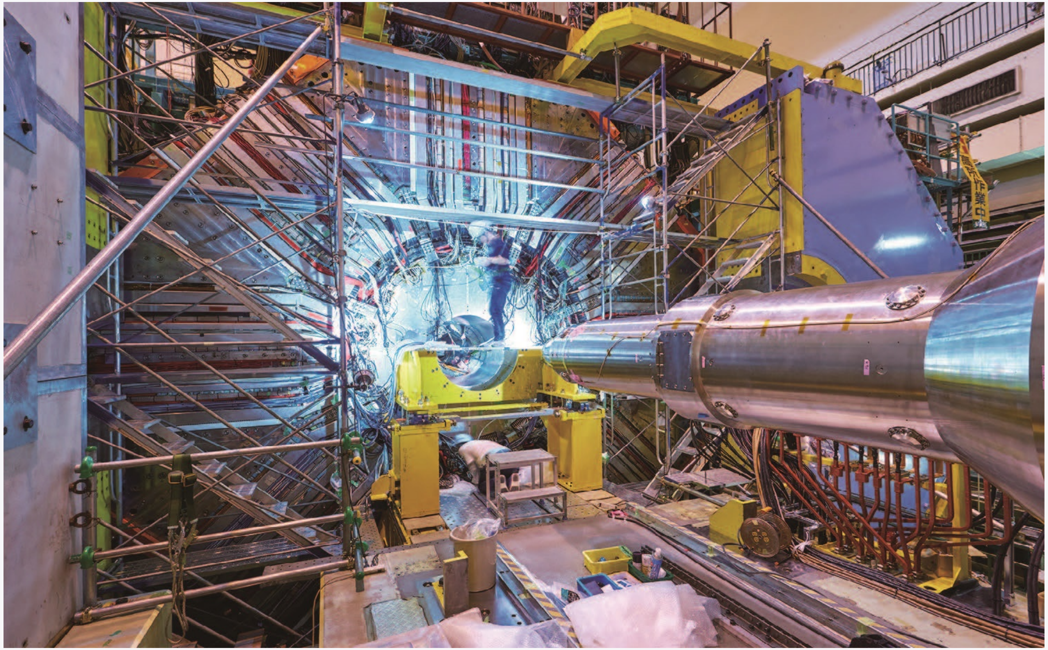
Optics Measurement at SuperKEKB

using Beam Based Calibration for BPM and BBA



Hiroshi Sugimoto

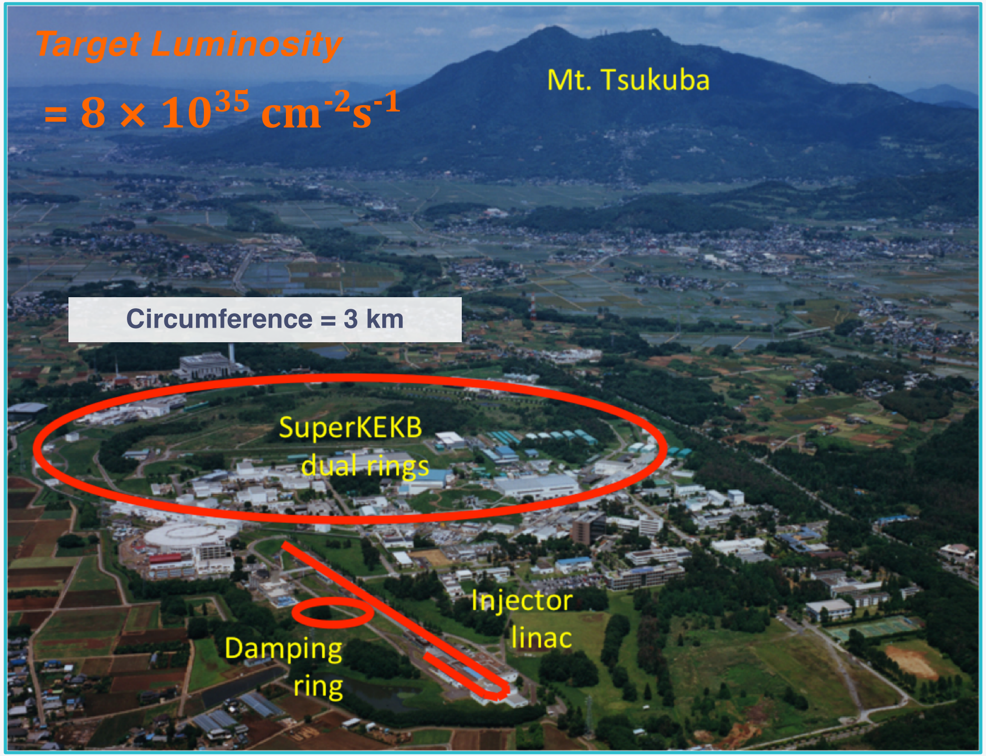
SuperKEKB

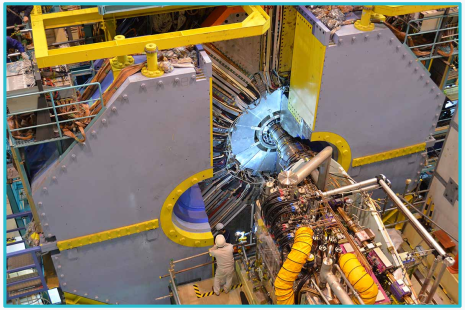
Beam Optics&Commissioning Group

KEK Unravelling the mysteries of matter, life and the universe.

SuperKEKB

- An electron-positron circular collider to open up new luminosity frontier.





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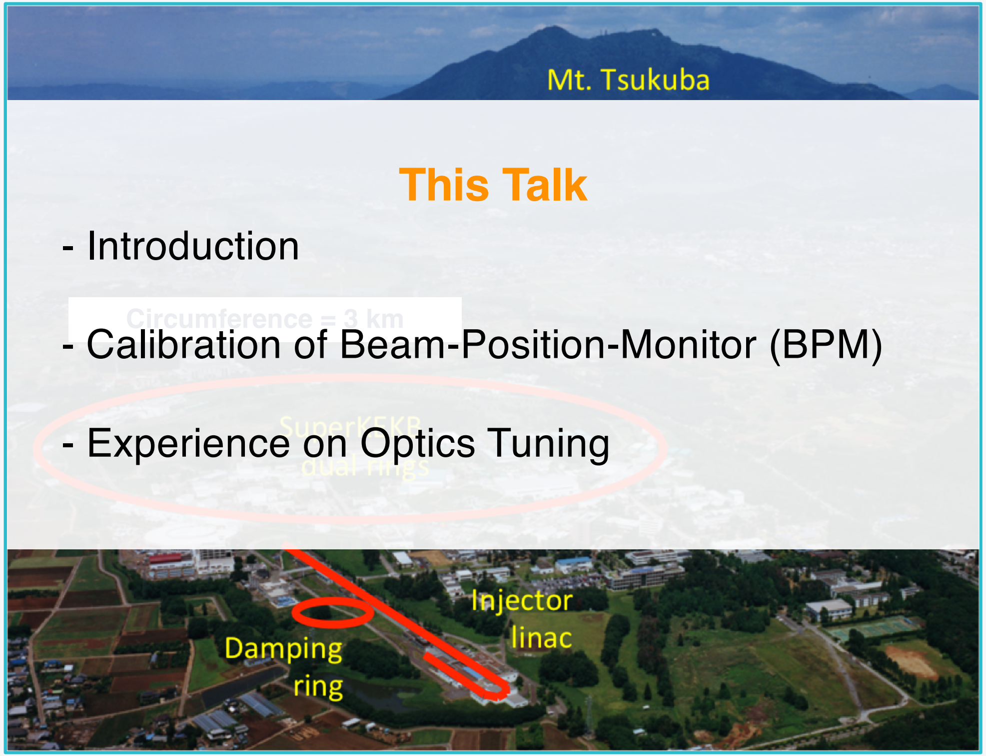
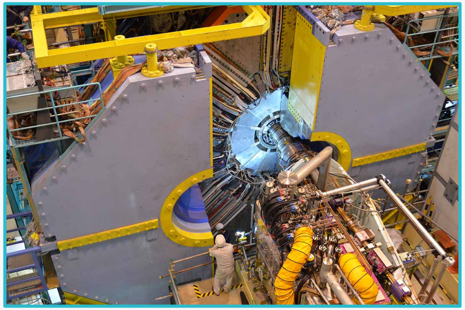


This Talk

- Introduction
- Calibration of Beam-Position-Monitor (BPM)
- Experience on Optics Tuning



SuperKEKB

Feb. 2016 ~ July 2016

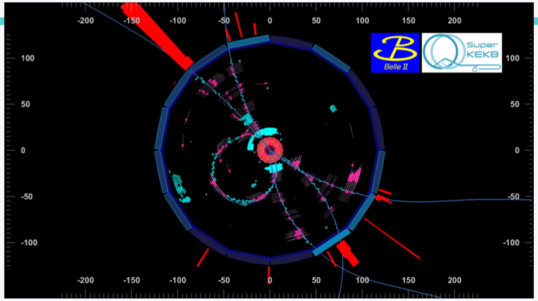
Basic tuning W/O beam collision

→ March 2018 ~ July 2018

Collision operation was started.

