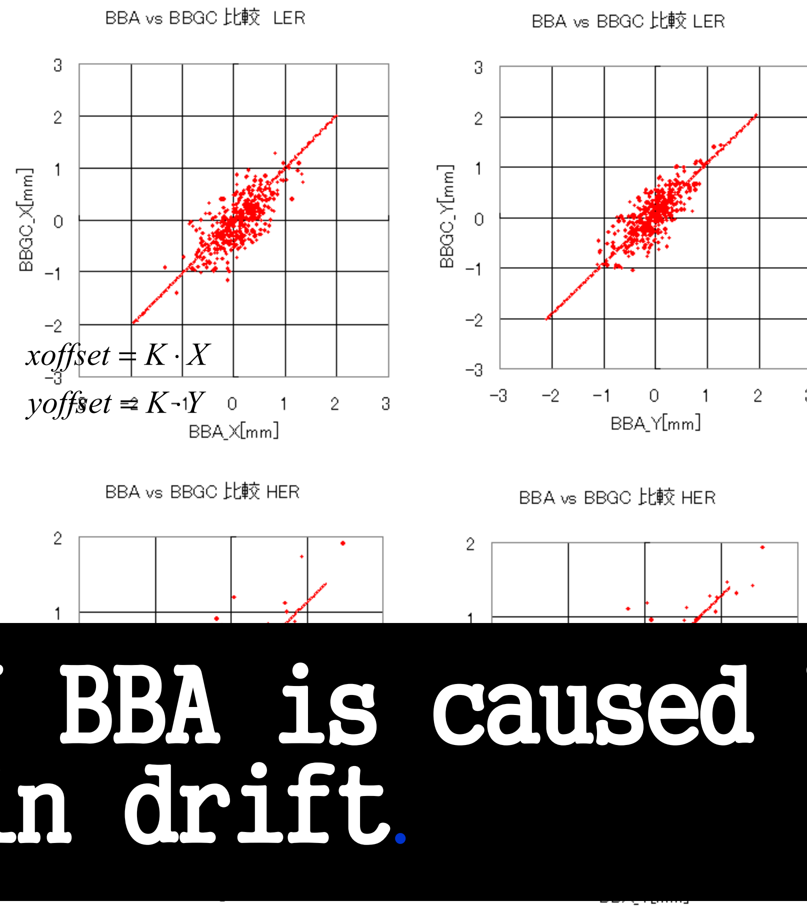
$$y_{offset} = K \cdot \frac{1 + 1/g_2 - 1/g_3 - 1/g_4}{1 + 1/g_2 + 1/g_3 + 1/g_4}$$

K is coefficient to position




We converted the measured value of BPM gain into BPM offset value, and tried to compare the offset with the offset from BBA.

