Optics Measurement at SuperKEKB using Beam Based Calibration for BPM and Beam Based Experiment

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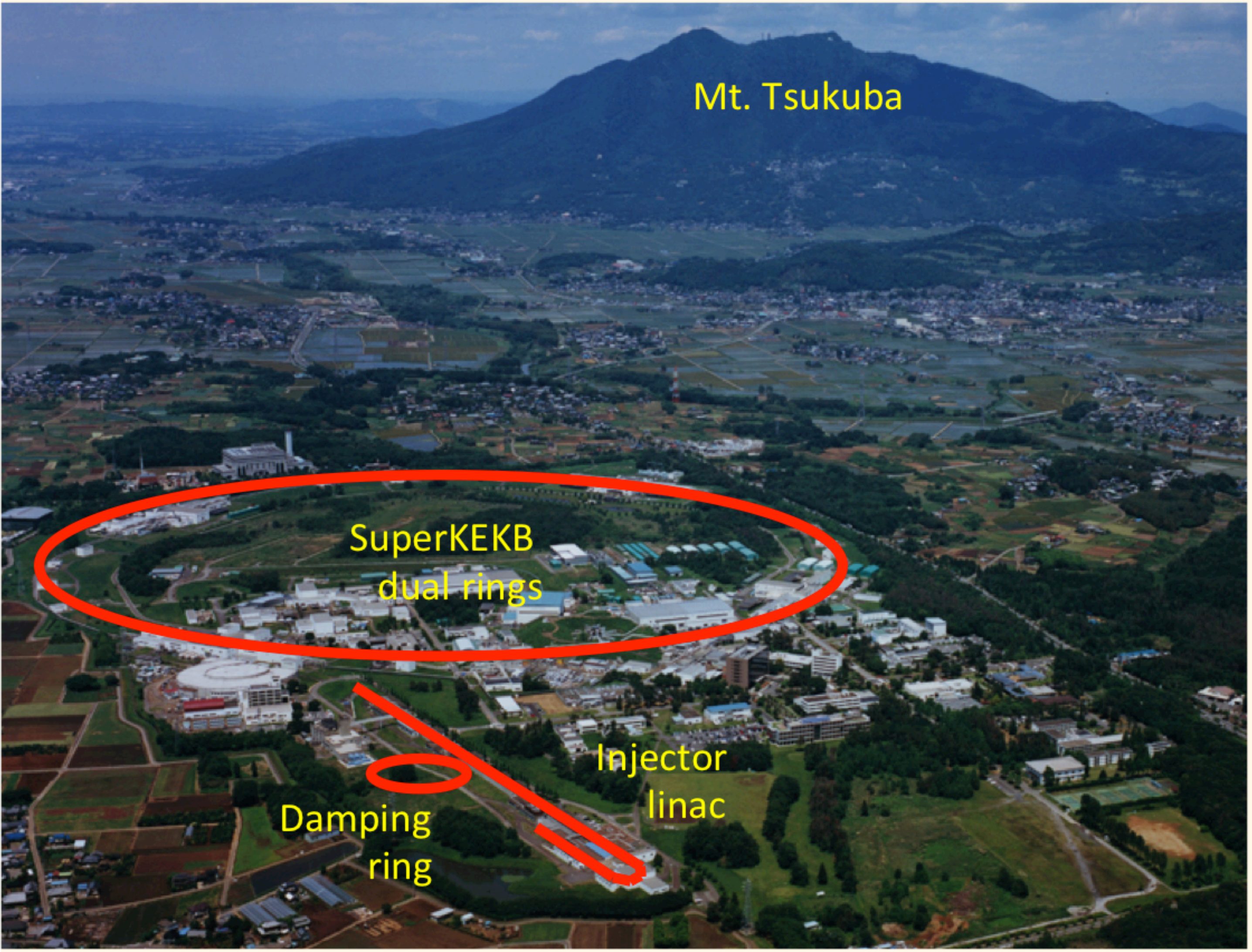
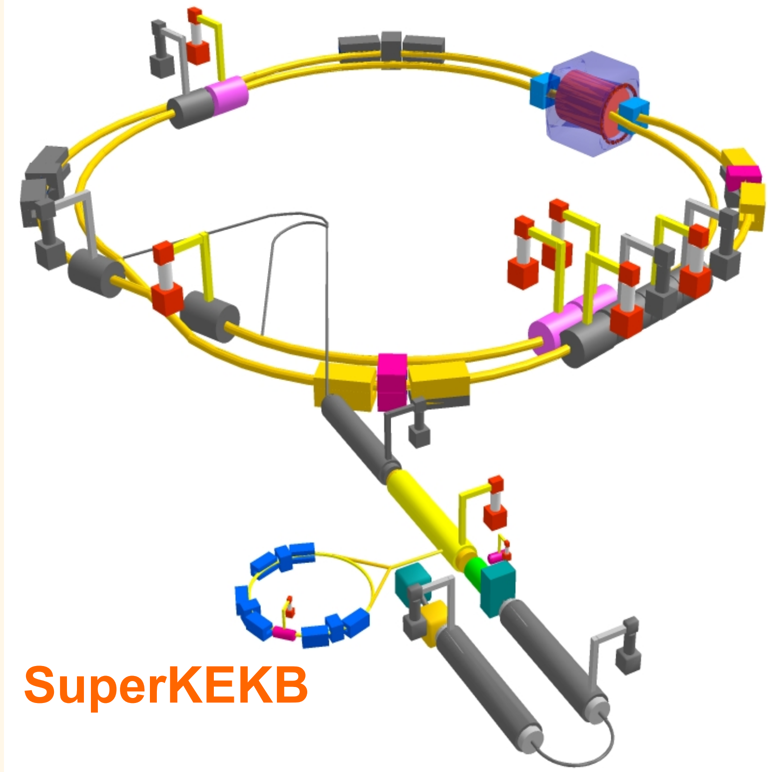
on behalf of SuperKEKB optics & commissioning groups

IBIC 2017, August 22th, 2017

This Talk

- SuperKEKB is a luminosity frontier collider
  and is an upgrade project of the KEKB electron-positron collider.





Target Luminosity

$$= 8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

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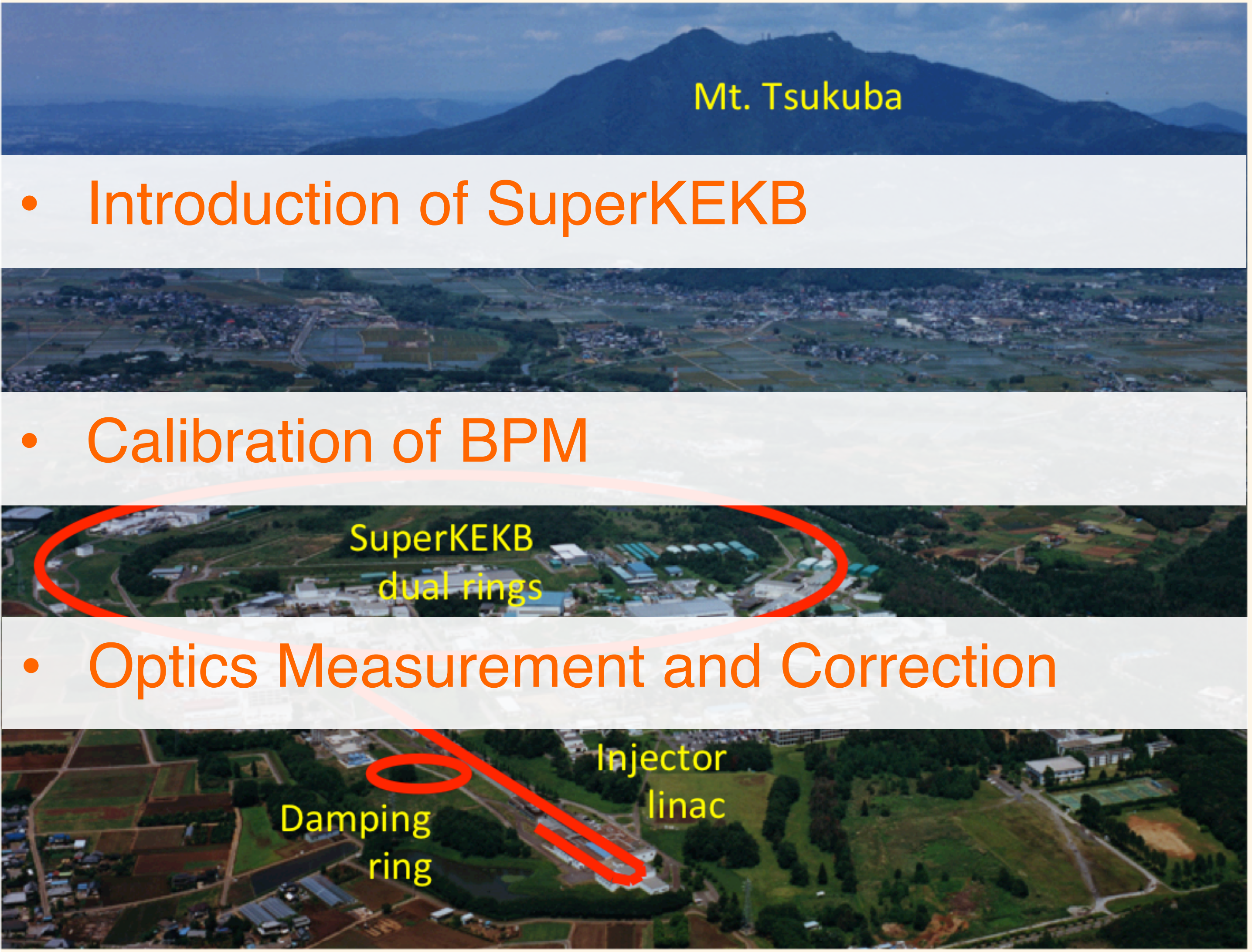
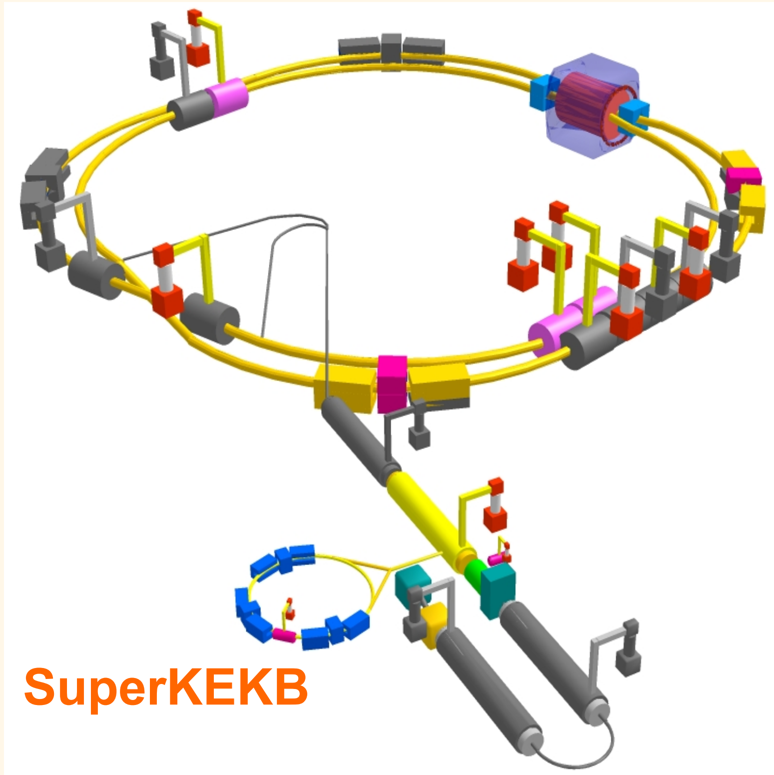


- Introduction of SuperKEKB
- Calibration of BPM
- Optics Measurement and Correction