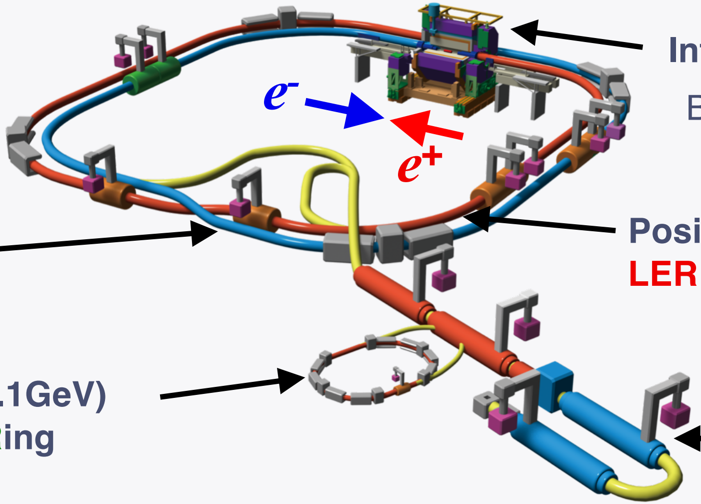
→ March 2019 ~

Continue collision tuning.



The first collision event
April 26th 2018

Find details in **WEYYPLM1**, "Luminosity performance of the SuperKEKB collider" by A. Morita



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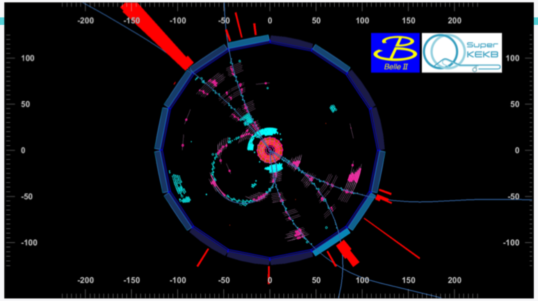

The first collision event
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Find details in WEYYPLM1
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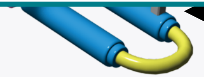
Elec
HER

Pos
DR = Positron Damping Ring



Injector Linac

- SuperKEKB is a very challenging machine.
- Reliable (BPM) system is essential.
    - For precise beam orbit control
    - For optics tuning including low emittance tuning

BPM Calibration
with Beam Measurements

BPM System and Its Calibration

- All quadrupole magnets have BPM. (~900 BPMs should be calibrated!)
  - Based on 509 MHz narrow band detectors (LER)
  - Based on 1 GHz narrow band detectors (HER)
- Averaging mode of 0.25 Hz is mainly used in optics measurement.
- More than 100 BPMs can be used with gated turn-by-turn mode.
  - Very helpful in the injection tuning.
- Two calibration parameters are determined by beam measurement.

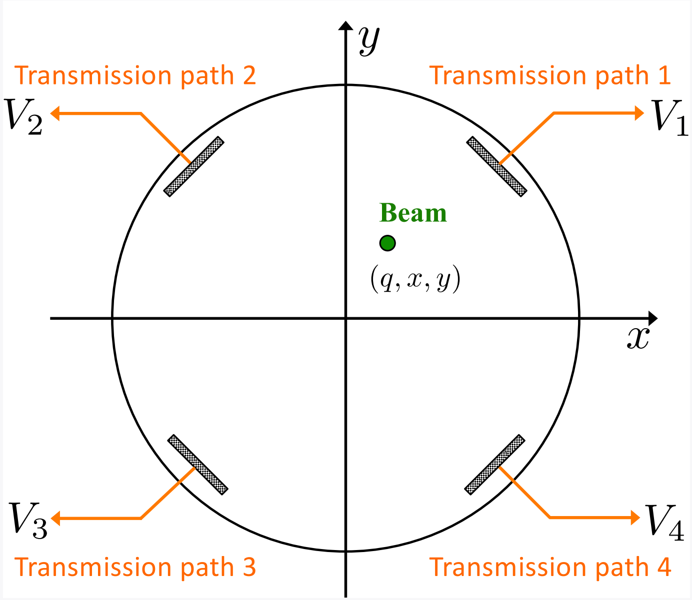
- Gain factor of the BPM electrodes.

- Offset of the BPM reading.

Gain Calibration of BPM Electrodes

BPM Model

- Detect four output voltages from pickup electrodes.



- Normalized voltages

$$u = \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4}$$

$$v = \frac{V_1 + V_2 - V_3 - V_4}{V_1 + V_2 + V_3 + V_4}$$

- Beam position using mapping functions

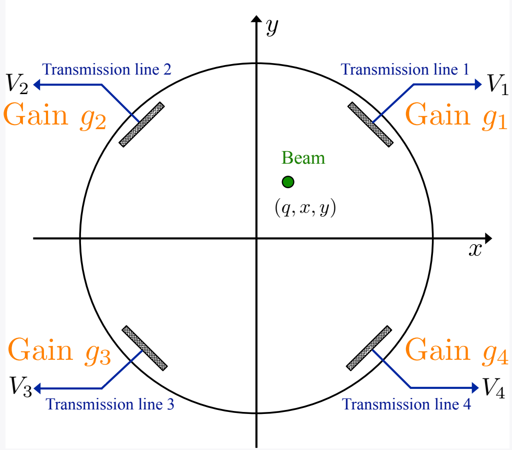
$$x = F_x(u, v) \quad y = F_y(u, v)$$

The mapping functions are obtained numerically with an 2D-electrostatic BPM model.

- The detected voltages depend on the electrical characteristic of the transmission lines also.

BPM Gain Calibration

- Introduce *" Gain Factor "* to the model.



$$V_{ij} = g_i \times q_j F_i(x_j, y_j)$$

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

m : # of measured data

q_j : Charge

g_i : Gain

$F_i(x, y)$: Ideal response function

- Minimize a chi-squared so that the model reproduces the measured voltages,

$$\chi^2(\boldsymbol{a}) = \sum_i^4 \sum_j^m \frac{\left[V_{ij} - g_i q_i F_i\left(x_i, y_i\right)\right]^2}{\sigma_{ij}^2}$$