# Correlation in the offset between BBA and BBGC

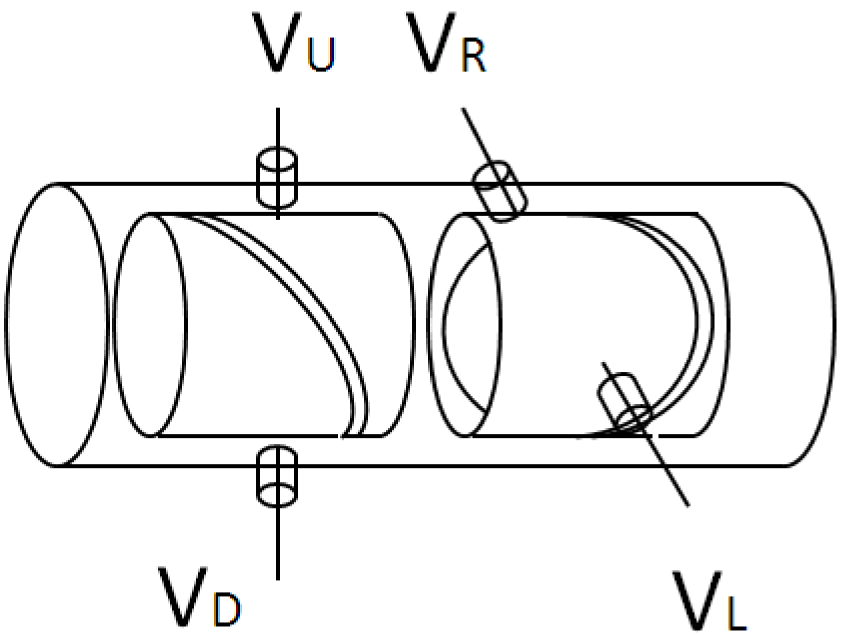



$$xoffset = K \cdot X$$

$$yoffset = K \cdot Y$$

**Some part of BBA is caused by gain drift.**

# BPM head with diagonal cut in J-PARC MR

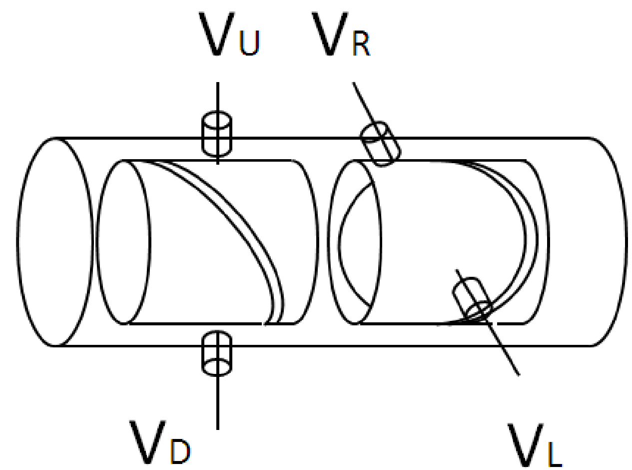



The horizontal and vertical beam positions are independently detected by two pairs of pickup

# Output of diagonal cut electrodes

$$V_L = \lambda\left(1+\frac{x}{a}\right),\quad V_R = g_R\lambda\left(1-\frac{x}{a}\right),$$

$$V_D = g_D\lambda\left(1-\frac{y}{a}\right),\quad V_U = g_U\lambda\left(1-\frac{y}{a}\right),$$




$\lambda$: proportional factor to beam current
$a$: radius of diagonal cut cylinder
$g_R$, $g_U$, $g_D$: relative gain to the $g_L$
$x$, $y$: beam position