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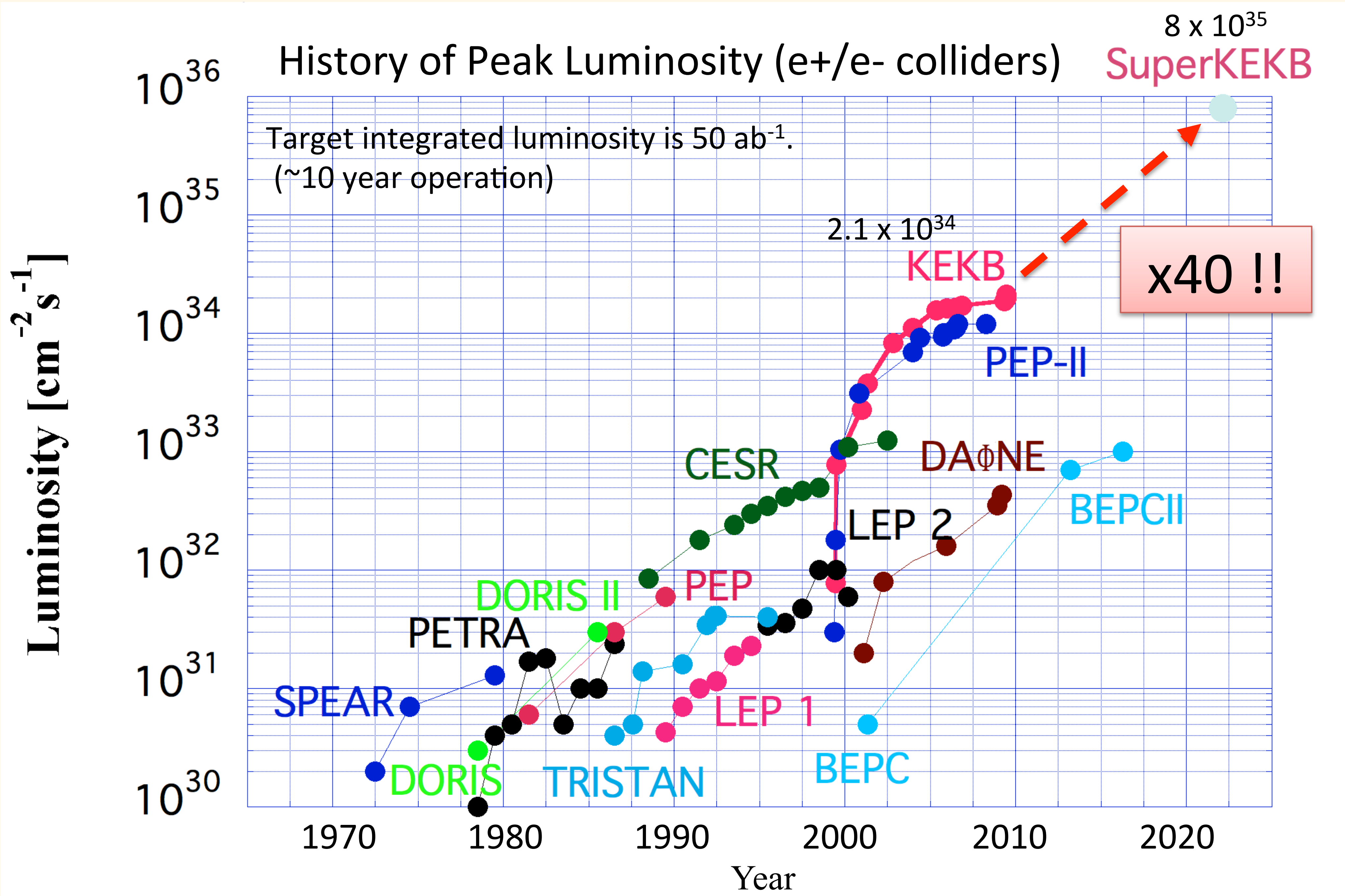
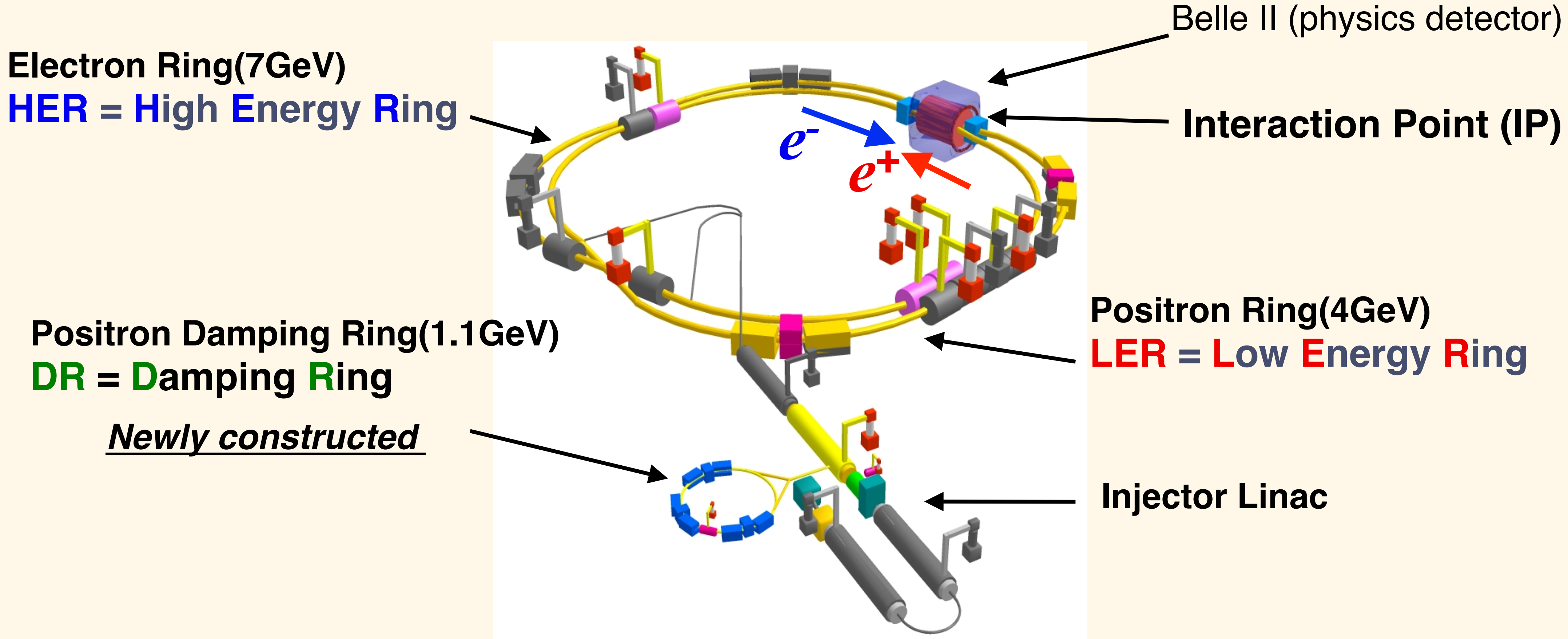
Peak Luminosity of e+/e- Colliders

Y. Funakoshi@IAS2017



SuperKEKB

- KEKB 1999~2010
  - World luminosity record $L = 2 \times 10^{34}\ cm^{-2}s^{-1}$
- **SuperKEKB** 2016~
  - Aims 40 times higher luminosity $L = 8 \times 10^{35}\ cm^{-2}s^{-1}$
  - Beam Commissioning started at Feb. 2016.



Commissioning Schedule

- Three steps to reach the target luminosity.
- No Final Focus System (FFS) and no beam collision in Phase 1
- Low Emittance Tuning (**LET**) is one of the most important issue.

Phase 1

Feb. ~ June 2016

W/O Belle II
W/O FFS

Basic Machine Tuning

This talk

We are here.

Phase 2

Feb. ~ June 2018

W/ Belle II
W/ FFS

Background study
Luminosity tuning

Phase 3

Oct. 2018~

Physics Run

Luminosity tuning

Commissioning of the damping ring will starts Dec. 2017

BPM Calibration

with Beam Measurement in Phase 1

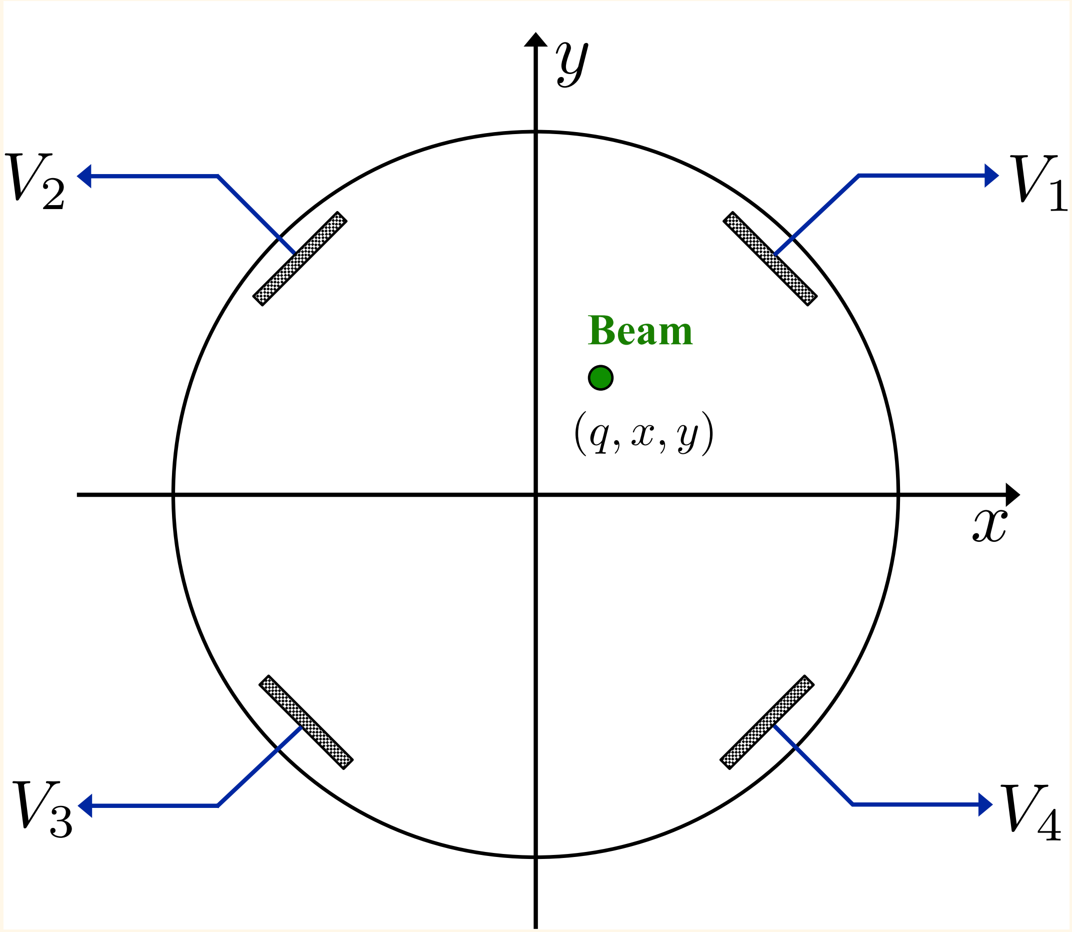
BPM System and Its Calibration

- 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 was mainly used in optics measurement.
- More than 100 BPMs can be used with gated turn-by-turn mode.
- Two calibration parameters are discussed in this talk.
  - **The gain factor of the BPM electrodes**
  - **The offset of the BPM reading**

BPM Gain Calibration

BPM Model

- Detect four output voltages from pickup electrodes.



- Normalized voltages

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

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

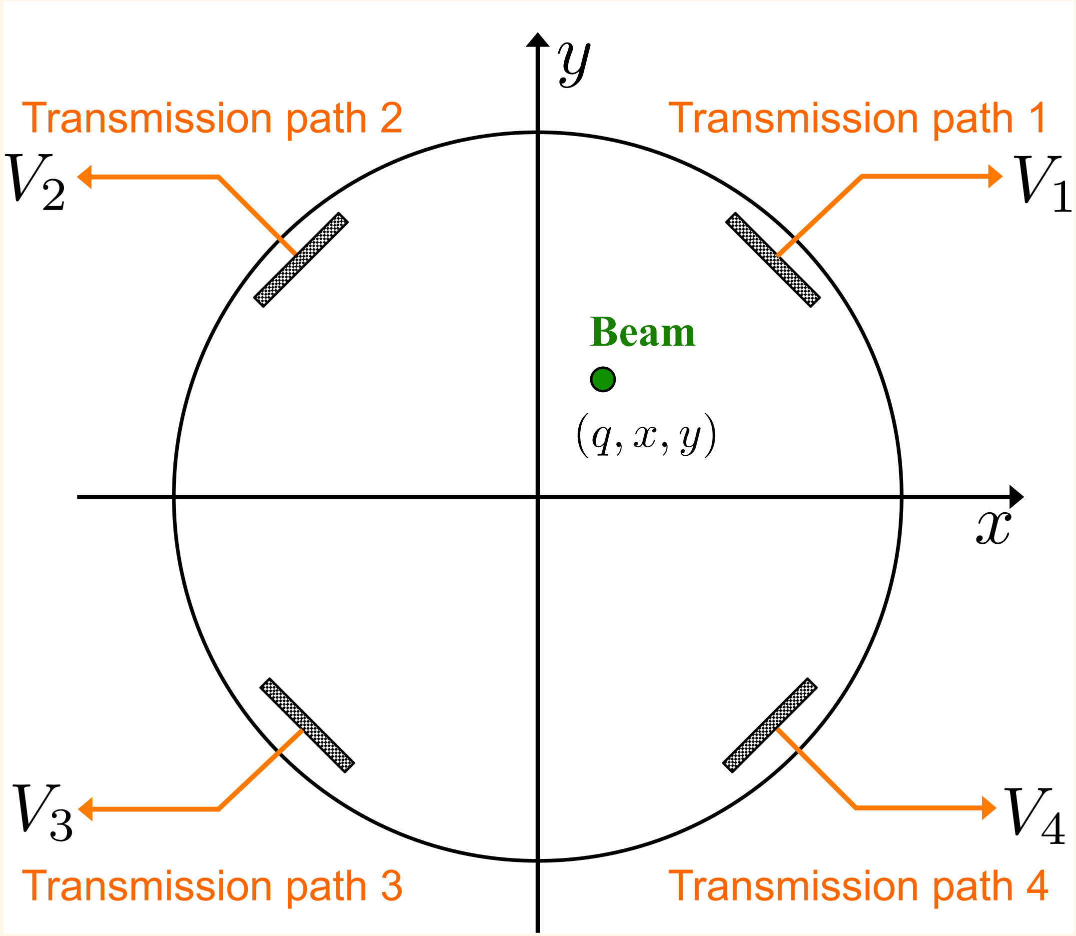
- Beam position using mapping functions

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

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

BPM Model

- Detect four output voltages from pickup electrodes.



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- Beam position using mapping functions