σ_{ij} : Measurement error

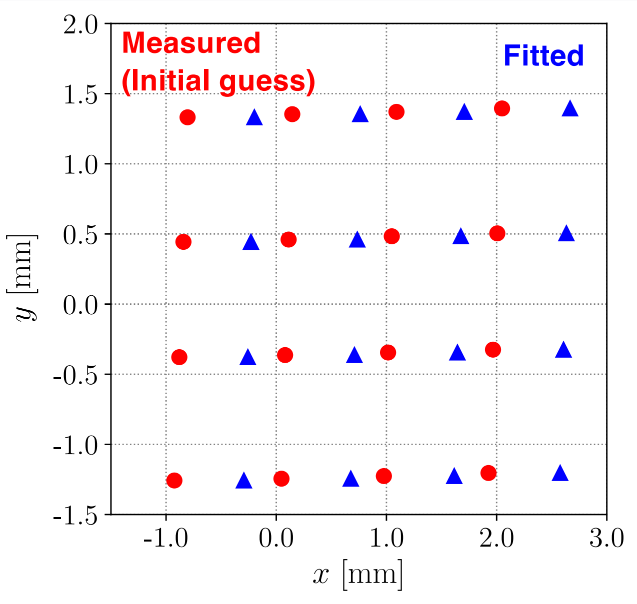
$$g_1 = 1$$

$$\boldsymbol{a} = (g_2, g_3, g_4, q_1, x_1, y_1, \ldots, q_m, x_m, y_m)$$

Fitting variables

Example

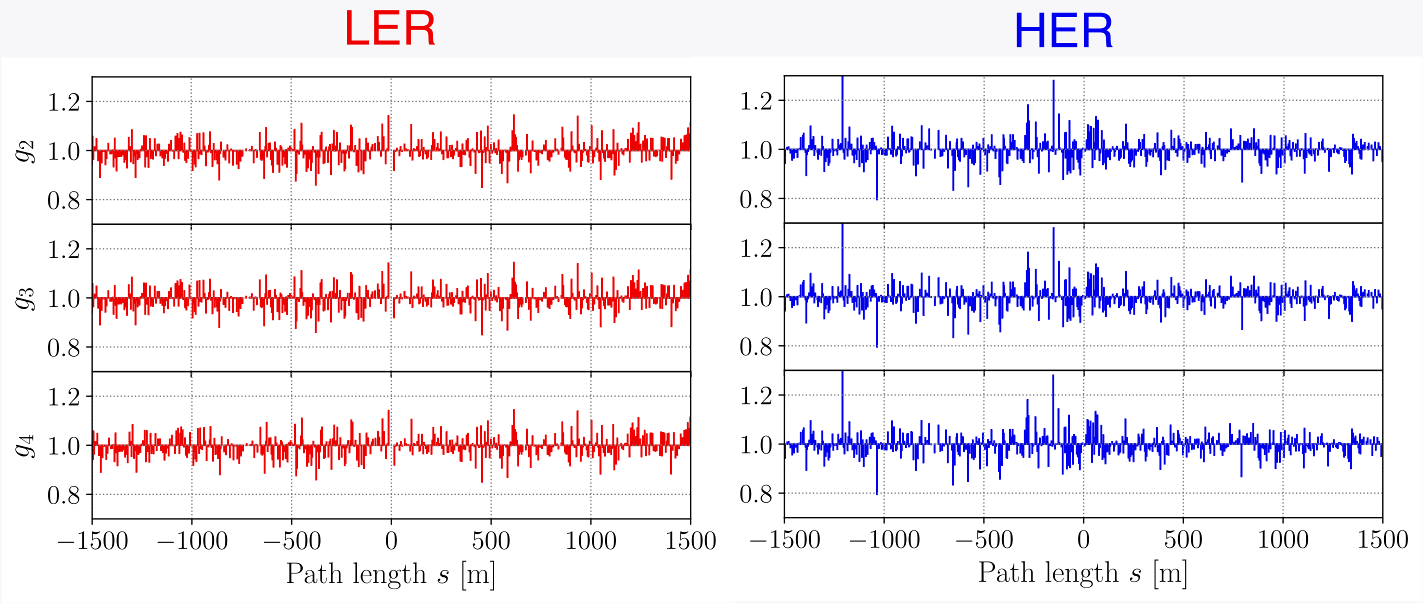
- Record the electrode voltages of BPM while changing beam positions.
- Nonlinear fitting using the measured beam position as an initial guess of the fitting variables.



Fitting Result

$$\chi^2 = 1.3$$
$$g_2 = 0.994$$
$$g_3 = 1.031$$
$$g_4 = 0.987$$

Results in LER and HER Rings



- The chi-squared is converged within 10~20 numerical iterations without adjusting the fitting parameters.
- The gain imbalance is ~5 % in the RMS sense.

Consistency Check between Real an Model BPMs

- Beam position is normally evaluated by using all four electrodes.
- Possible to calculate the beam position with only 3 electrodes.

(x_a, y_a) : ← Obtained with 1,2,3 -th electrode signals.

(x_b, y_b) : ← 2,3,4

(x_c, y_c) : ← 3,4,1

(x_d, y_d) : ← 4,1,2

- Define the ***Consistency Error*** by the standard deviation of the 4 beam positions.

$$C_z \equiv \sqrt{\frac{1}{4} \sum_{i=a,b,c,d} (z_i - <z>)^2},$$

$$<z> \equiv \frac{1}{4} \sum_{i=a,b,c,d}^{4} z_i,$$

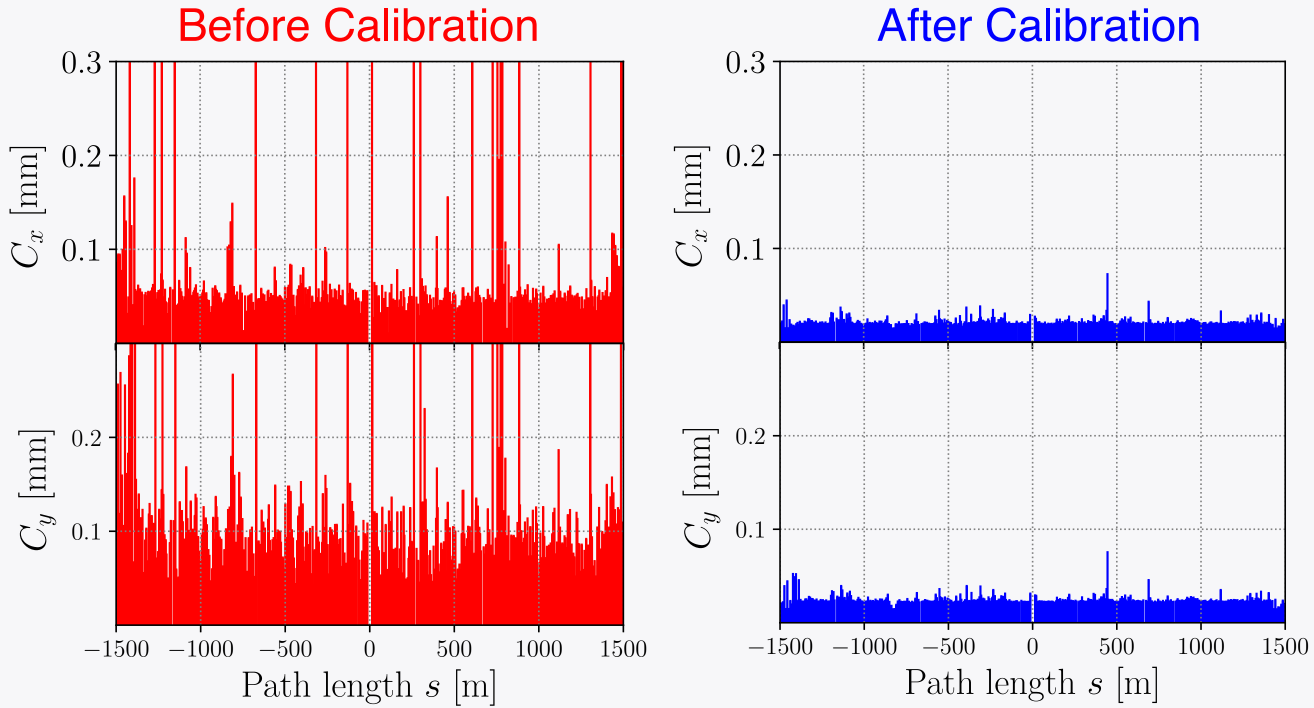
where $z = x$ or y

- For the ideal BPM, those 4 beam positions coincide each other.

$$\longrightarrow C_z = 0$$

Consistency Error of BPMs

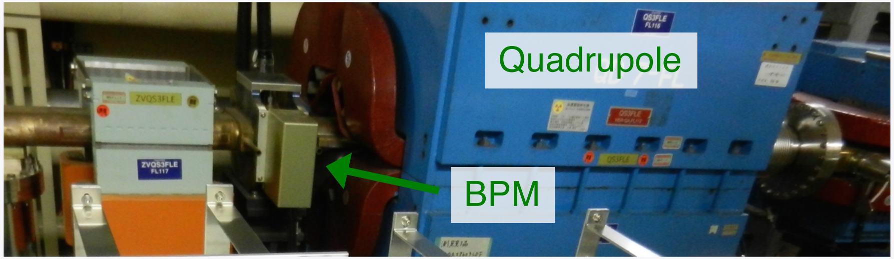
LER



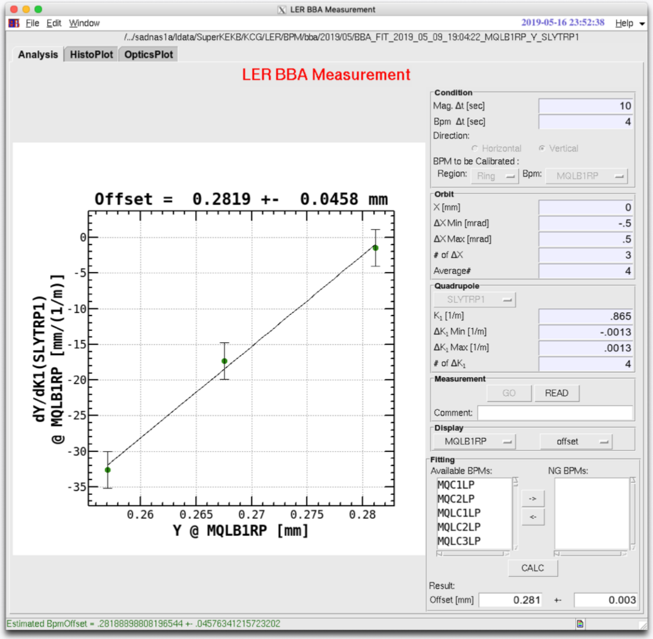
- We routinely monitor the consistency during the operation to detect hardware troubles in the BPM system.