By eliminate $\lambda$, $x$, $y$ and $a$

$$V_L = -\frac{V_R}{g_R} + \frac{V_U}{g_D} + \frac{V_D}{g_D}$$

# Expression of m times measurement

Matrix representation

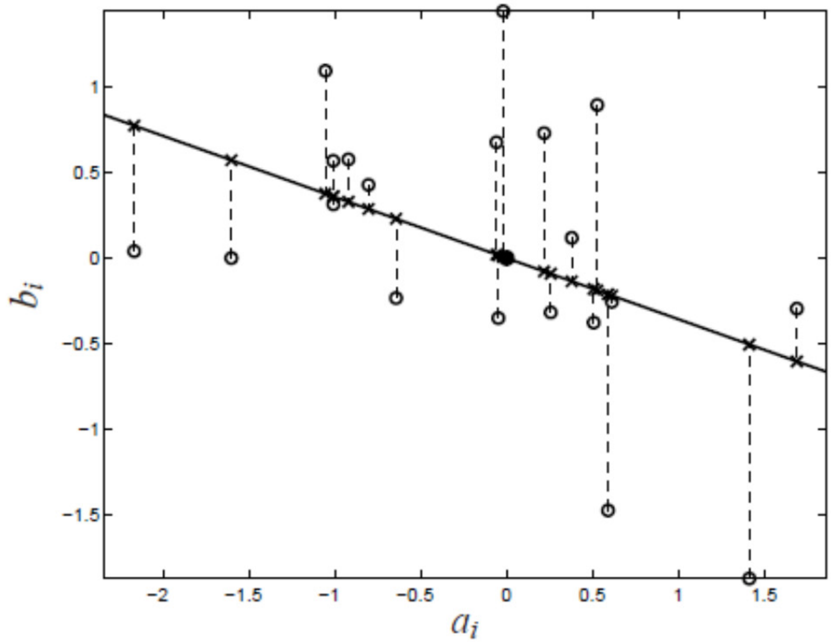
$$\boldsymbol{Ax} = \boldsymbol{b}$$

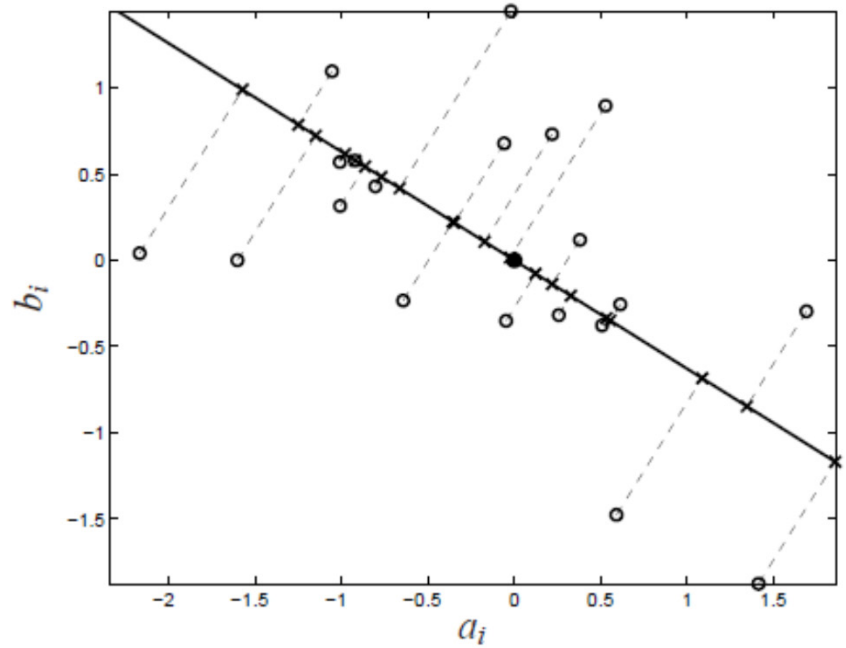
$$\boldsymbol{A} = \begin{pmatrix} -V_{R,1} & V_{U,1} & V_{D,1} \\ & \vdots & \\ -V_{R,j} & V_{U,1} & V_{D,j} \\ & \vdots & \\ -V_{R,m} & V_{U,m} & V_{D,m} \end{pmatrix} \quad \boldsymbol{x} = \begin{pmatrix} 1/g_R \\ 1/g_U \\ 1/g_D \end{pmatrix} \quad \boldsymbol{b} = \begin{pmatrix} V_{L,1} \\ \vdots \\ V_{L,j} \\ \vdots \\ V_{L,m} \end{pmatrix}$$

$g_L=1$

# What LS & TLS

Reference:I. Markovsky and S. V. Huffel, Signal Processing 87





$$\Delta r = \sum_{i=1}^{m} \left(-g_R V_{R,i} + g_U V_{U,i} + g_D V_{D,i} - V_{L,i}\right)^2$$

$V_R, V_U, V_D$ have no error , $V_L$ have error

$$\Delta d = \frac{1}{\left\|\boldsymbol{G}_\perp\right\|^2} \sum_{i=1}^{m} \left(-g_R V_{R,i} + g_U V_{U,i} + g_D V_{D,i} - V_{L,i}\right)^2$$

$$G_\perp = \left(-1, -g_R, g_U, g_D\right)$$

Normal vector to the plane in $(V_R, V_U, V_D, V_L)$ space expressed as

$$-g_R V_R + g_U V_U + g_D V_D - V_L = 0$$

# Linear least squares

## Least squares

Put the $A^T$ to both sides

$$A^T A x = A^T b$$

Put the $[A^T A]^{-1}$ to both sides

$$\underbrace{\left[A^T A\right]^{-1} A^T A}_{=I} x = \left[A^T A\right]^{-1} A^T b$$