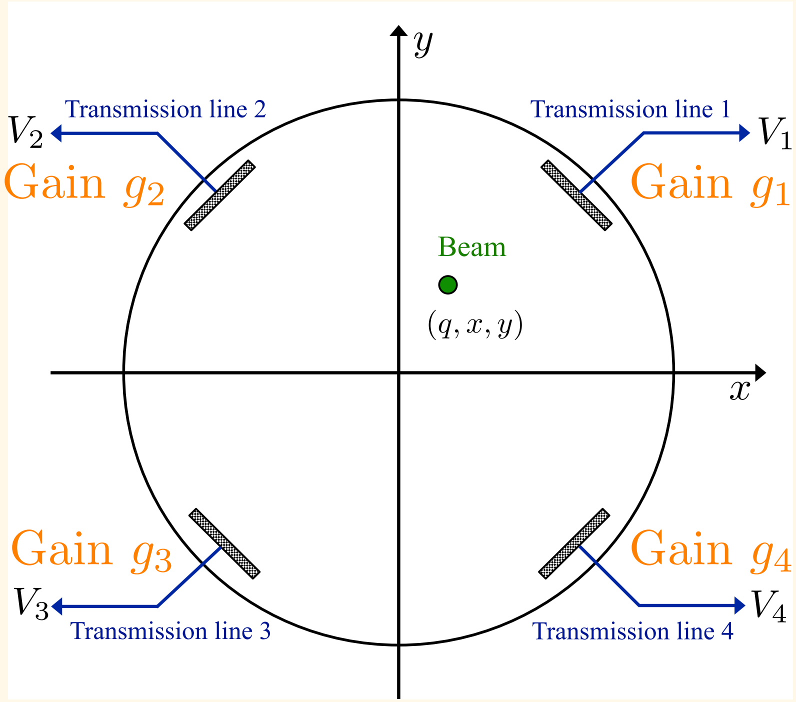
$$x = F_x(u, v) \quad y = F_y(u, v)$$

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



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

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

m : # of measured data

q_j : Charge

g_i : Gain

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

- We minimize a chi-squared so that the model reproduce the measured voltages,

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

σ_{ij} : Measurement error

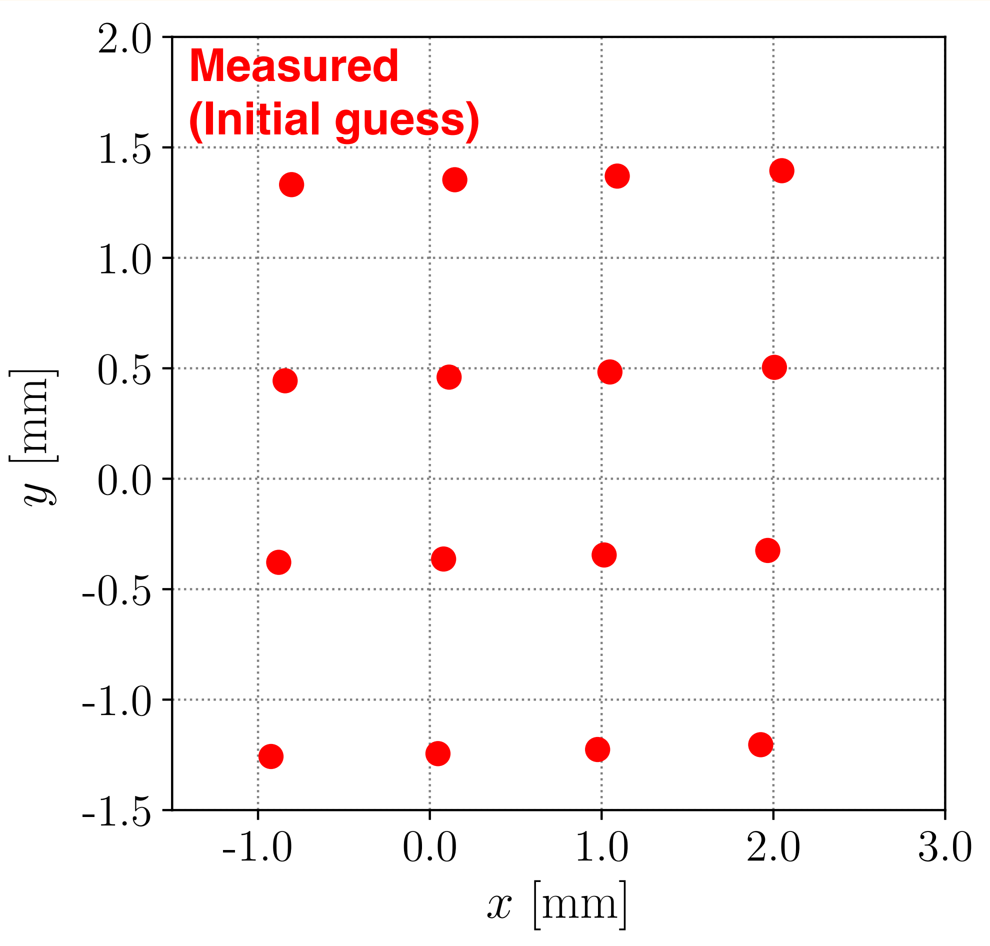
$g_1 = 1$

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

M. Tejima, in Proc. of IBIC2015, Melbourne (Australia, 2015) pp. 267-272.

Example

- Record the electrode voltages of BPM while changing strength of horizontal and vertical steering magnets.
- Perform nonlinear fitting using the measured beam position as an initial guess of the fitting variables.



Example

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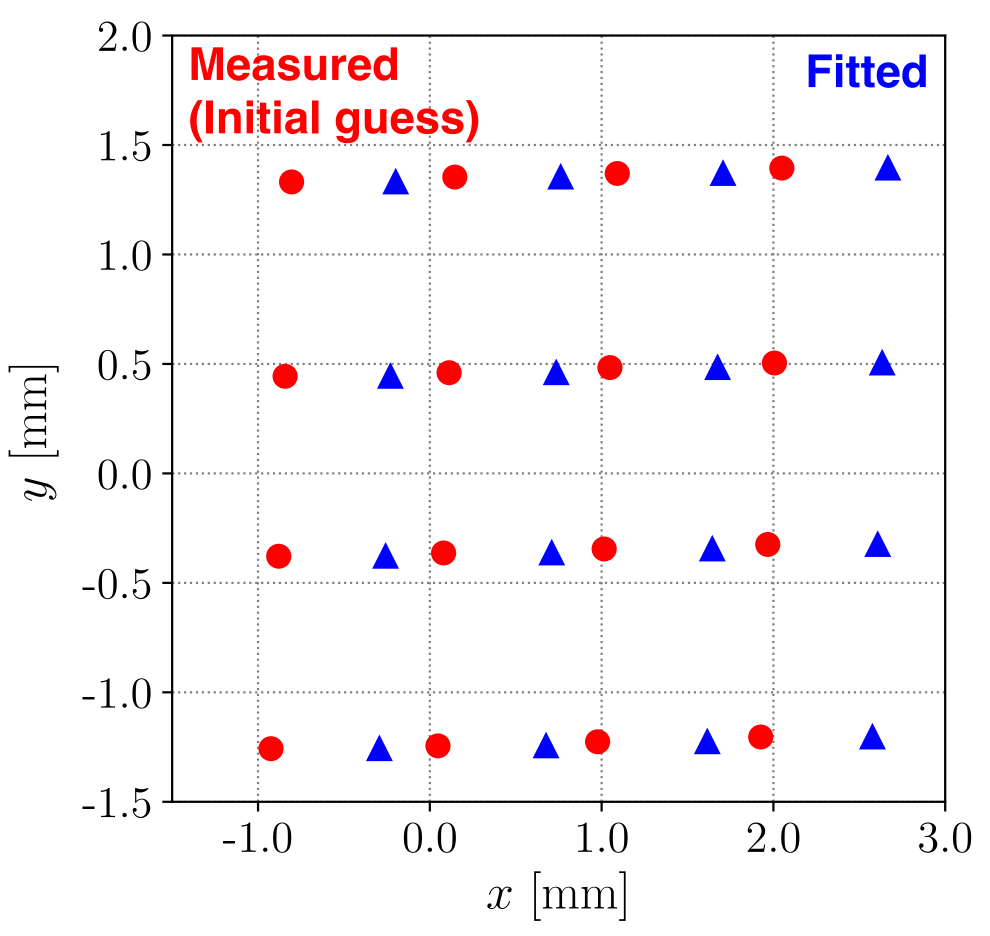


Fitting Results

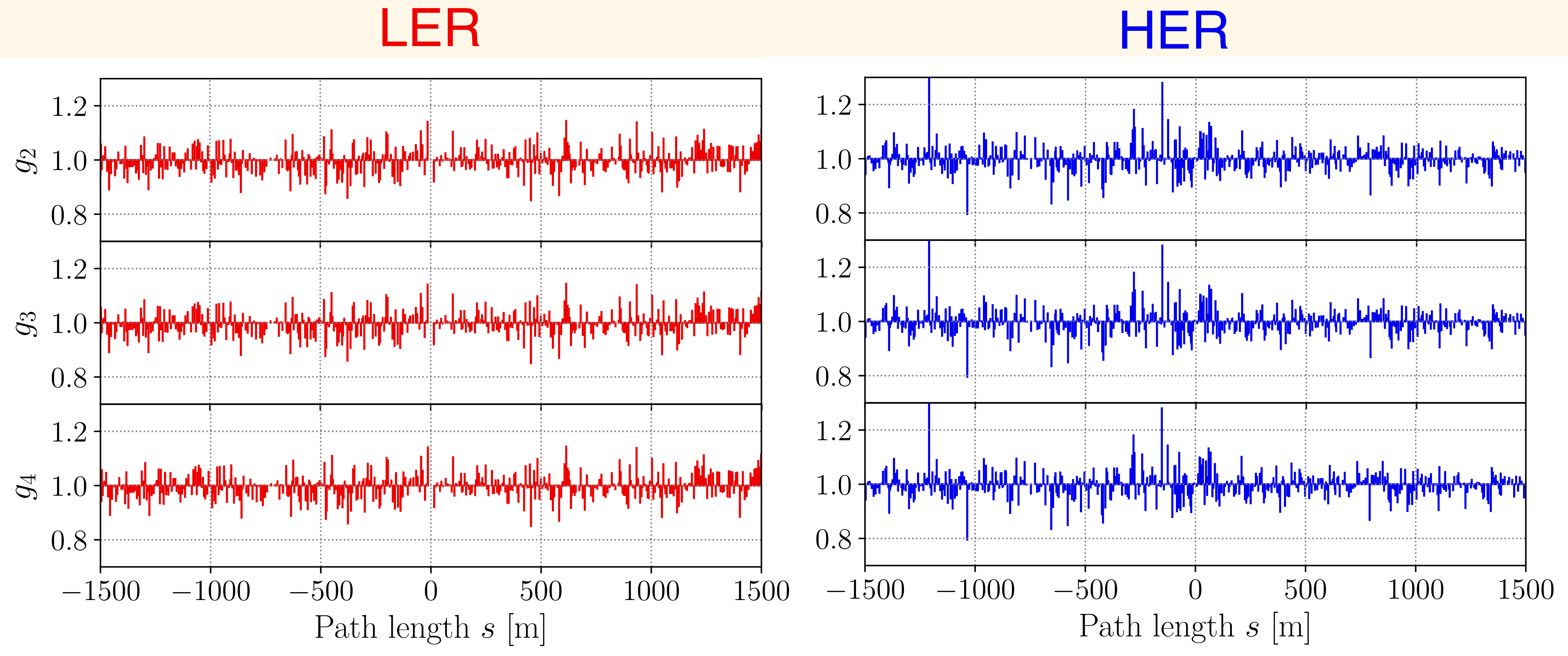
$$\chi^2 = 1.3$$

$$g_2 = 0.994$$

$$g_3 = 1.031$$

$$g_3 = 0.987$$

Results in LER and HER Rings



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

Consistency Check of BPM

- Our model well describes the real BPM system?
- Calculate the beam position with only 3 electrodes.

(x_a, y_a) : ⟵ Obtained with 1,2,3 -th electrode voltages.

(x_b, y_b) : ⟵ 2,3,4

(x_c, y_c) : ⟵ 3,4,1

(x_d, y_d) : ⟵ 4,1,2

- Define "consistency error"

by the standard deviation of the 4 beam positions.

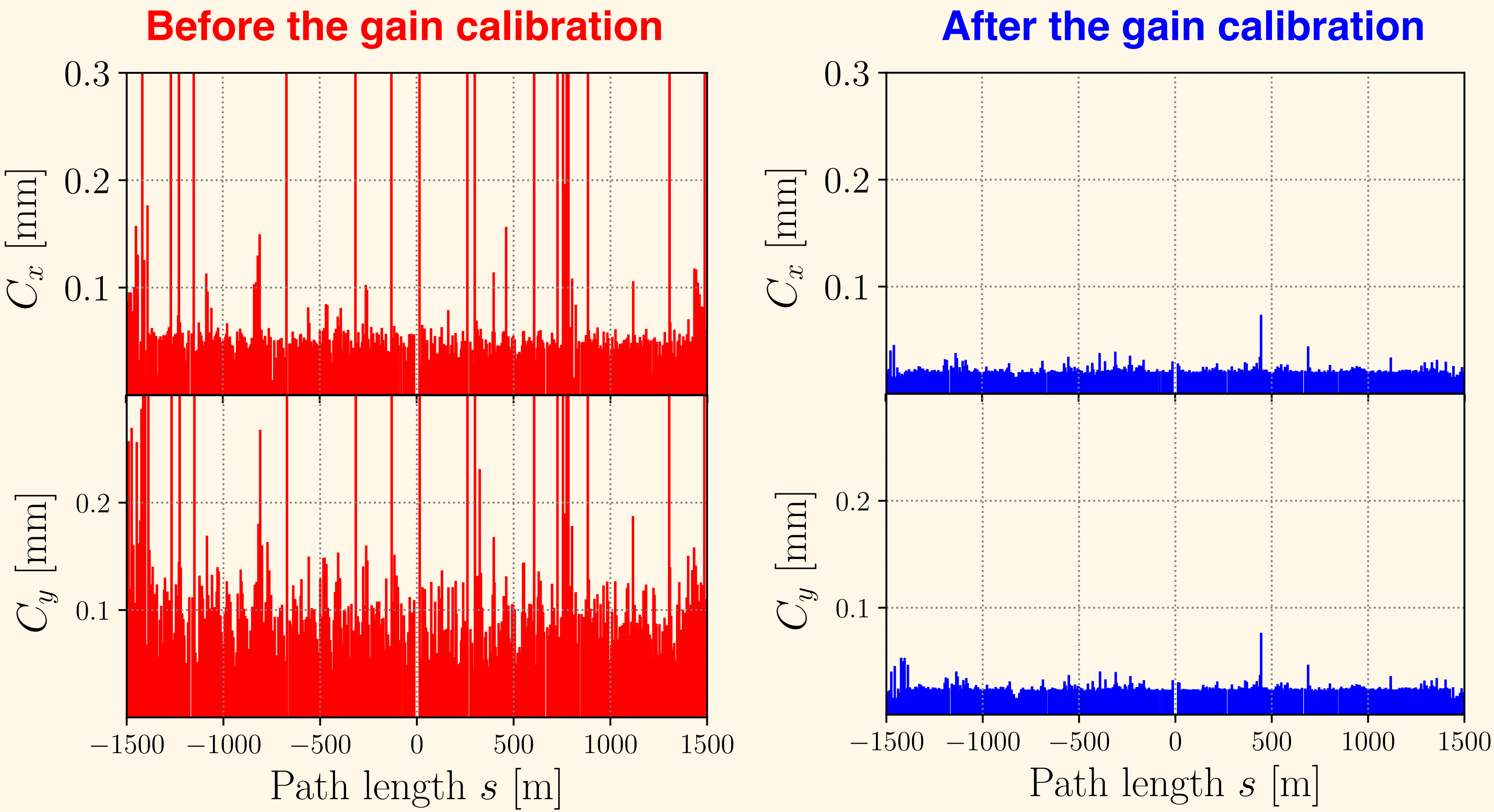
$$C_z \equiv \sqrt{\frac{1}{4} \sum_{i=a,b,c,d} (z_i - < z >)^2}, \quad \text{where } z = x \text{ or } y \qquad < z > \equiv \frac{1}{4} \sum_{i=a,b,c,d}^{4} z_i,$$

- For the ideal BPM, those 4 beam positions should be identical.