BPM Offset Calibration with Beam Based Alignment (BBA)

Beam-Based Alignment (BBA)



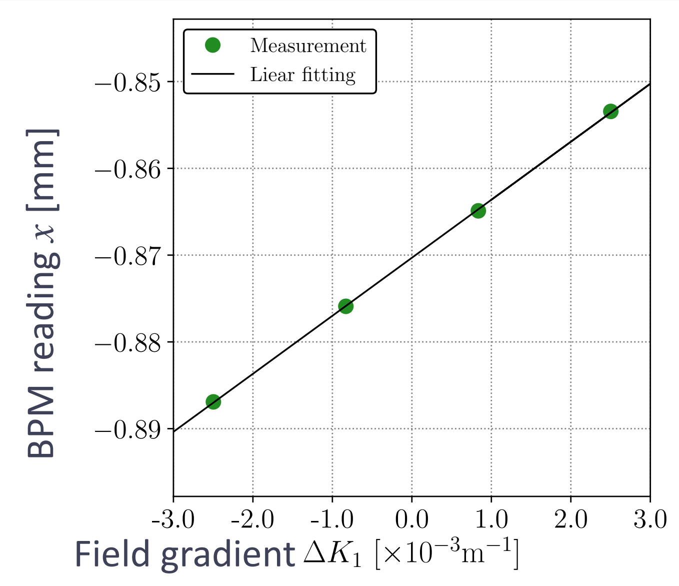
BBA Tool



- Calibrate BPM offset so that the beam passes through the magnetic center of the nearby magnet.
- To do so, we find BPM reading which is insensitive to the field gradient of the magnet.
- We developed a semi-automated software to perform a huge number of BBA measurements.

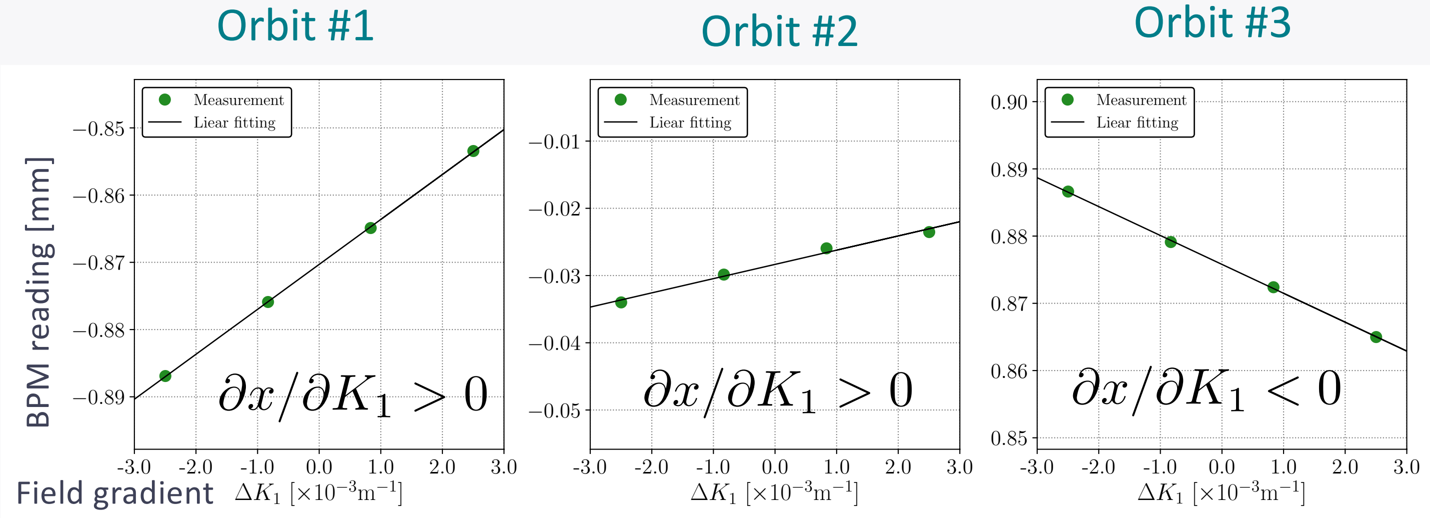
Beam-Based Alignment (BBA)

- Measure the response of BPM reading respect to the field gradient of quadrupole magnet.
- Linear fitting to the measurement data to obtain the slope, $\partial x / \partial K_1$



Beam-Based Alignment (BBA)

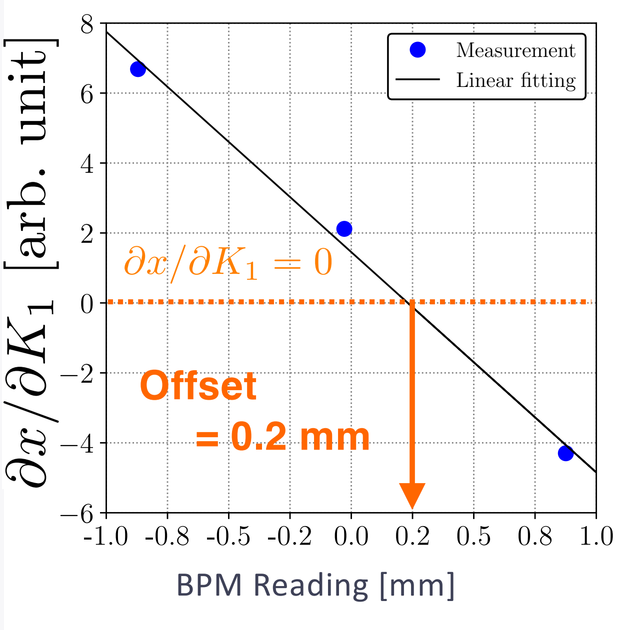
- Measure $\partial x / \partial K_1$ for three different kinds of closed orbits.



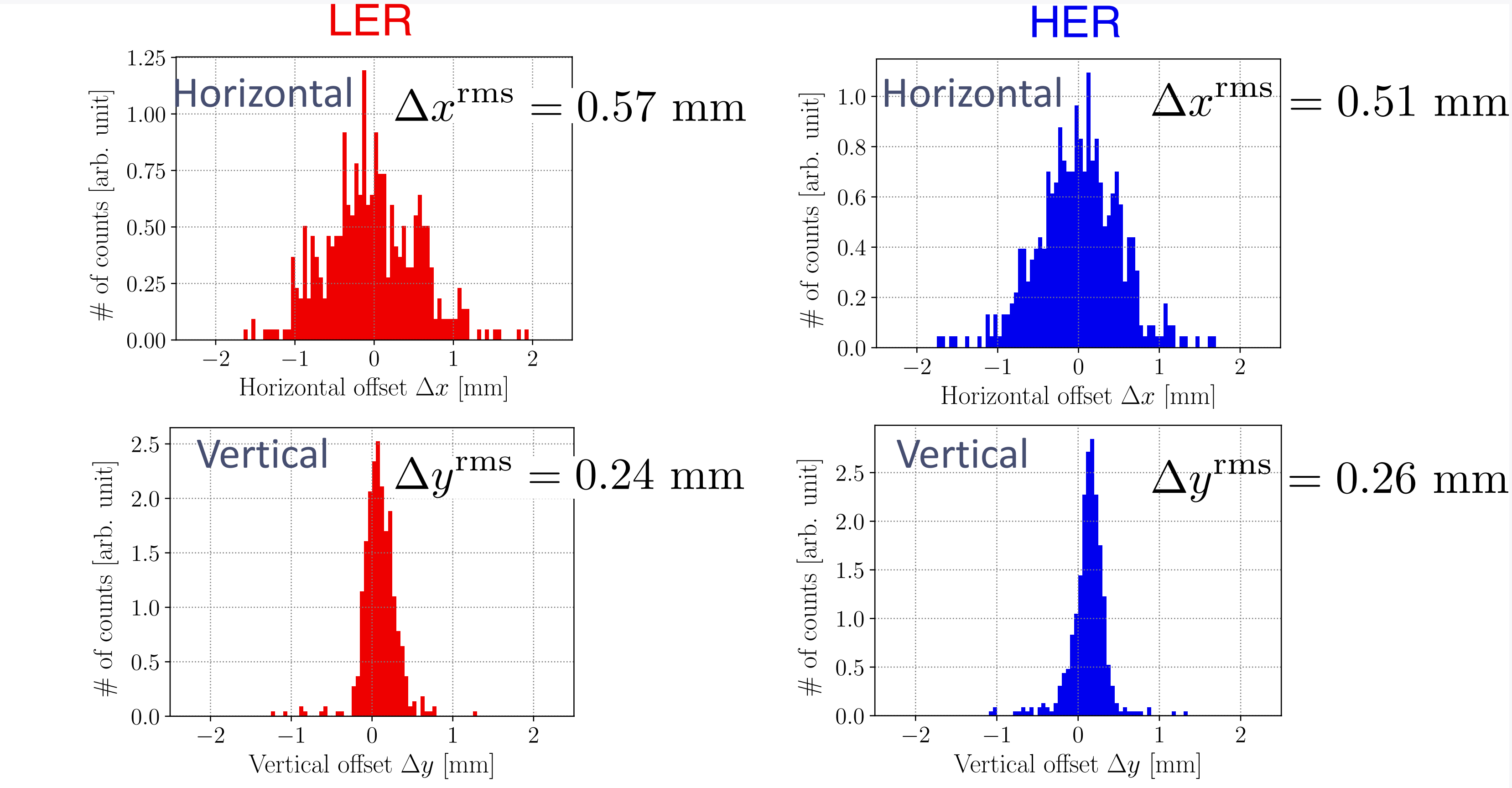
- The magnetic center should be located between Orbit #2 and #3.