$$x_{LS} = \left(A^T A\right)^{-1} A^T b$$

$A$ have no error , $b$ have error

## Total least squares

$$A^T A x = A^T b$$

$$\left[A^T A - \sigma^2 I\right] x = A^T b$$

Put the $[A^T A - \sigma^2 I]^{-1}$ to both sides

$$x_{TLS} = \left[\left(A^T A\right)^{-1} - \sigma^2 I\right]^{-1} A^T b$$

$\sigma$ : the smallest singular value of $[Ab]$

$I$: unit matrix

$A^T$ : transposed matrix of $A$

$A$ and $b$ have error

# Simulation of LS & TLS

**For the simulation,**
**The gains set $g_R$=1.01,$g_U$=1.005,$g_D$=0.975**

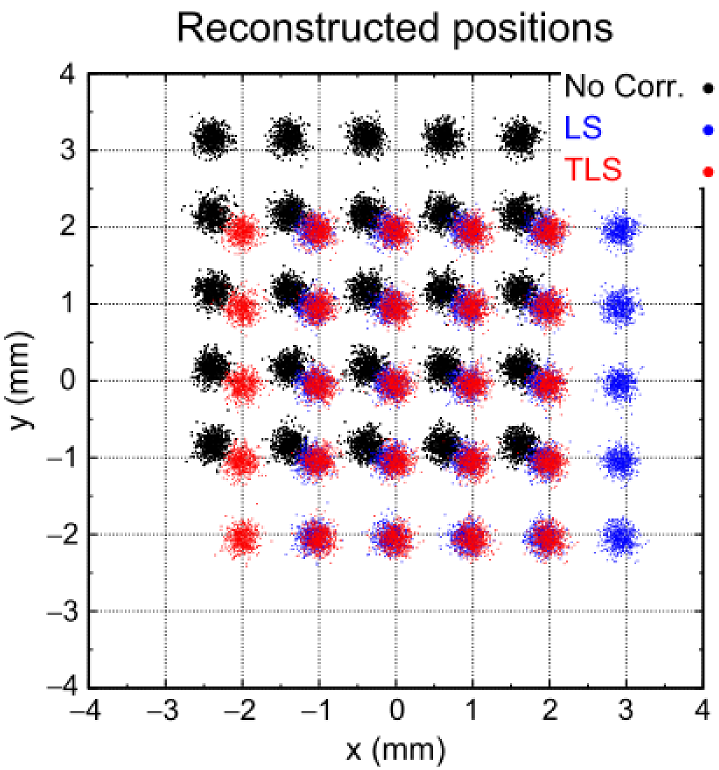
$$V_L = \lambda\left(1+\frac{x}{a}\right), \quad V_R = g_R\lambda\left(1-\frac{x}{a}\right),$$
$$V_D = g_D\lambda\left(1-\frac{y}{a}\right), \quad V_U = g_U\lambda\left(1-\frac{y}{a}\right),$$

5x5=25 positions with 0.2% Gausssian noise.
=>12500 points

Simulation result

| | $g_R$ | $g_U$ | $g_D$ |
|---|---|---|---|
| True | 1.01 | 1.005 | 0.975 |
| LS | 1.034 | 1.015 | 0.988 |
| TLS | 1.012 | 1.005 | 0.977 |

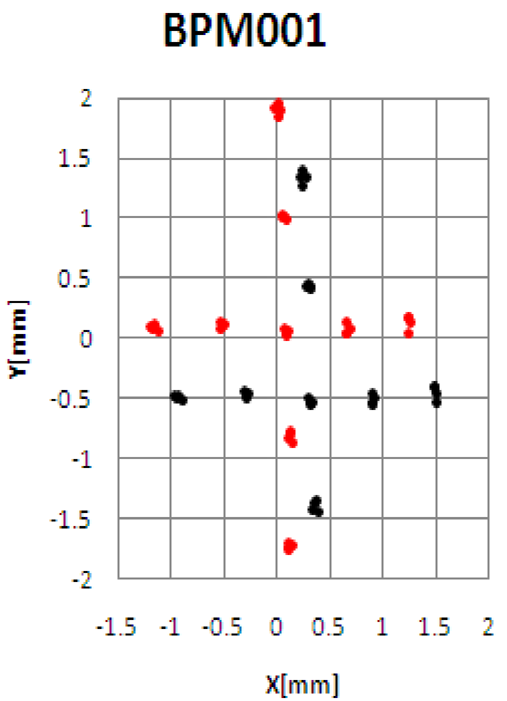
**Reconstruted mapping data .**
**Black is Position(x,y) without correction**
**Red is (x,y) with TLS correction**