$$\longrightarrow C_z = 0$$

Consistency of BPM

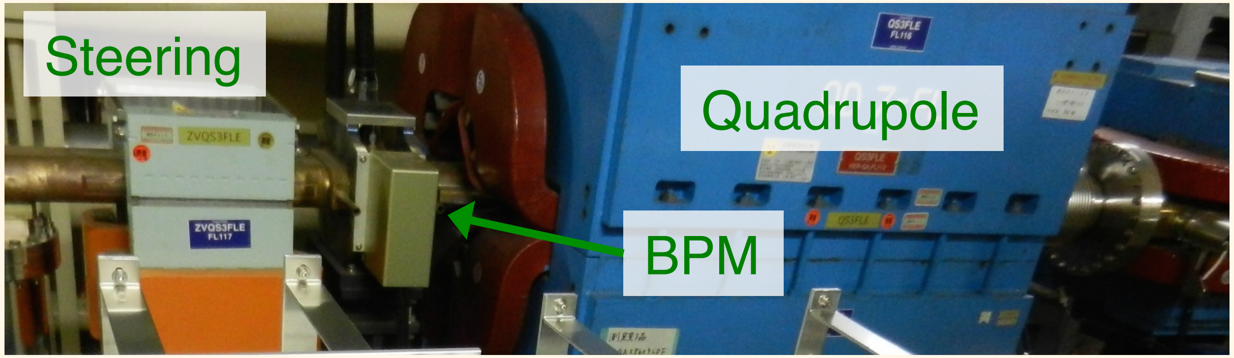
LER

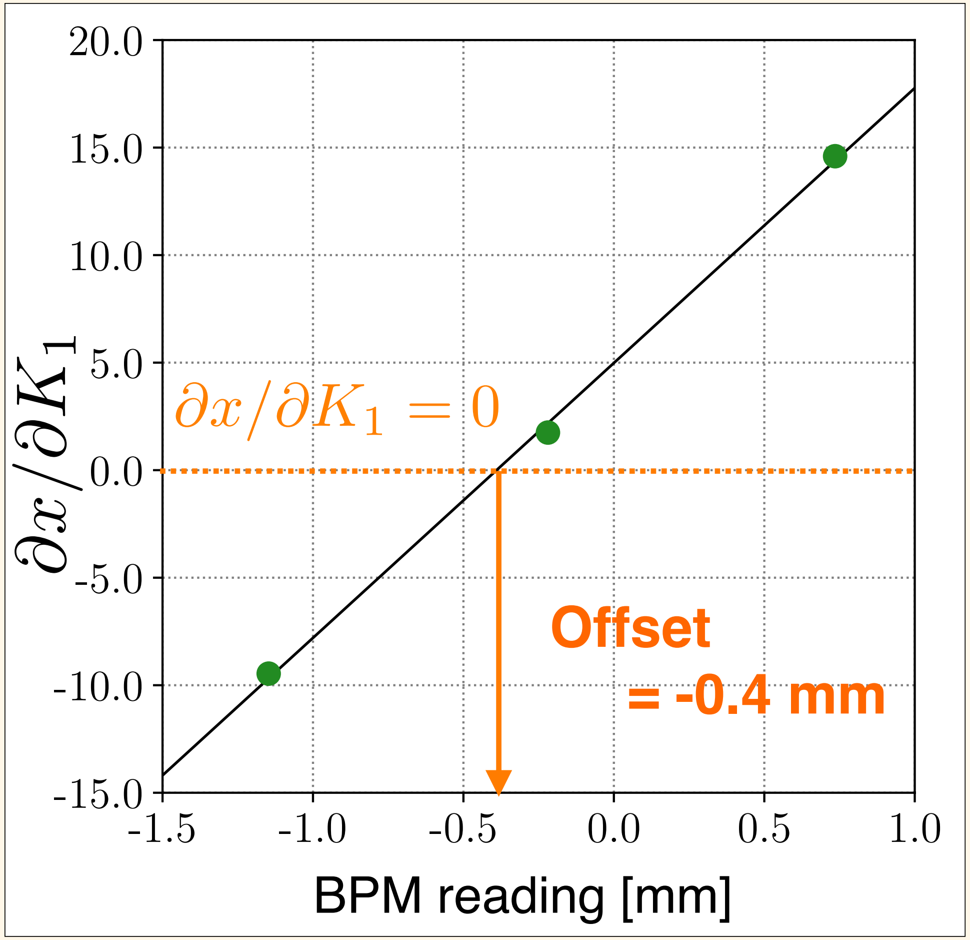


- We routinely check the consistency during the operation in order to detect hardware troubles in the BPM system.

Beam Based Alignment

Beam-Based Alignment (BBA)

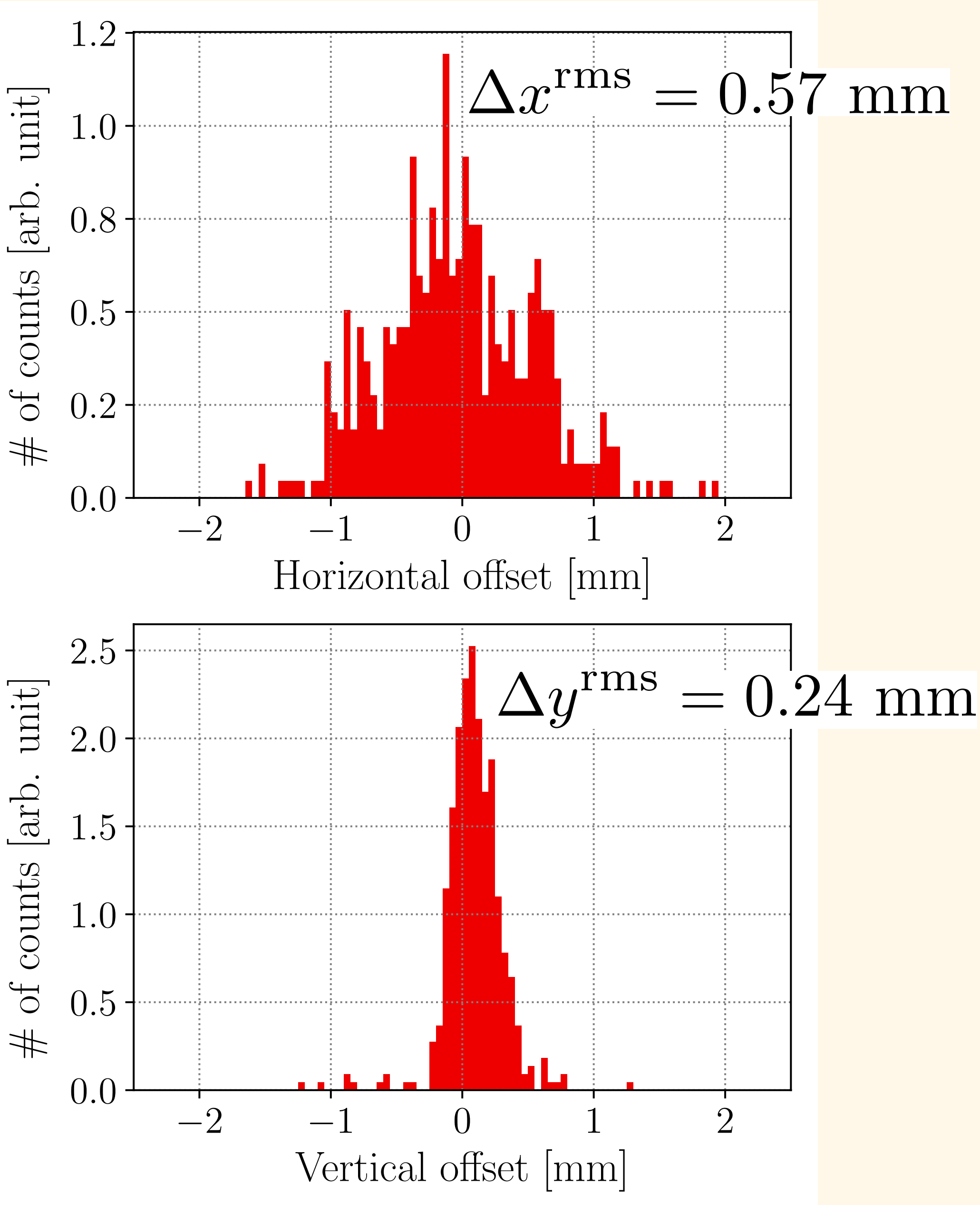




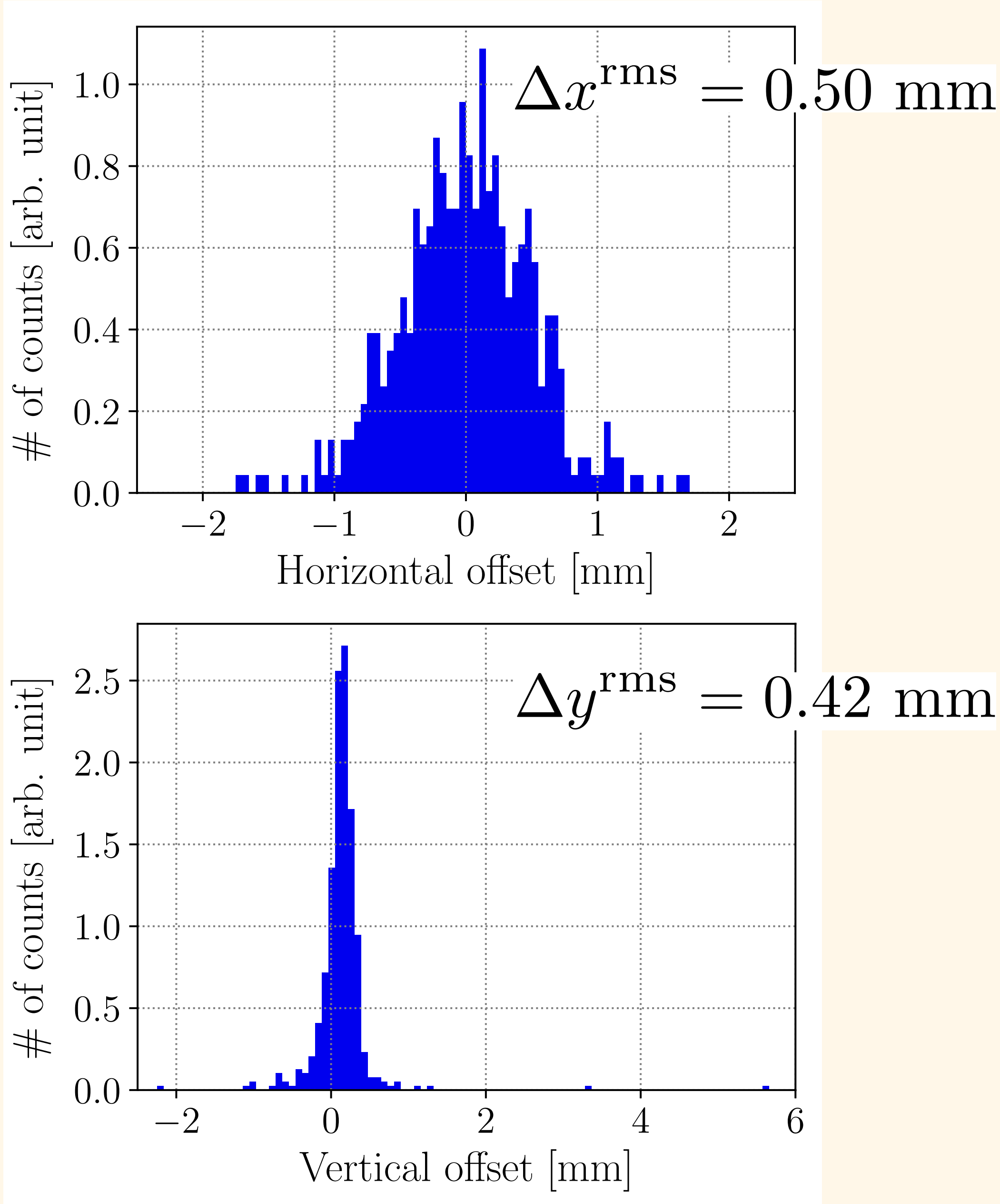
- Calibrate BPM offset so that the beam passes through the magnetic center of the nearby magnet.
- To do so, we find BPM reading which is insensitive to the field strength of the magnet.
- The measurement is carried out using a semi-automated software.
- The offset is imported to the BPM system.

Offset Parameter for BPM System

LER



HER

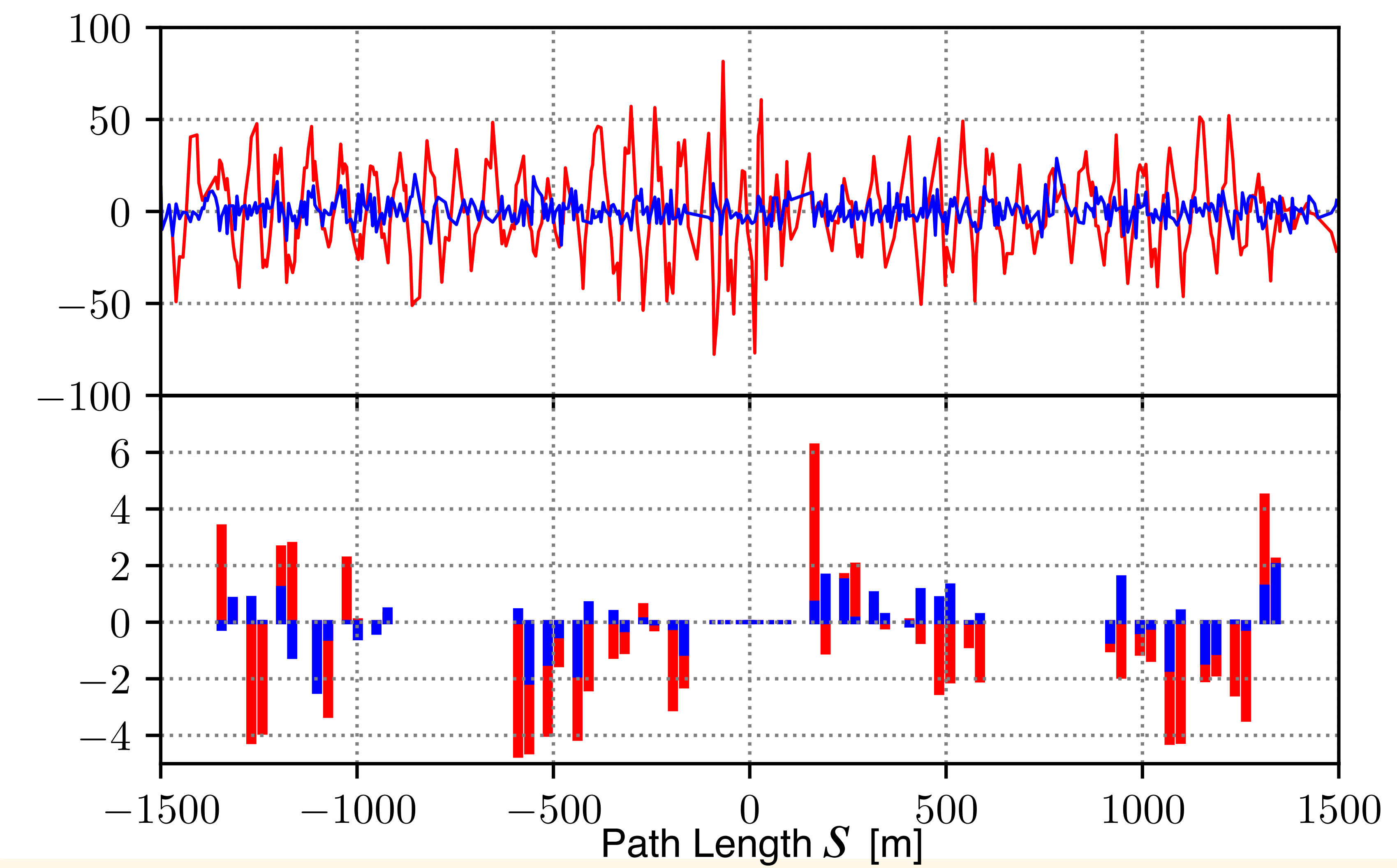


Benefit from BBA on Optics Correction

- Before BBA: Hit hardware limit of the corrector strength.
- After BBA: Required corrector strength is remarkably reduced and allows us to further correction.