Beam-Based Alignment (BBA)

- Find BPM reading which is insensitive to the field gradient of the magnet, that is, $\partial x / \partial K_1 = 0$



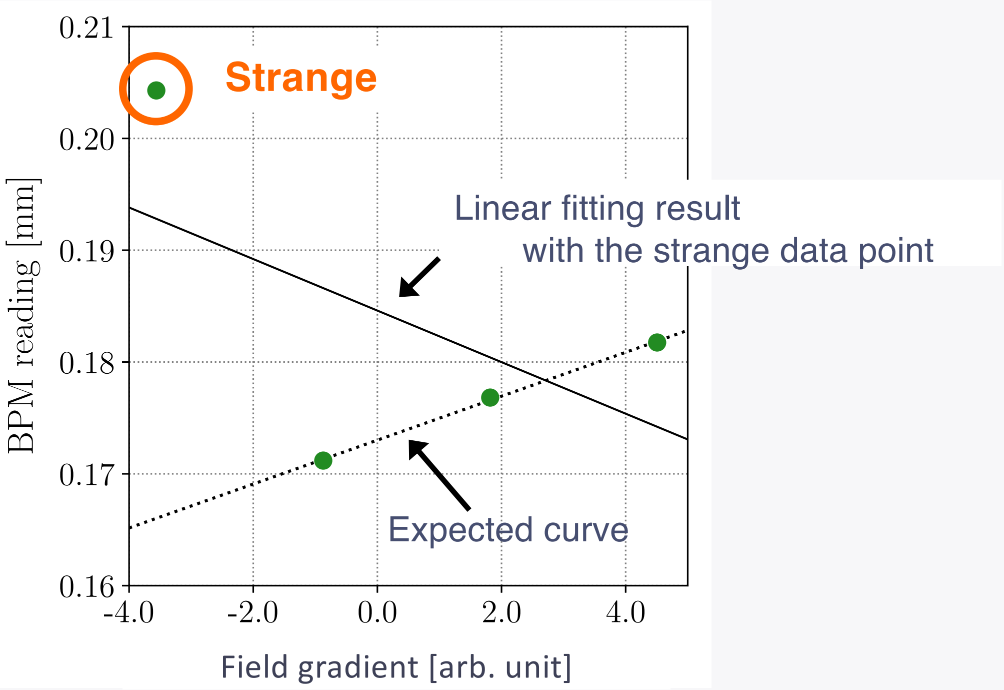
Offset Parameters of the BPM System



Unexpected Observation in BBA

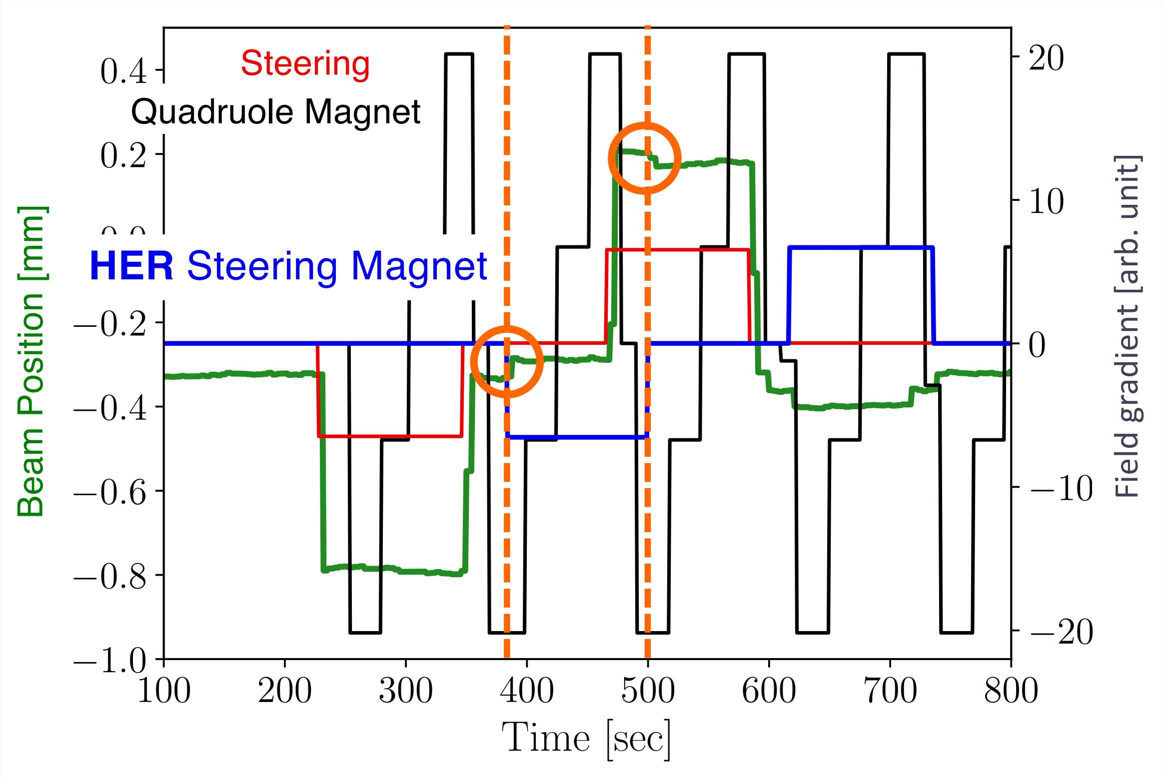
- A strange change of beam position is observed in the BBA measurement.
- It disturbs the BBA measurement.

BBA measurement in LER



Time History

- **HER** steering magnet affects the **LER** beam orbit.