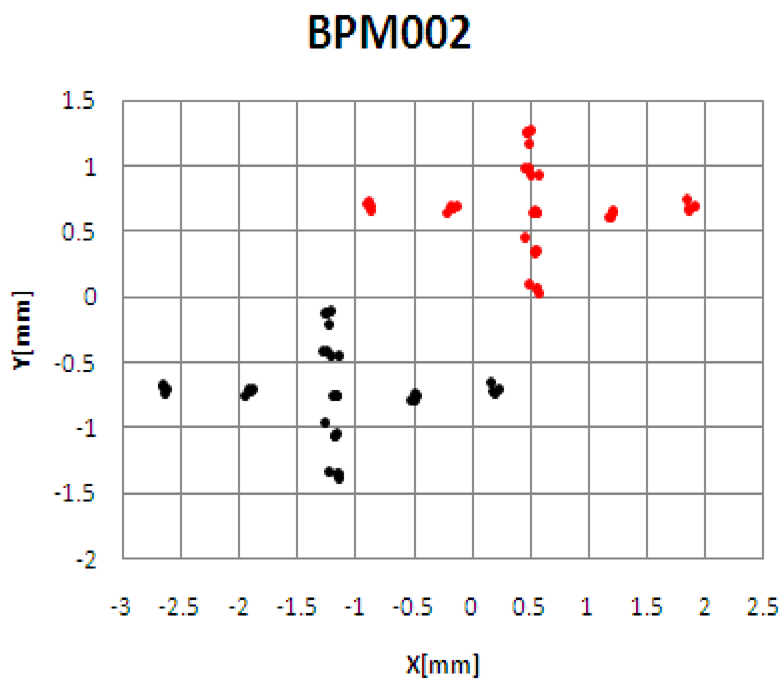



TLS method indicate d good reproducibility of gains

# Beam test

Output data in nine displacements of beam positions at a BPM.



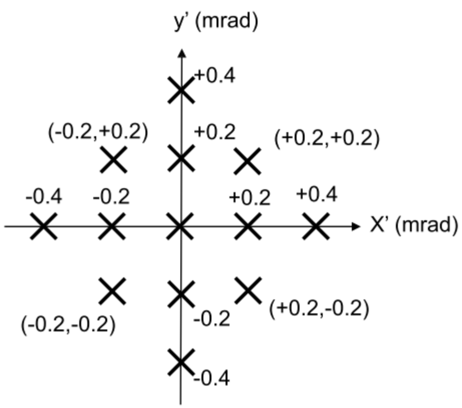




Reconstructed mapping data.
Red: (x, y) without correction,
Black: (x, y) with TLS gains

| BPM001 | $g_L$ | $g_U$ | $g_D$ |
|---|---|---|---|
| TLS | 1.0062 | 1.0024 | 0.9873 |
| LS | 1.0103 | 1.0045 | 0.9892 |
| BPM002 | $g_L$ | $g_U$ | $G_D$ |
| TLS | 0.9568 | 0.9811 | 0.9463 |
| LS | 0.9617 | 0.9838 | 0.9487 |

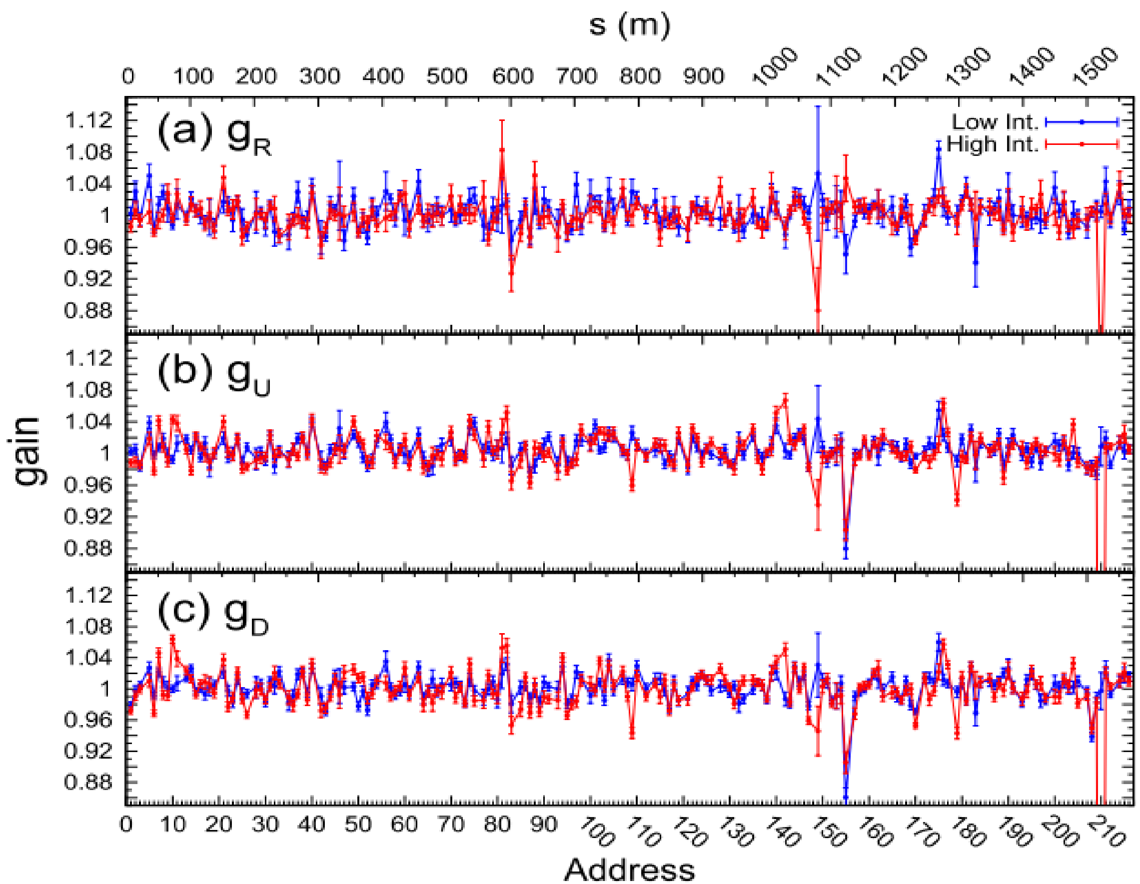
$\Delta g \approx 0.5\%$ Difference in the relative gains between LS and TLS