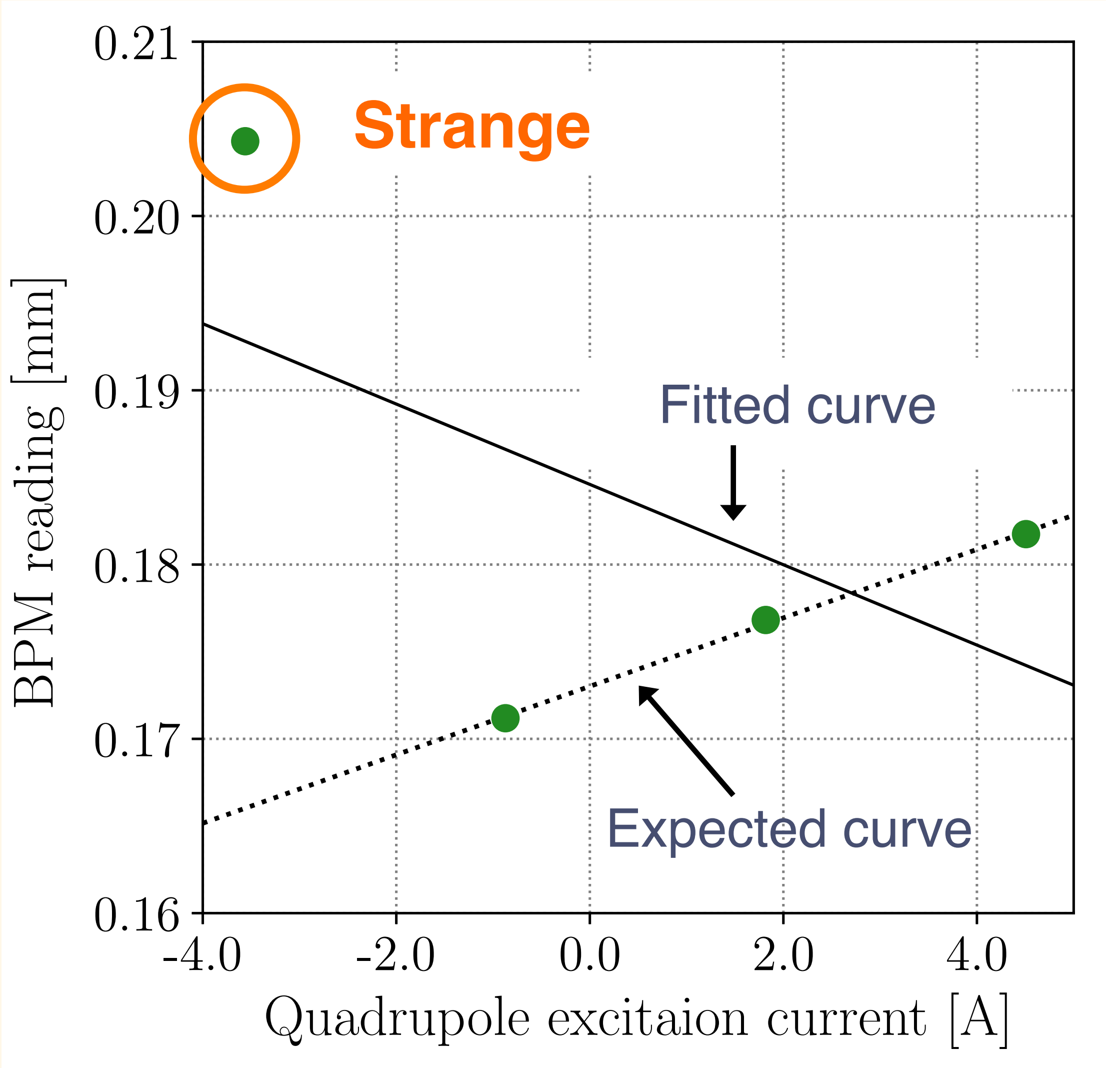
Vertical dispersion $\Delta\eta_y$ [mm]

Corrector strength K_1 [$\times 10^{-3}$m^{-1}]



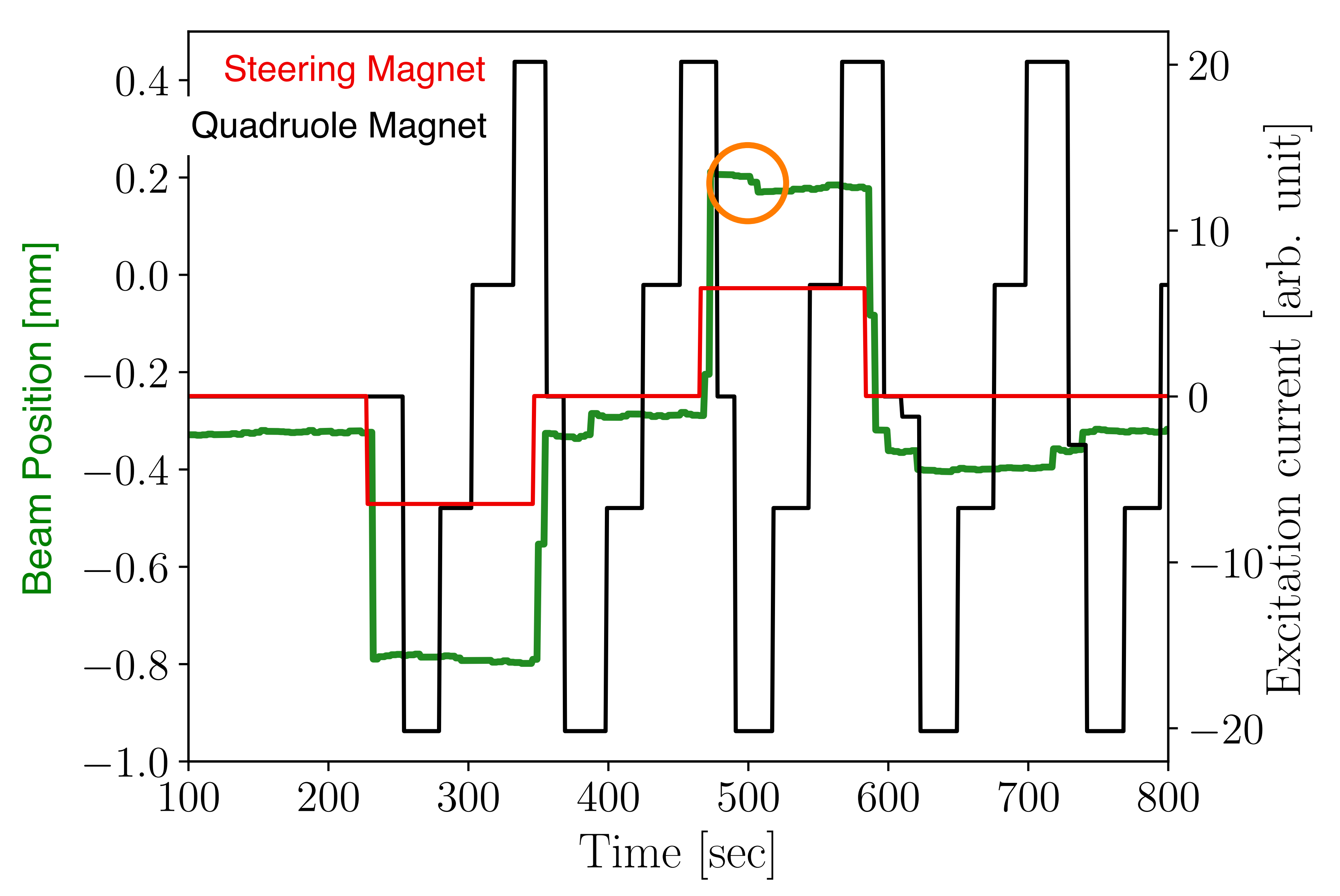
Unexpected Observation in BBA

- A strange jump of beam position is observed.
- An example: Measured beam position while changing quadrupole field strength.



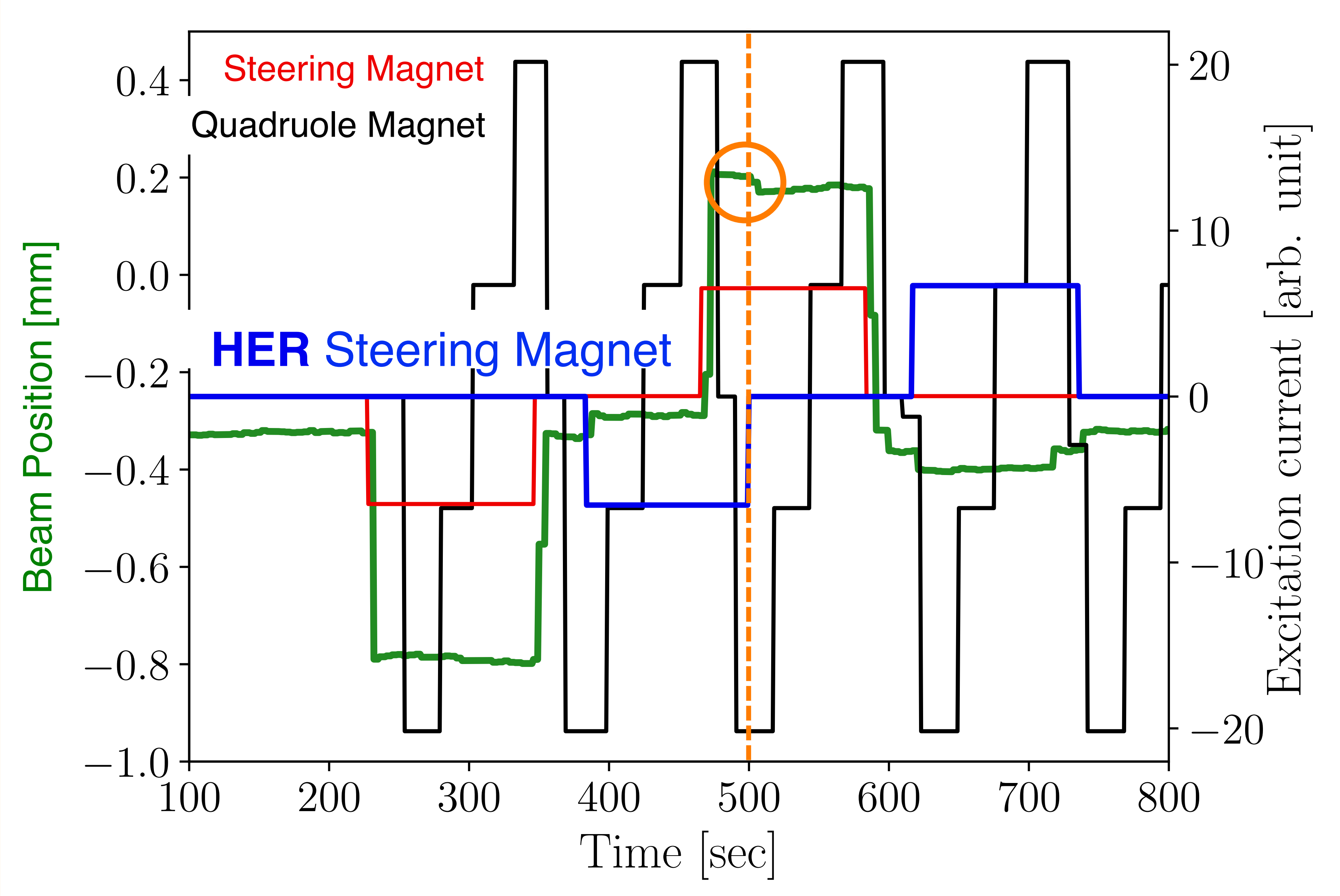
Time History

- Time history of beam position and excitation current of magnets in LER.



Time History

- The beam position jump is caused by a steering magnet of the other ring(HER).