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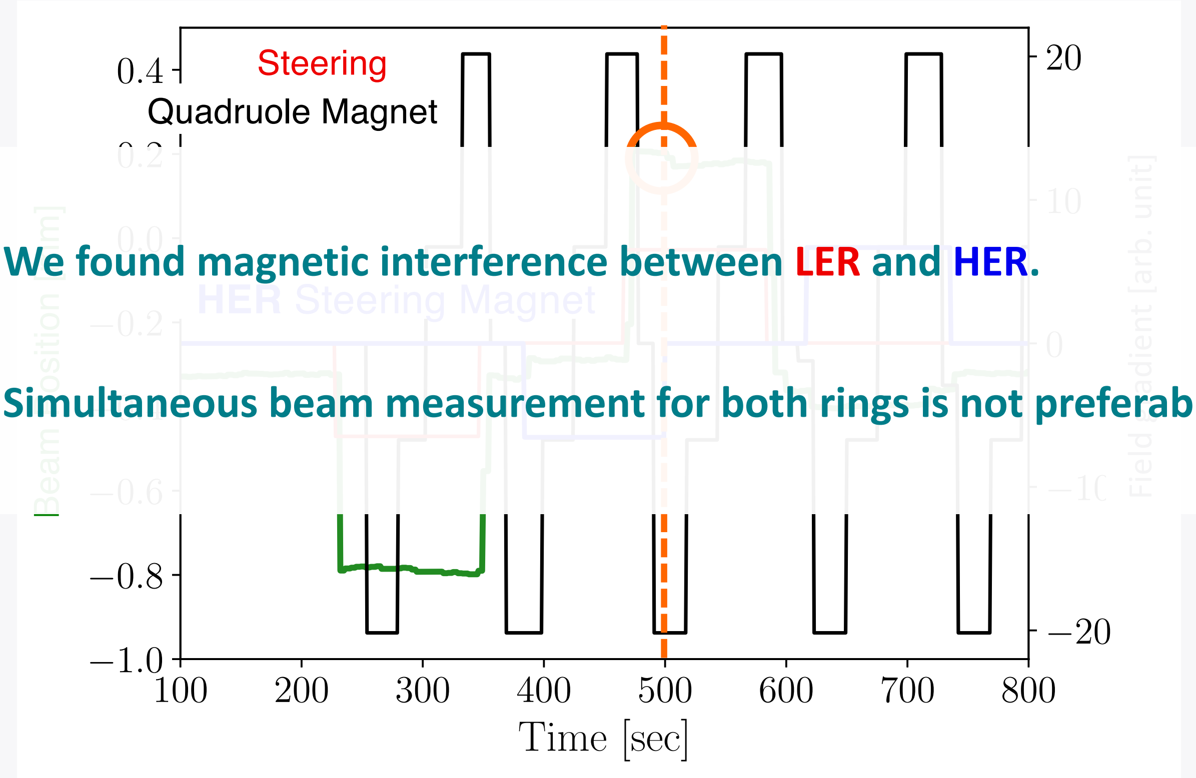


- We found magnetic interference between LER and HER.

- Simultaneous beam measurement for both rings is not preferable.

Optics Measurement and Correction

Measurement Method

- Measurement with orbit response analysis.

  - Beta function:

    Orbit response analysis with DC dipole kicks.

$$\Delta x_i = \frac{\sqrt{\beta_i \beta_0}}{2 \sin \pi \nu} \theta \cos \left(|\phi_i - \phi_0| - \pi \nu \right)$$

  - Dispersion:

    Response with RF frequency change.

$$\eta_x = f_0 \frac{\Delta x}{\Delta f} \xi$$

RF frequency (f_0), Orbit change (Δx), Frequency change (Δf), Phase slip factor (ξ)

- Horizontal-vertical (XY) coupling:

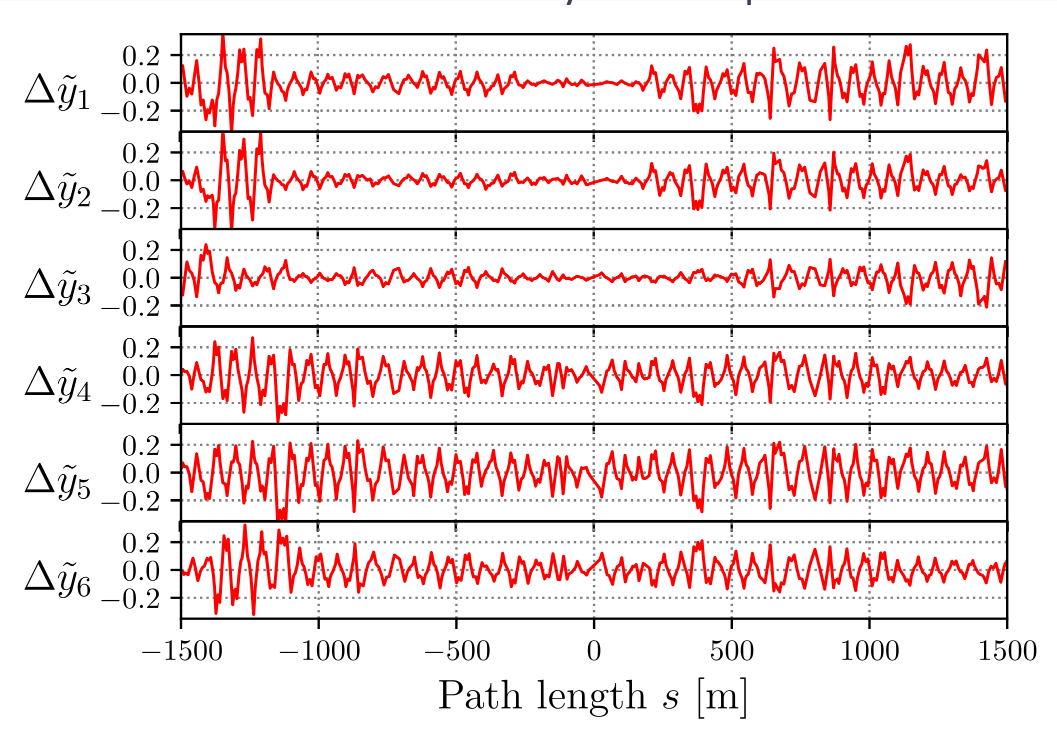
Vertical leakage orbits induced by horizontal dipole kicks.

XY-Coupling *before* Correction

LER

- Six kinds of vertical leakage orbits induced by horizontal dipole kicks.

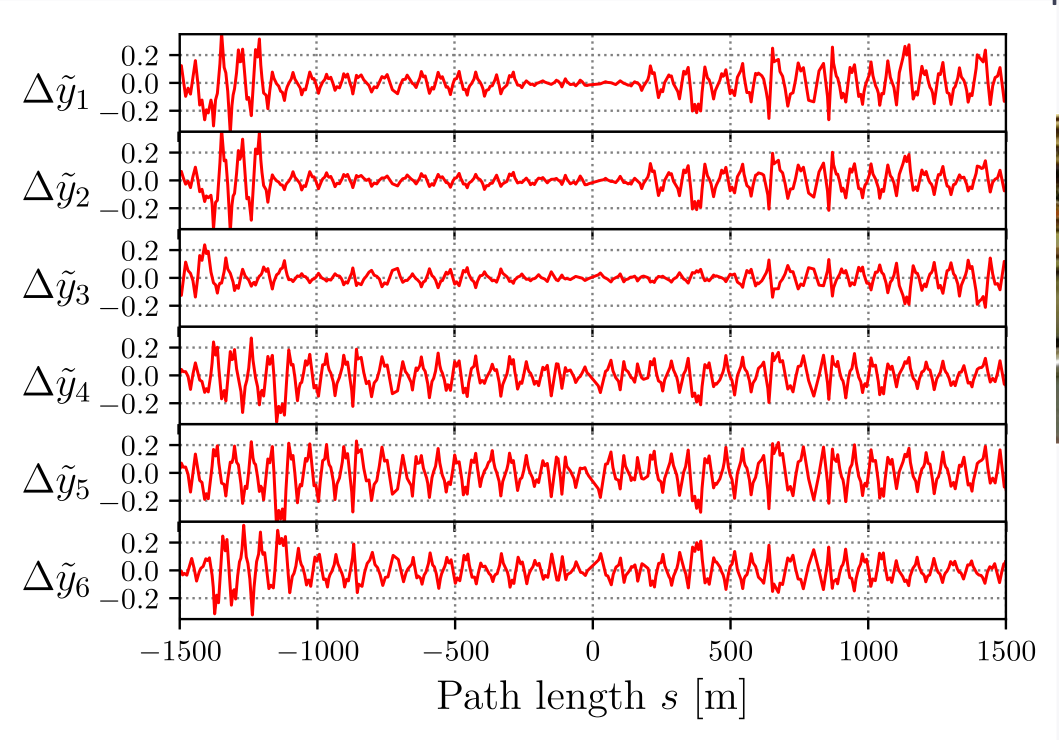
  The vertical axis is normalized by RMS amplitude of the horizontal orbits.

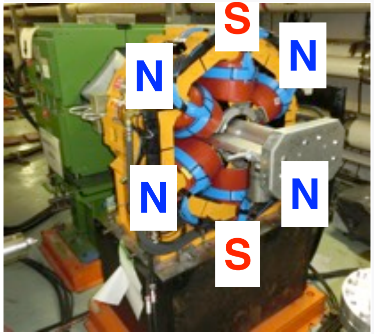


XY-Coupling *before* Correction

LER

- Correction using skew quadrupole coils installed in some of sextupole magnets.