# Result of the relative gains of all BPMs in J-Parc MR




Kick angles of the steering magnets

To obtain the data with mapped beam positions




Blue: Low intensity as $10^{13}$[PPP]
Red: High intensity as $10^{14}$[PPP]

# Evaluation of gain correction

## 4 buttons pickups at the KEKB

- Beam position calculation from the 4 outputs

$$X = \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4}, \quad Y = \frac{V_1 + V_2 - V_3 - V_4}{V_1 + V_2 + V_3 + V_4}$$

Normalization

$$\boxed{x = F_X(X,Y),\ y = F_Y(X,Y)}$$

$$F_X(X,Y) = a_0 + a_1X + a_2Y + a_3X^2 + a_4XY + a_5Y^2 + a_6X^3 + a_7X^2Y + a_8XY^2 + a_9Y^3$$

$$F_Y(X,Y) = b_0 + b_1X + b_2Y + b_3X^2 + b_4XY + b_5Y^2 + b_6X^3 + b_7X^2Y + b_8XY^2 + b_9Y^3$$

3rd order polynominals

The coefficients ( $a_n$, $b_n$ ) are obtained by fitting of the mapping data.

# Four Positions by selected 3 outputs

The beam position is also obtainable from the output voltage of any three electrodes chosen out of four electrodes.

$$\begin{cases} X_1 = (V_1 - V_2)/(V_1 + V_2),\ X_2 = (V_3 - V_4)/(V_3 + V_4) \\ Y_1 = (V_2 - V_3)/(V_2 + V_3),\ Y_2 = (V_1 - V\ )/(V_1 + V_4) \end{cases}$$

Normalization

$$\begin{cases} (x_1, y_1) = \left(F_X^{ABC}(X_1, Y_1),\ F_Y^{ABC}(X_1, Y_1)\right) \\ (x_2, y_2) = \left(F_X^{BCD}(X_2, Y_1), F_Y^{BCD}(X_2, Y_1)\right) \\ (x_3, y_3) = \left(F_X^{ACD}(X_2, Y_2), F_Y^{ACD}(X_2, Y_2)\right) \\ (x_4, y_4) = \left(F_X^{ABD}(X_1, Y_2), F_Y^{ABD}(X_1, Y_2)\right) \end{cases}$$

3rd order polynominals

$$\begin{cases} \sigma_X = \sqrt{\frac{1}{4}\sum_{i=1}^{4}\left(X_i - \overline{X}\right)^2} \quad with \quad \overline{\mathrm{X}} = \frac{1}{4}\sum_{i-1}^{4}(X_i) \\ \sigma_Y = \sqrt{\frac{1}{4}\sum_{i=1}^{4}\left(Y_i - \overline{Y}\right)^2} \quad with \quad \overline{\mathrm{Y}} = \frac{1}{4}\sum_{i-1}^{4}(Y_i) \end{cases}$$