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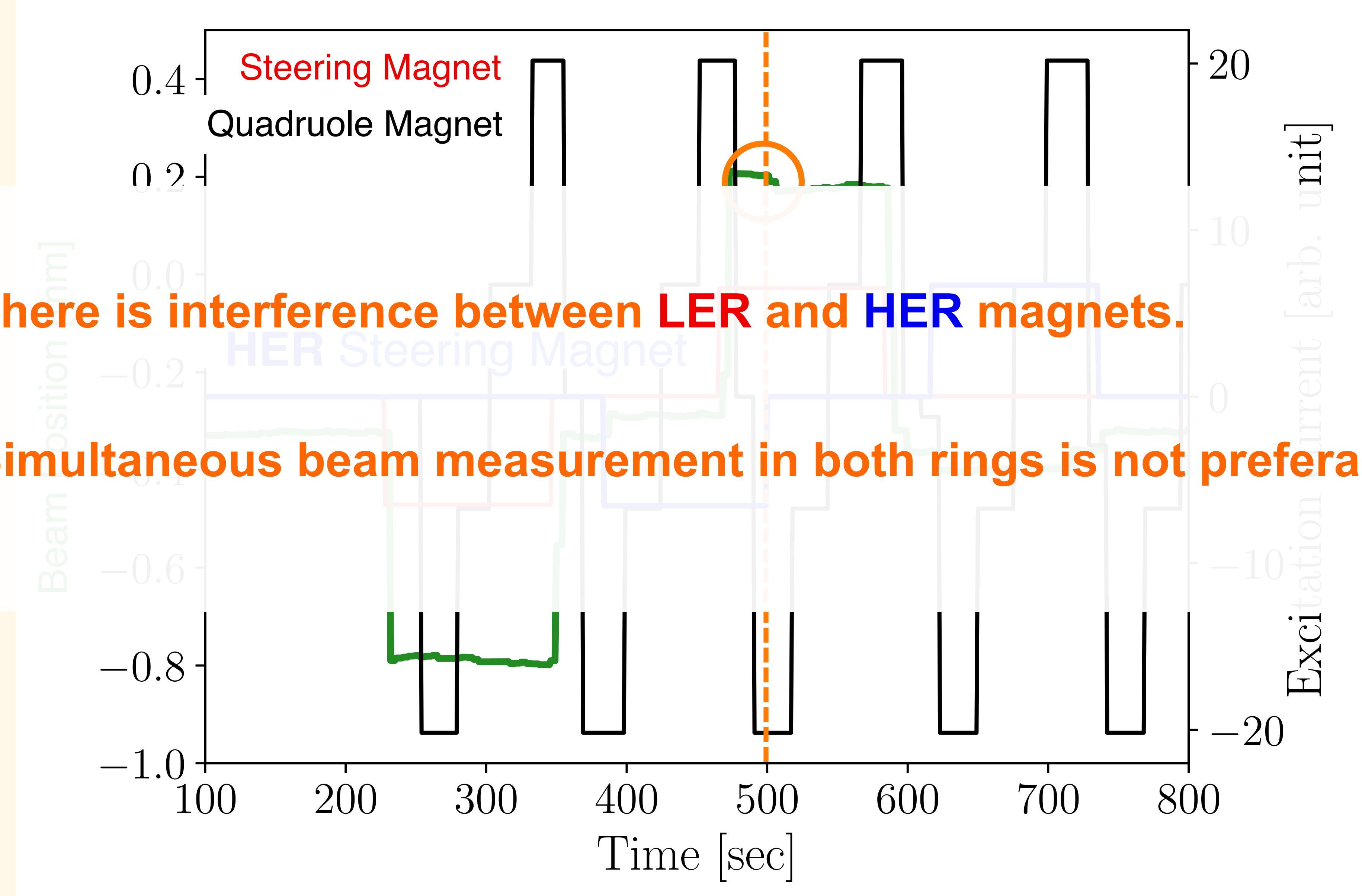


- There is interference between LER and HER magnets.

- Simultaneous beam measurement in both rings is not preferable.

Optics Measurement and Correction

Measurement Method

- Measurement with orbit response analysis.

  - Betatron 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.

$$\eta_x = \overset{\text{RF frequency}}{f_0} \frac{\overset{\text{Orbit change}}{\Delta y}}{\underset{\text{Frequency change}}{\Delta f}} \underset{\text{Phase slip factor}}{\xi}$$

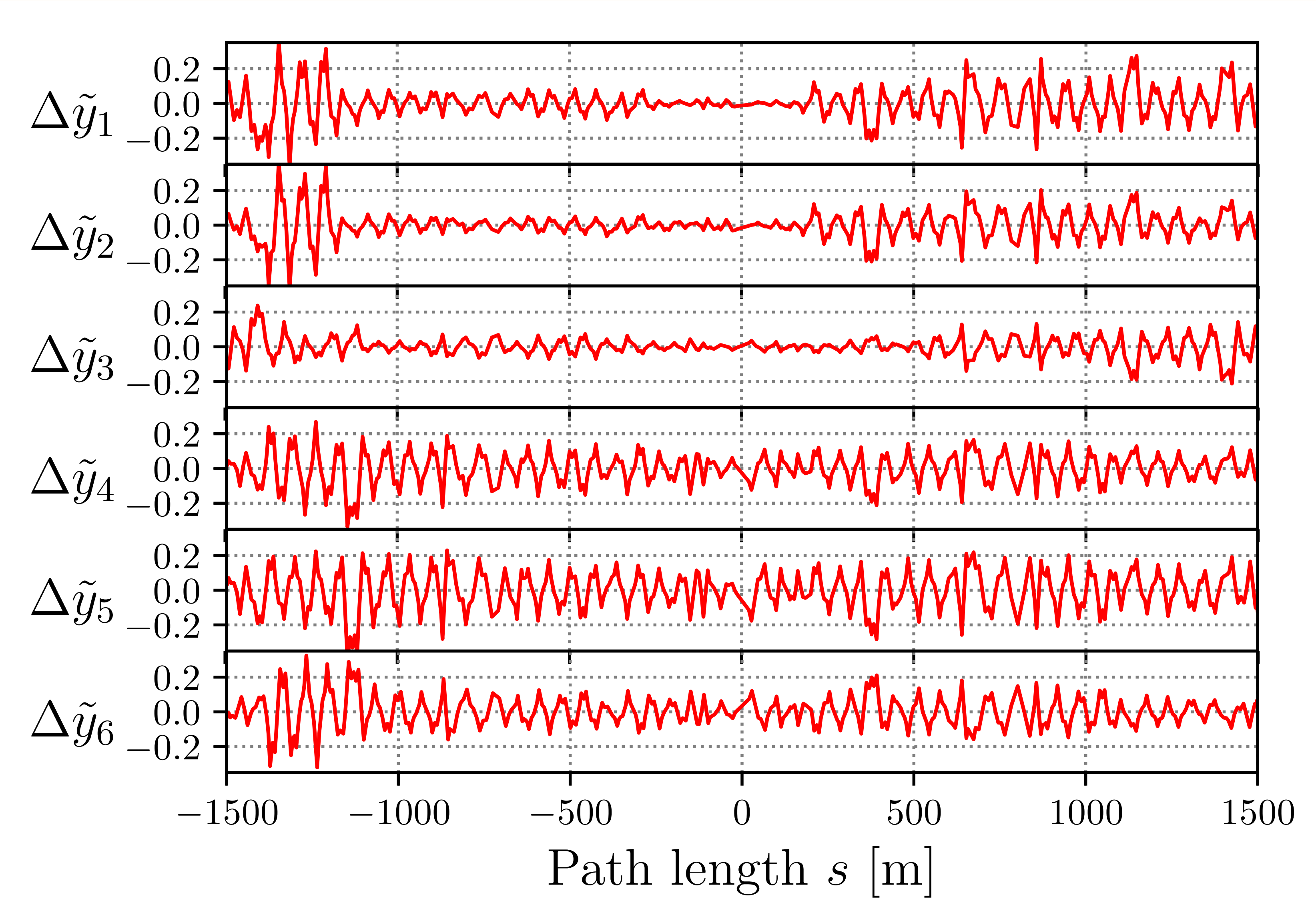
  - Horizontal-vertical (XY) coupling:

    Vertical leakage orbits induced by horizontal kicks.

XY-Coupling *before* Correction

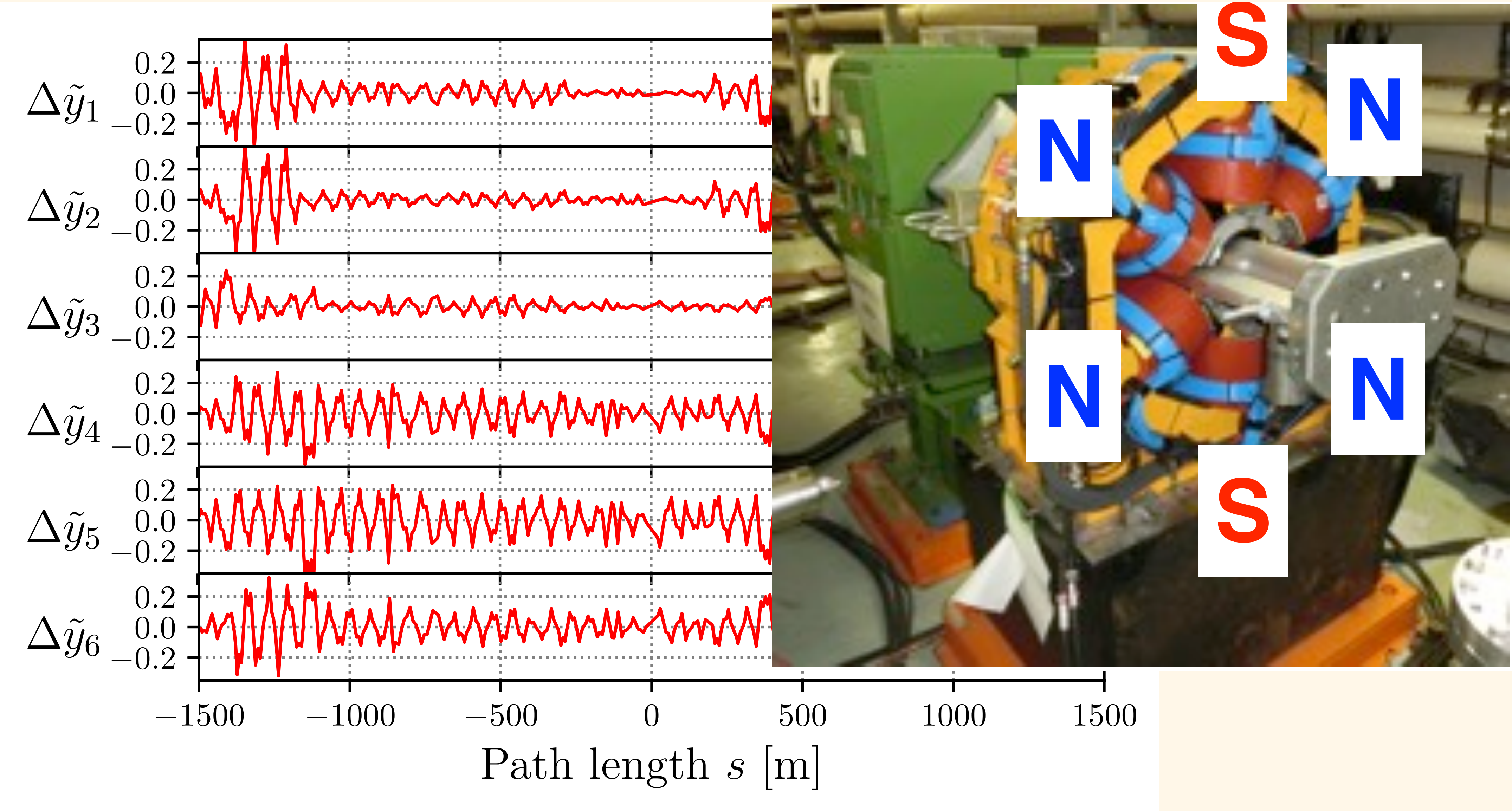
LER

- Six kinds of vertical leakage orbits induced by horizontal dipole kicks. (Normalized by RMS amplitude of the horizontal orbits)



Corrector for XY-Coupling

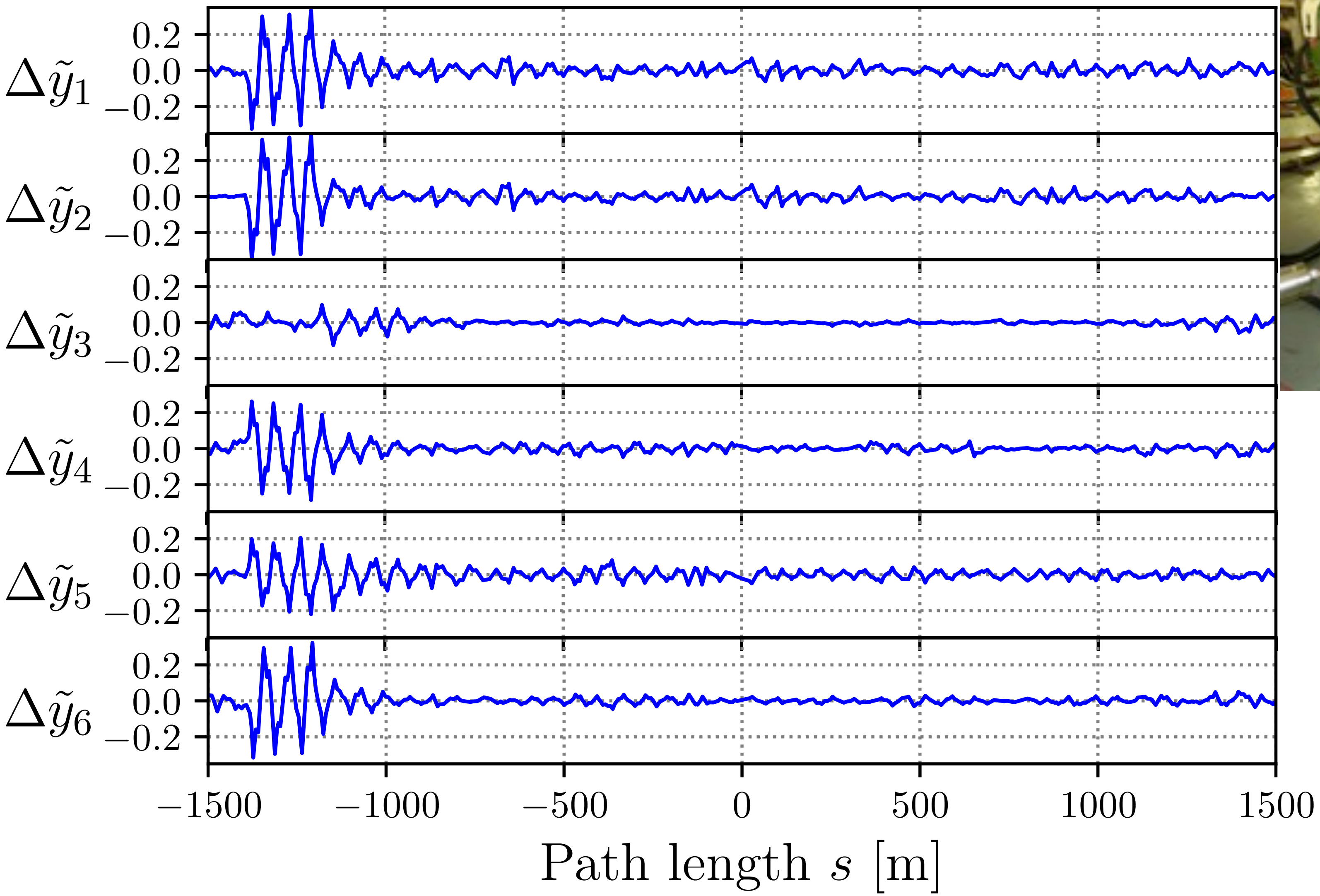
- Additional skew quadrupole coils installed in some of sextupole magnets.