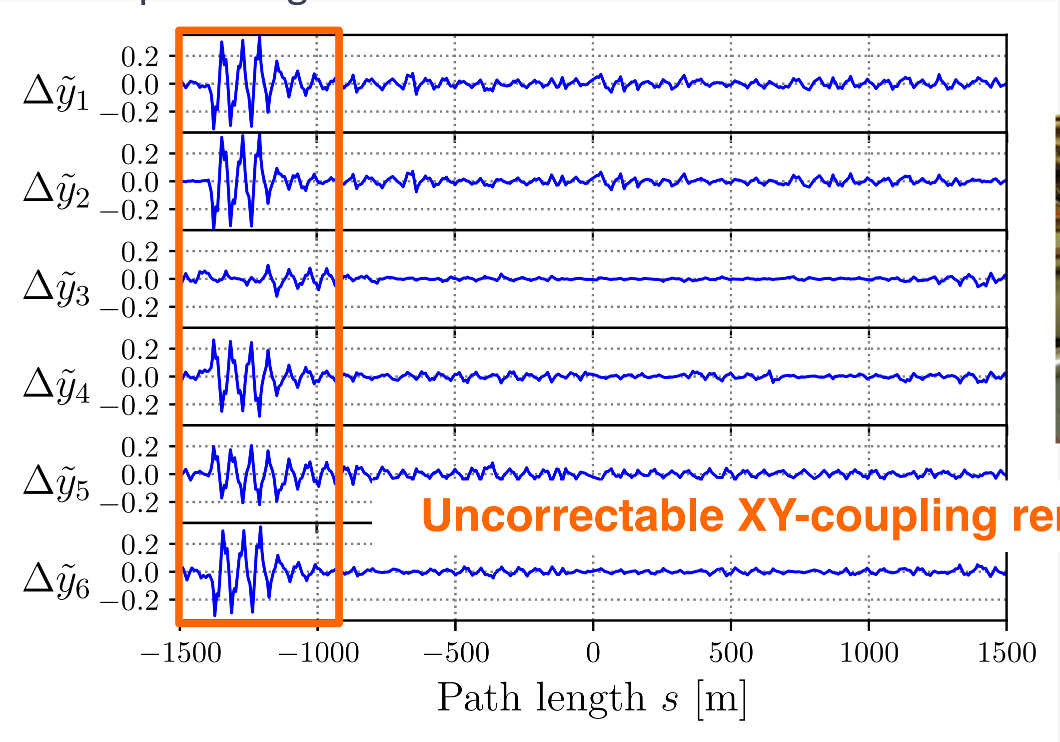


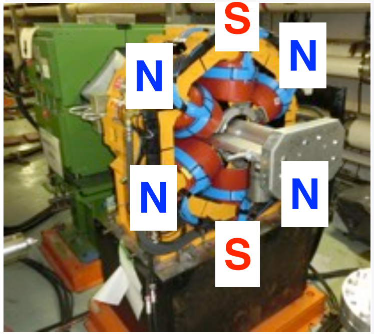


XY-Coupling *after* Correction

LER

- Correction using additional skew quadrupole coils installed in some of sextupole magnets.

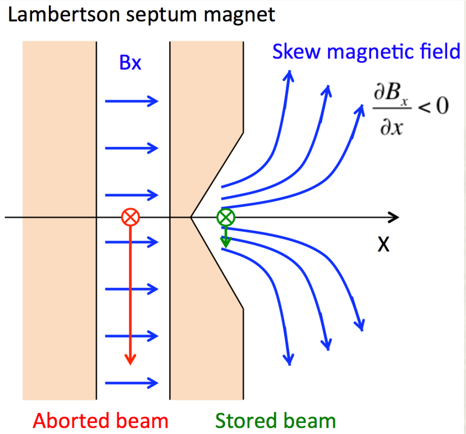


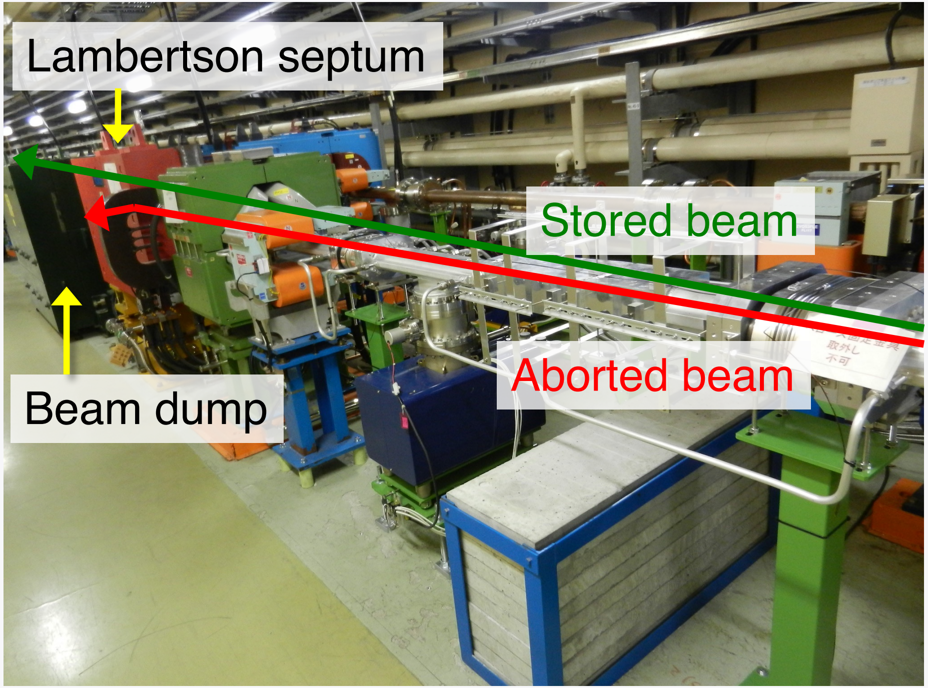


Uncorrectable XY-coupling remains.

Leakage Fields from a Lambertson Septum

- A Lambertson septum used to deliver aborted beam to a beam dump.
- It creates unexpected leakage field to the stored beam line.

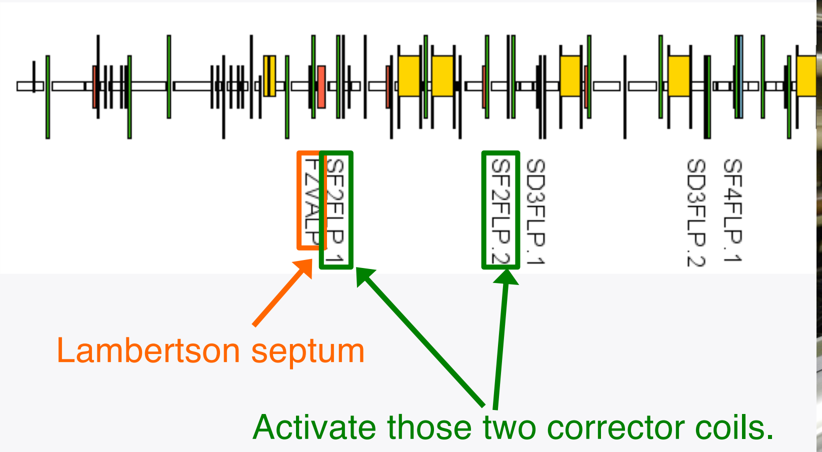


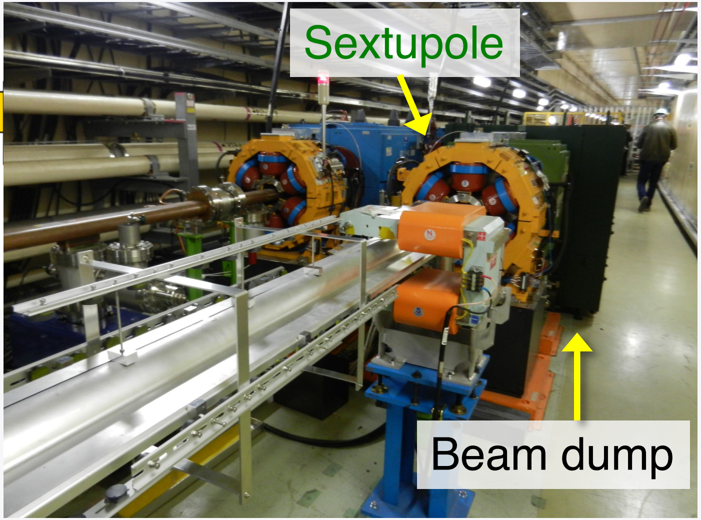


1st Countermeasure

- Activate two skew quadrouple coils

  installed in sextupole magnets using spare PS.