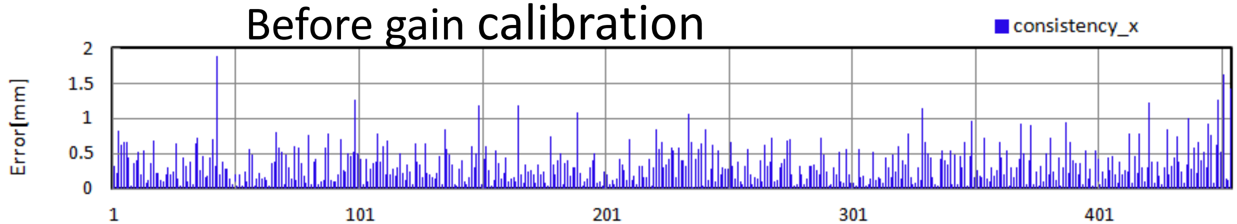
Consistency error

If the four outputs have ideal correlation,
(($x_1$, $y_1$), ($x_2$, $y_2$), ($x_3$, $y_3$), ($x_4$, $y_4$)) should coincide with each other.

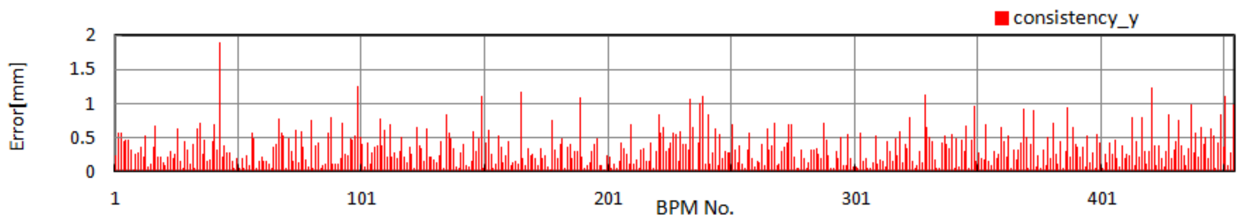
# Consistency error in LER at KEKB

Before gain calibration

Cons.Err.(X)

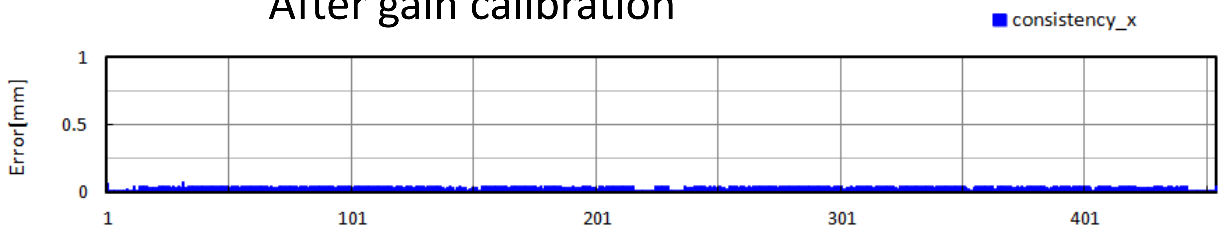



Cons.Err.(Y)

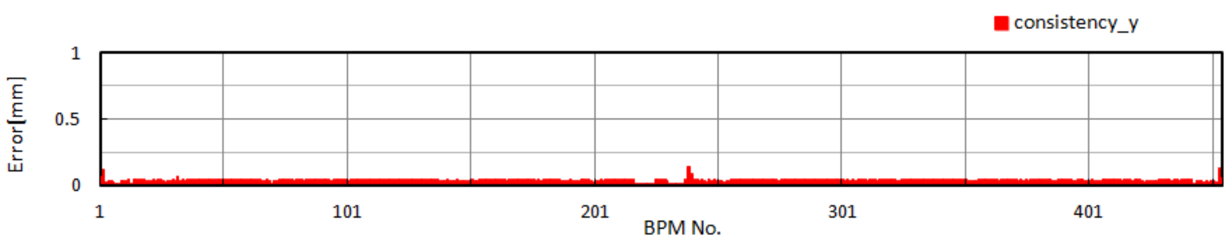



After gain calibration

Cons.Err.(X)




Cons.Err.(Y)