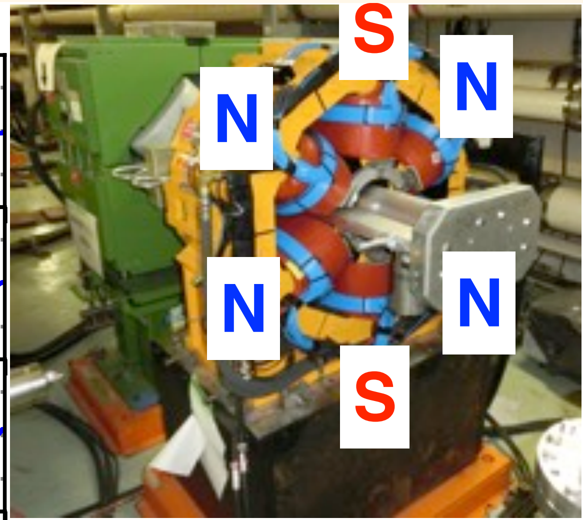


XY-Coupling *after* Correction

LER

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





XY-Coupling *after* Correction

LER

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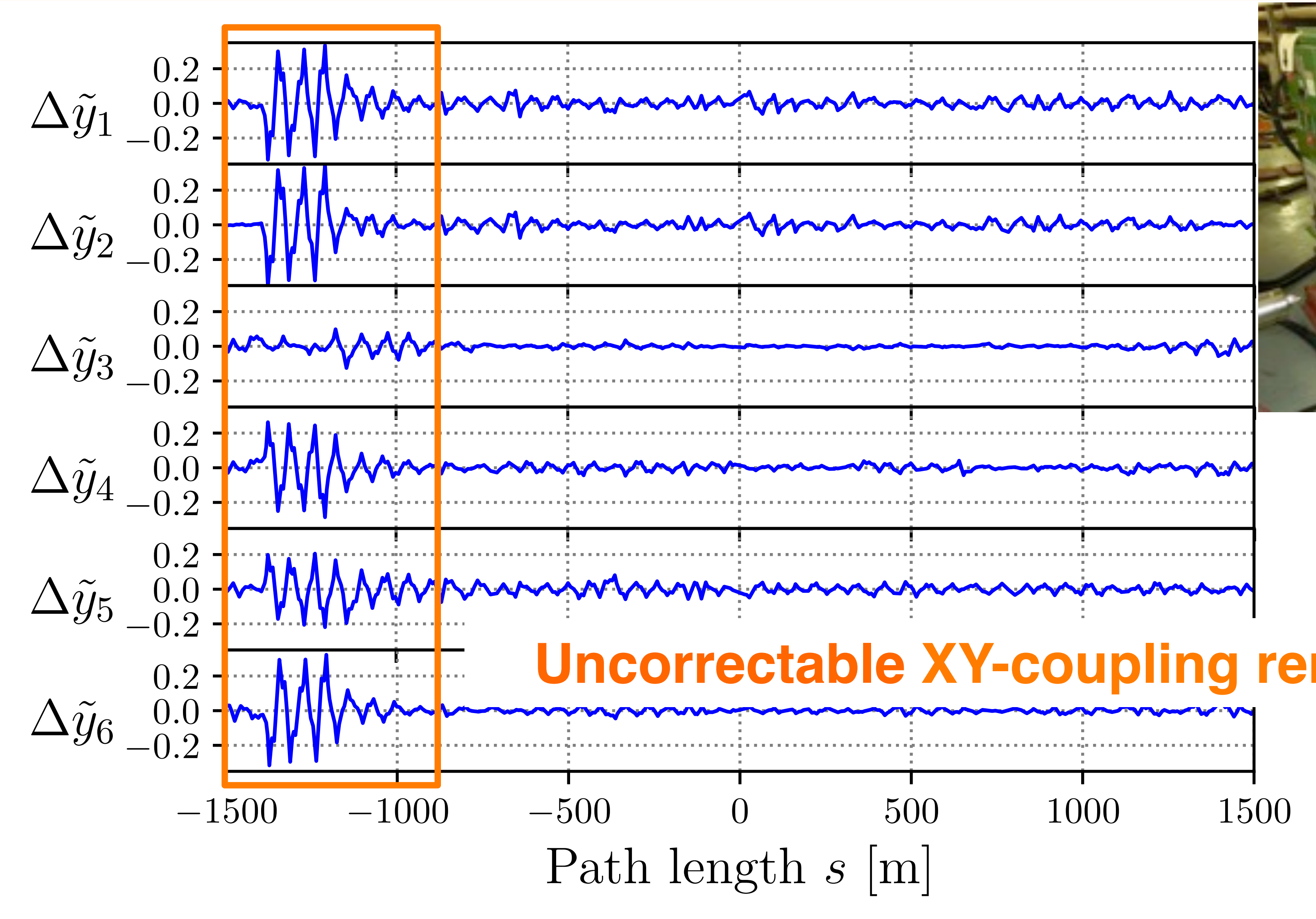
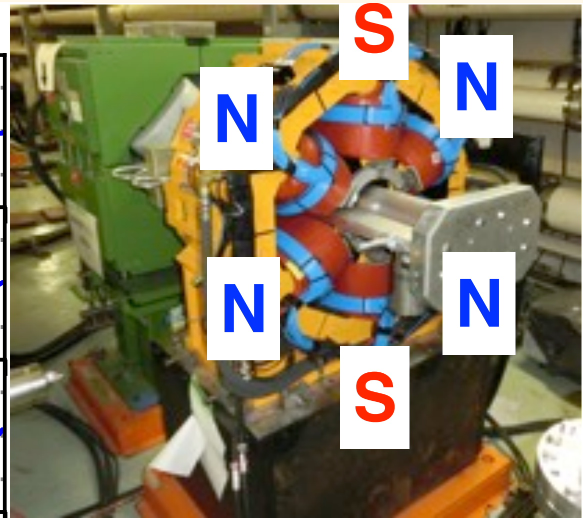
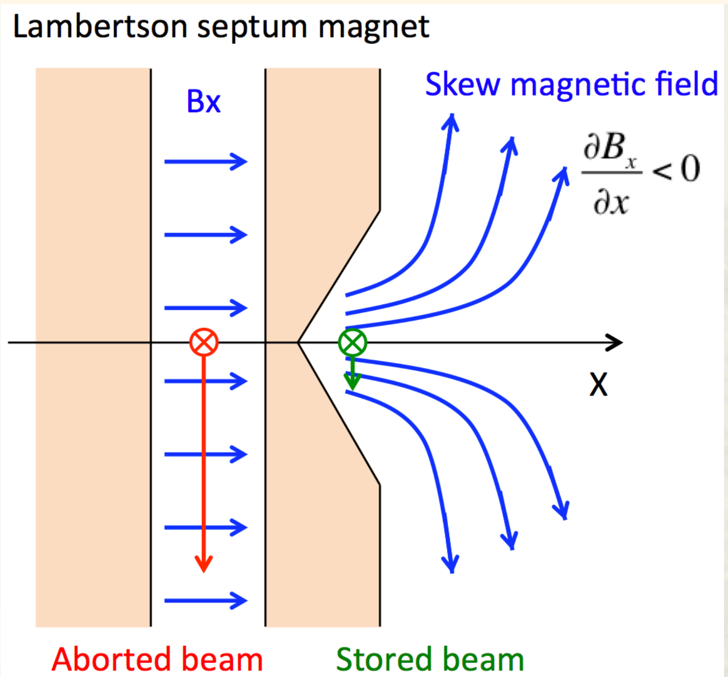


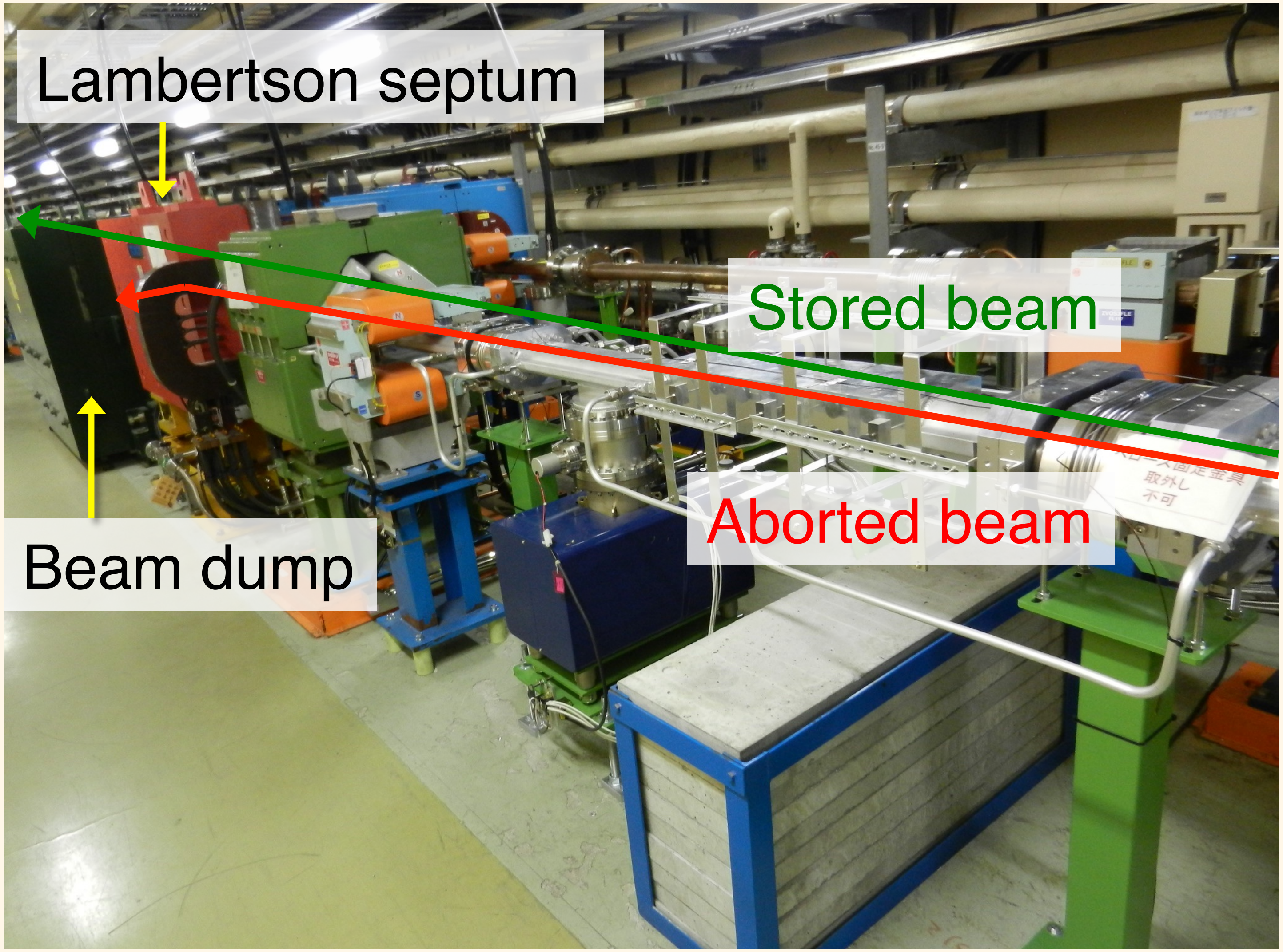


Uncorrectable XY-coupling remains.

Leakage Fields from a Lambertson Septum

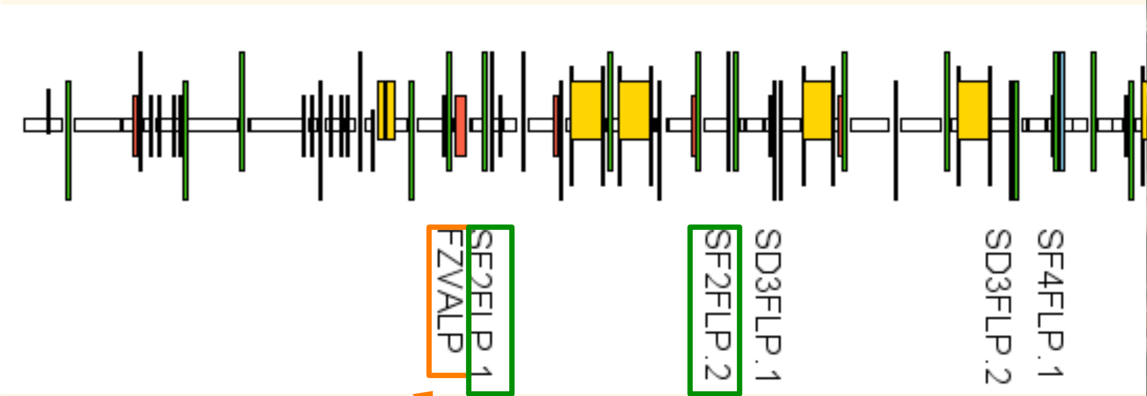
- A Lambertson septum is used to deliver aborted beams to a beam dump.
- It creates unexpected leakage field to the stored beam line.