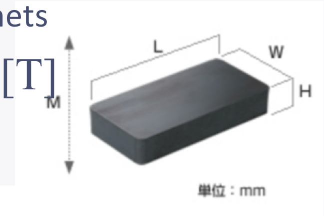


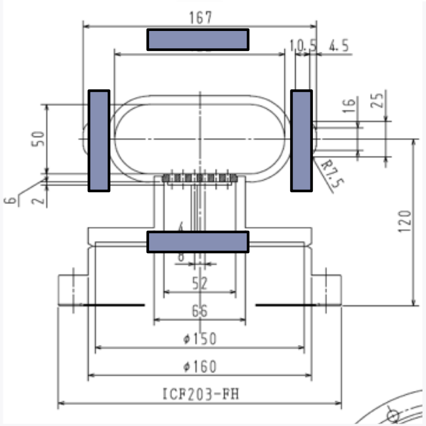
2nd Countermeasure

- Iinstalled a permanent skew corrector using Ferrite magnets.

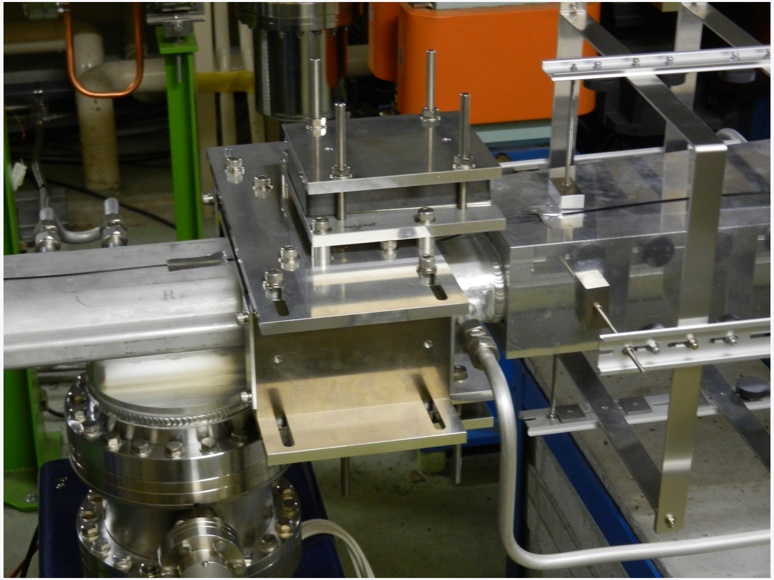
Ferrite magnets

$B \sim 0.07$ [T]





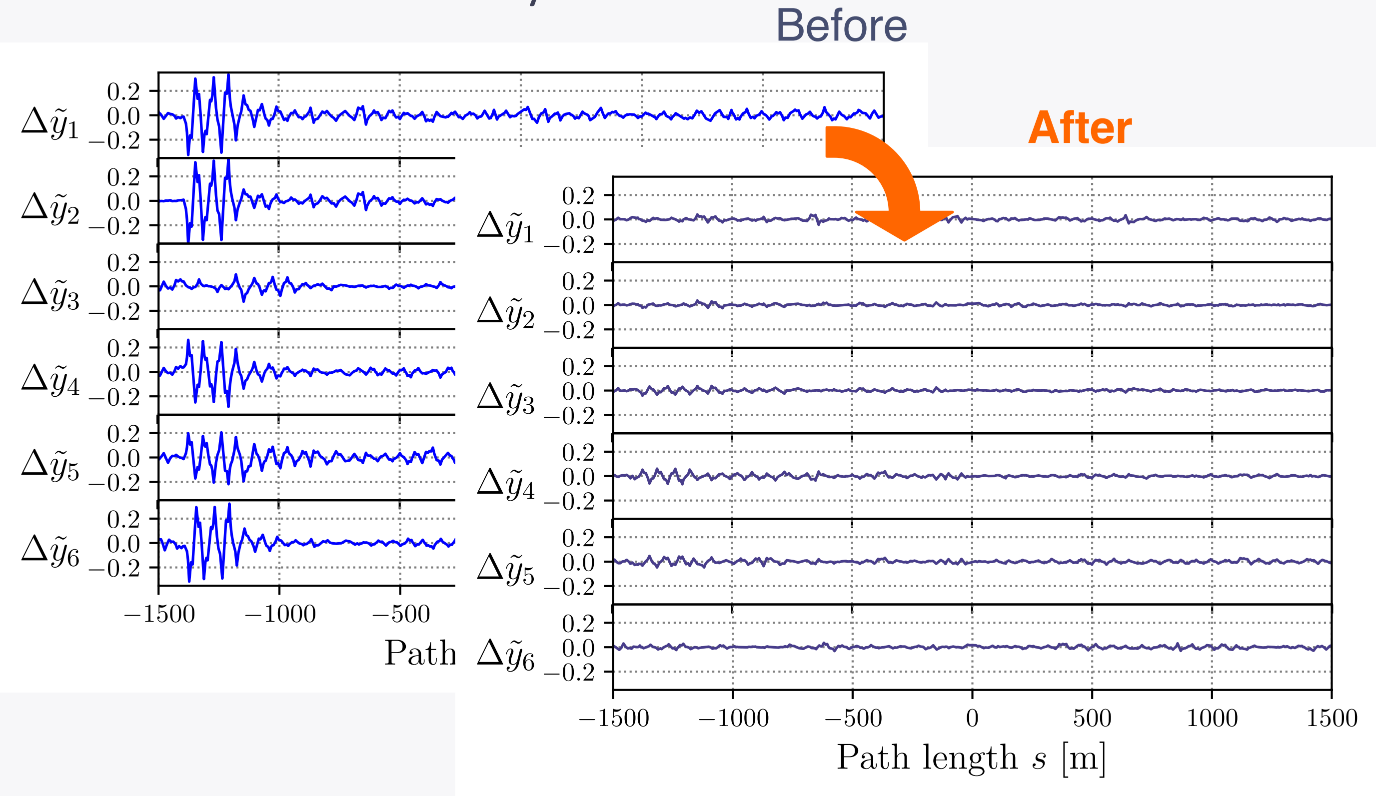
Ferrite magnets installed with supporting system



XY-Coupling *after* the Countermeasures

LER

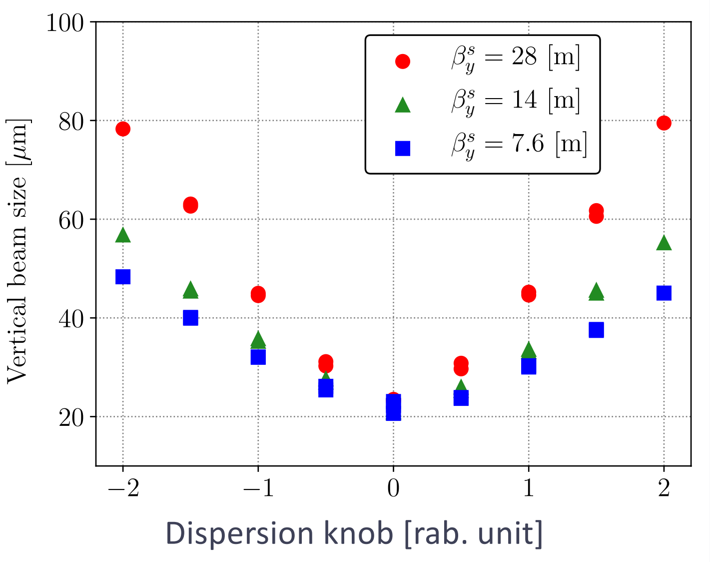
- The two cures effectively work.



Vertical Beam Size Measured with a X-ray Monitor

HER

- Vertical beam size is measured with changing global vertical dispersion and betatron function at the X-ray source point.



We Find that

- Measured size becomes less sensitive to the vertical-dispersion knob when β_y^s becomes smaller as expected.
- The minimum measured beam size is independent on β_y^s
- The monitor system has some smearing effects which limit the resolution. Comprehensive study estimates the size of smearing effect is about 6 μm.

Summary

- Calibration of the BPM system is performed based on beam experiments
  - Relative gains of BPM electrodes
  - Alignment between BPM and a neighbor magnet.
- The calibrated BPMs enable us to perform Optics&Orbit corrections.
- Unexpected optics distortion due to a Lambertson septum magnet.
  -> Resolved with installation of additional correctors.
- The lowest achieved vertical emittance so far

  Positron beam -> 10 pm   Electron beam -> 8 pm

Thank You for Your Kind Attention!