The consistency error became very small

# Four positions of diagonal cut pickups at J-PARC

$$x_1 = \frac{V_L - V_R/g_R}{V_L + V_R/g_R} a, \quad y_1 = \frac{V_U/g_U - V_D/g_\mathrm{D}}{V_U/g_U + V_D/g_\mathrm{D}} a$$

$$x_2 = \frac{V_L - V_R/g_R}{V_U/g_U + V_D/g_\mathrm{D}} a, \quad y_2 = \frac{V_U/g_U - V_D/g_\mathrm{D}}{V_L + V_R/g_R} a$$

$$x_3 = \left( \frac{2V_L}{V_U/g_U + V_D/g_\mathrm{D}} - 1 \right) a, \quad y_3 = \left( \frac{2V_U/g_U}{V_L + V_R/g_R} - 1 \right) a$$

$$x_4 = \left( \frac{-2V_R/g_R}{V_U/g_U + V_D/g_\mathrm{D}} + 1 \right) a, \quad y_4 = \left( \frac{-2V_D/g_\mathrm{D}}{V_L + V_R/g_R} + 1 \right) a$$

$$\begin{cases} \sigma_X = \sqrt{\frac{1}{4}\sum_{i=1}^{4}\left(X_i - \overline{X}\right)^2} \quad with \quad \overline{\mathrm{X}} = \frac{1}{4}\sum_{i-1}^{4}\left(X_i\right) \\ \sigma_Y = \sqrt{\frac{1}{4}\sum_{i=1}^{4}\left(Y_i - \overline{Y}\right)^2} \quad with \quad \overline{\mathrm{Y}} = \frac{1}{4}\sum_{i-1}^{4}\left(Y_i\right) \end{cases}$$

Consistency error

# Consistency error of the beam test at J-PARC

| | Before | | After | |
|---|---|---|---|---|
| | [mm] | [mm] | [mm] | [mm] |
| BPM001 | 0.524 | 0.518 | 0.018 | 0.018 |
| BPM002 | 0.964 | 0.954 | 0.025 | 0.025 |

Consistency error before and after gain calibration of BPMs at J-PARC MR

# Conclusions

- We should pay special attention to guarantee the precise measurement of beam positions over a long time.
- The BBA calibration is necessary for correction of the BPM offset error.
- The BBGC is also important for correction of the imbalanced gains among four outputs of a BPM.

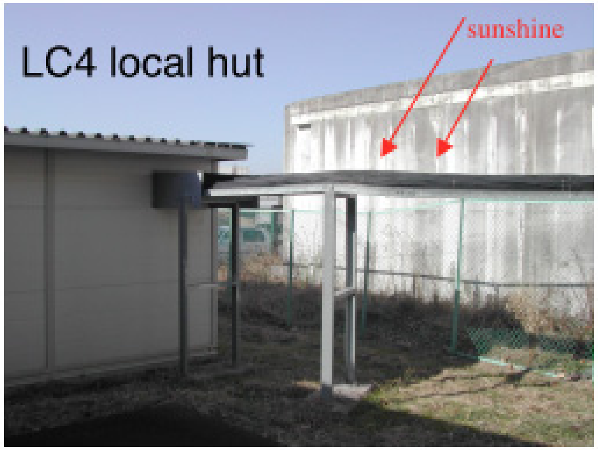
**We have realized a high-precision BPM system by monitoring the consistency error and applying the beam-based gain calibration**

Thank you for your attention

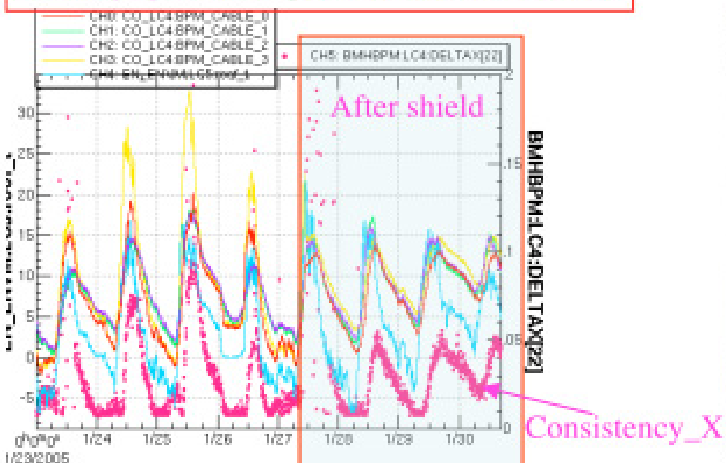
# Diurnal variation of BPM consistency

Increasing the temperature made impedance of coaxial cable drift.

- BPM signal cables were installed from ground level to tunnel.
- Part of the total cable length are cabled in outdoor area.
- Effect of air temperature and sunshine caused the diurnal variation of BPM consistency.
- To avoid sunshine, cables are wrapped by the insulating sheet.




Yellow & red line: temperature over the cable rack
Blue & purple line: temperature under the cable rack




Temperature & consistency

Wrapping by using insulating sheet