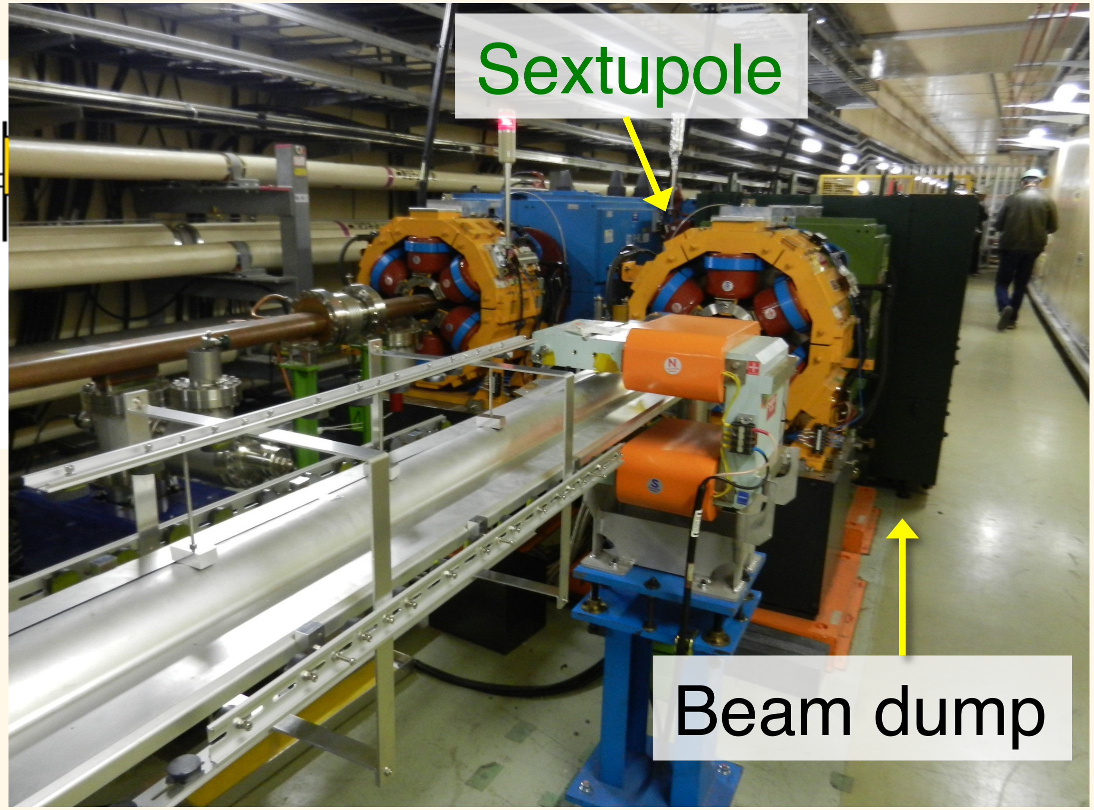
1st Countermeasure

- Activate two skew quadrouple coils
  installed in sextupole magnets using spare power supplies.



Lambertson septum

Activate those two corrector coils

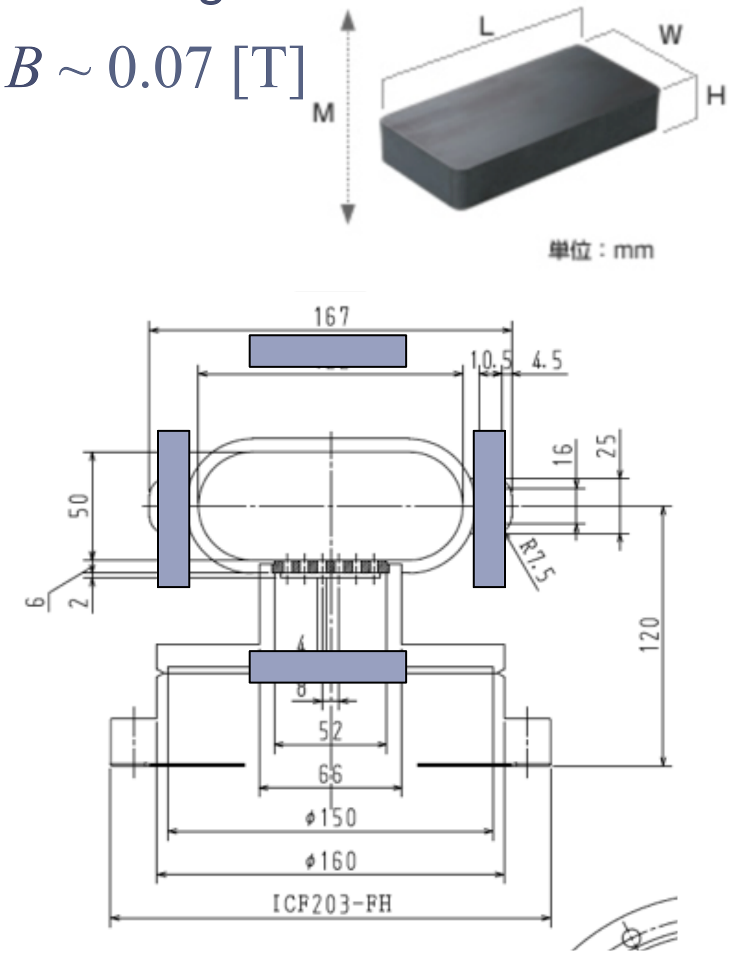


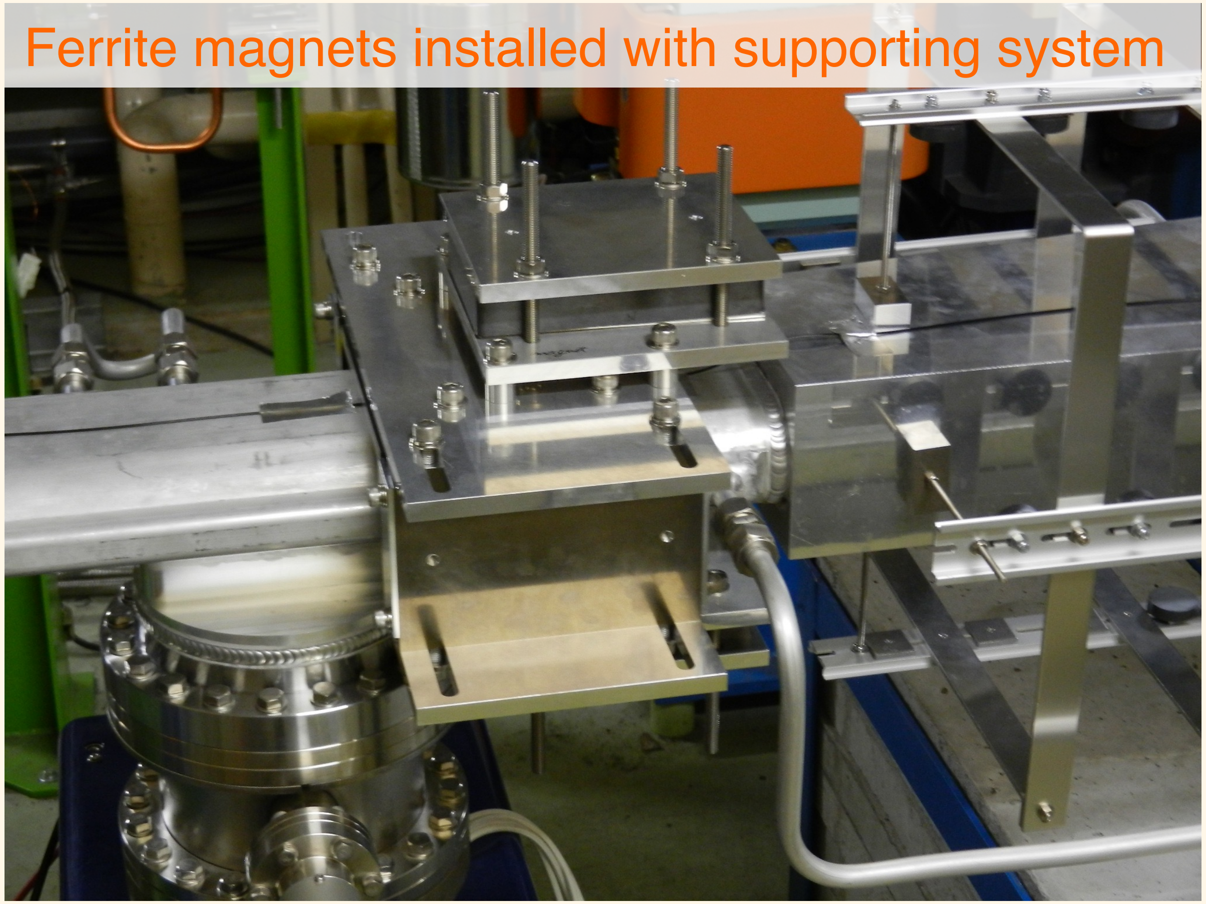
2nd Countermeasure

- Attached a permanent skew corrector using Ferrite magnets.

Ferrite magnets

$B \sim 0.07$ [T]

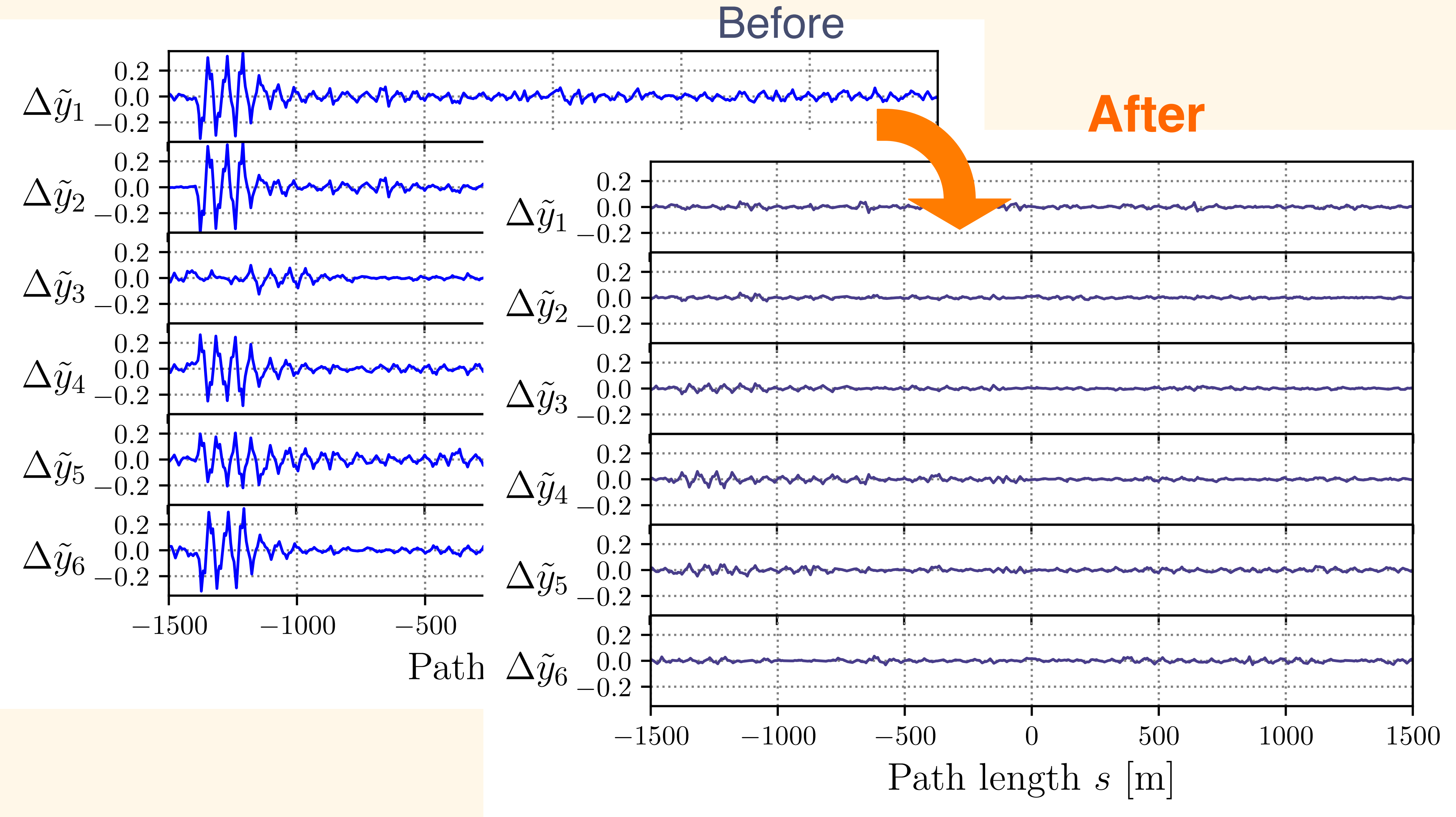




XY-Coupling *after* the Countermeasures

LER

- The two cures effectively work.

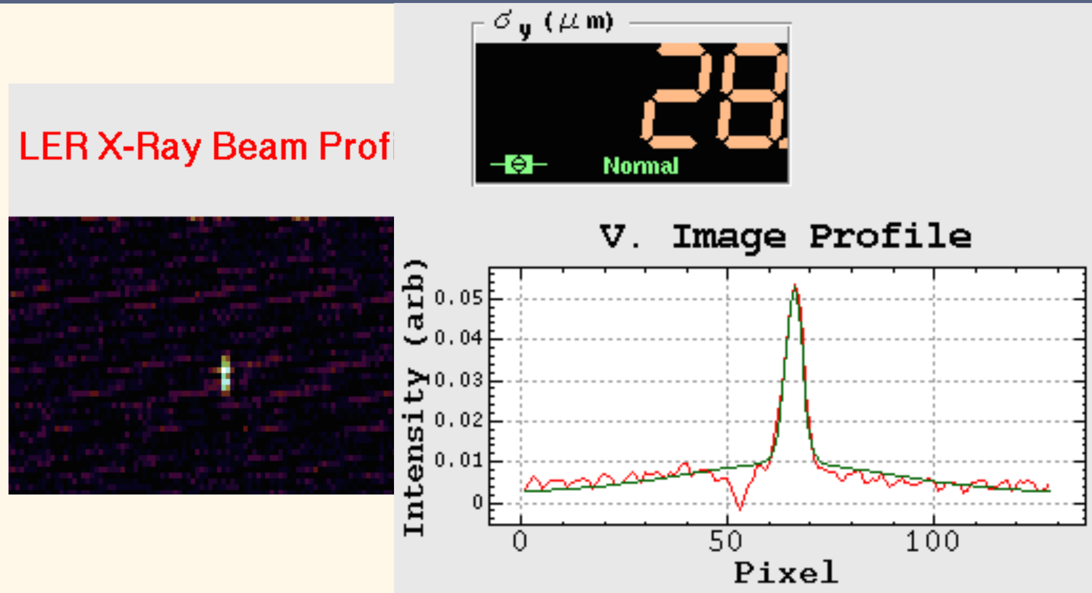


Vertical Emittance

- Two evaluation methods

<u>- X-ray beam size monitor</u>

<u>- Estimation by measured beam optics</u>



	LER	HER
X-ray Monitor	10 pm	40 pm
Beam Optics	10 pm	10 pm

- Discrepancy in the HER ring.

-> We plan to study more in the next commissioning.

Summary

- Calibration of the BPM system based on beam measurement.
  - Relative gains of BPM electrodes
  - Alignment between BPM and a neighbor magnet.
- Successful optics correction with the reliable BPM system.
- Magnetic interference between LER and HER magnets.
  -> Should be taken care for precise beam measurement.
- Unexpected optics distortion due to a Lambertson septum magnet.
  -> Resolved within the commissioning period.
- The lowest achieved vertical emittance
  Positron beam -> 10 pm
  Electron beam -> 10~40pm
  -> We plan to study more in the next commissioning.

Installation of Final Focus System is Ongoing

Thank You for Your Kind Attention!