Optics Correction

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1. Correction of XY Coupling and Vertical Dispersion
2. Correction of Betatron Function
3. Full Optics Correction

Introduction

- Correction of beam optics errors will be a critical factor in SuperKEKB.
- Innovative optics measurement & correction schemes are probably necessary at high-current beam operation.

  i.e. Horizontal & vertical (XY) coupling measurement with single-pass BPMs.

  (Ref. Ohnishi's talk @ the 16th KEKB review)
- On the other hand, KEKB based optics measurement using closed orbit distortion (COD) will be employed at early stage of the commissioning and low-current and non-collision operation.
- It is informative to investigate how effective is KEKB based scheme.

Today's Report

Optics Correction with KEKB based scheme

1. XY-Coupling and Vertical Dispersion
2. Betatron Function
3. Full Optics Correction

XY-Coupling and Vertical Dispersion

Measurement & Correction Scheme

- XY-coupling measurement & correction.

  1. XY-coupling is estimated by observing the vertical leakage orbits associated with horizontal kick.
  2. Suppress the vertical leakage orbit by skew correctors.

- Vertical dispersion measurement

  Use vertical orbit response with RF frequency change.

Orbit change

RF frequency

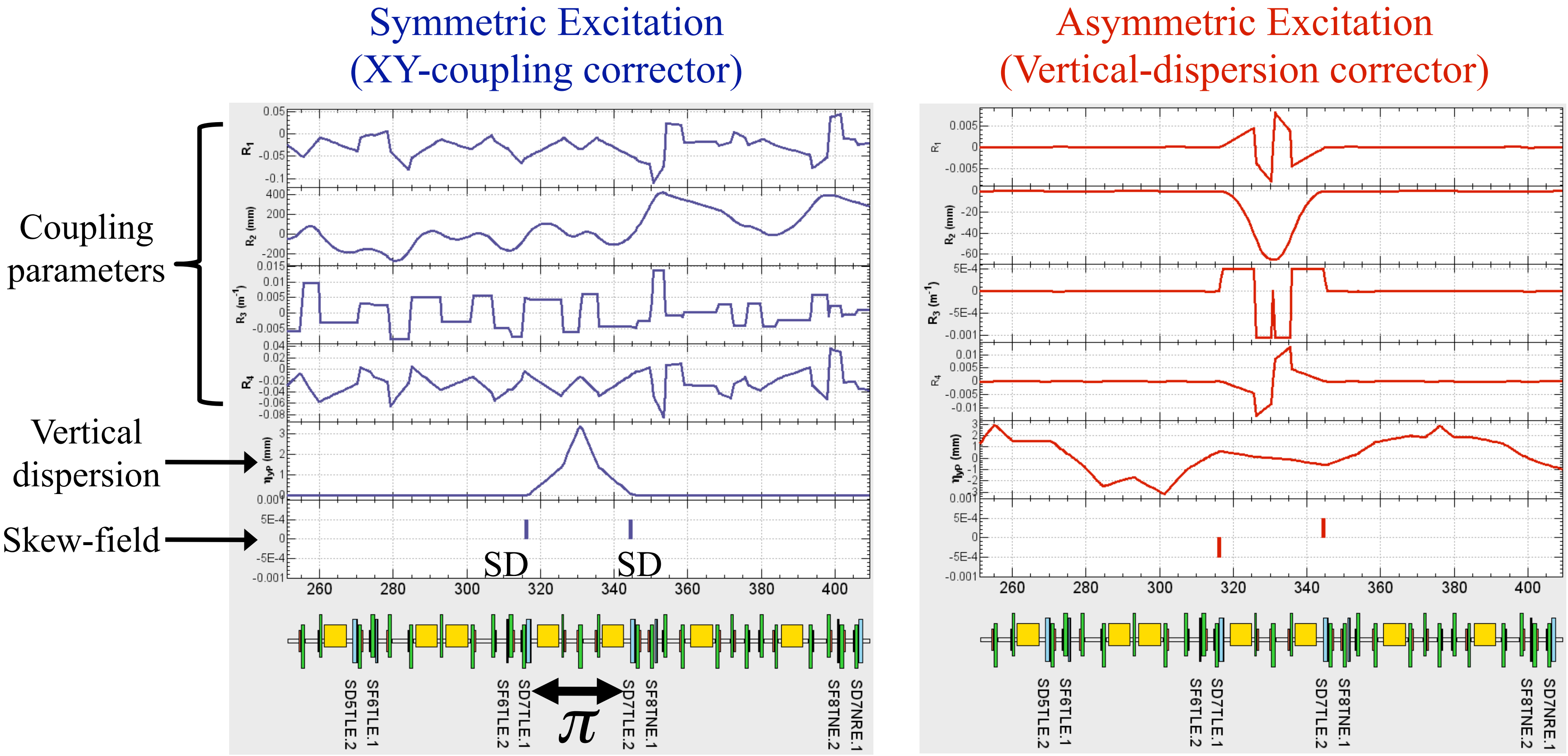
$$\eta_y \approx -f_0 \frac{\Delta y}{2\Delta f} \xi$$

Phase slip factor

Frequency change

Correctors

- Skew winding of sextupole magnet will be available.
- Symmetric / asymmetric excitation of skew-corrector pare can be used as orthogonal correctors for coupling and vertical dispersion.



Symmetric Excitation (XY-coupling corrector)

Asymmetric Excitation (Vertical-dispersion corrector)

Simulation

- Assumptions
  - No orbit drift in time.
  - Zero-current (ignore intra-beam scattering in emittance evaluation).
  - No error source in the IR region.

Error Source

	Vertical misalignment [μm]	Rotation error [μrad]
Normal quadrupoles	0	100
Normal sextupoles	100	0
Sextupoles (local chromaticity)	50	0

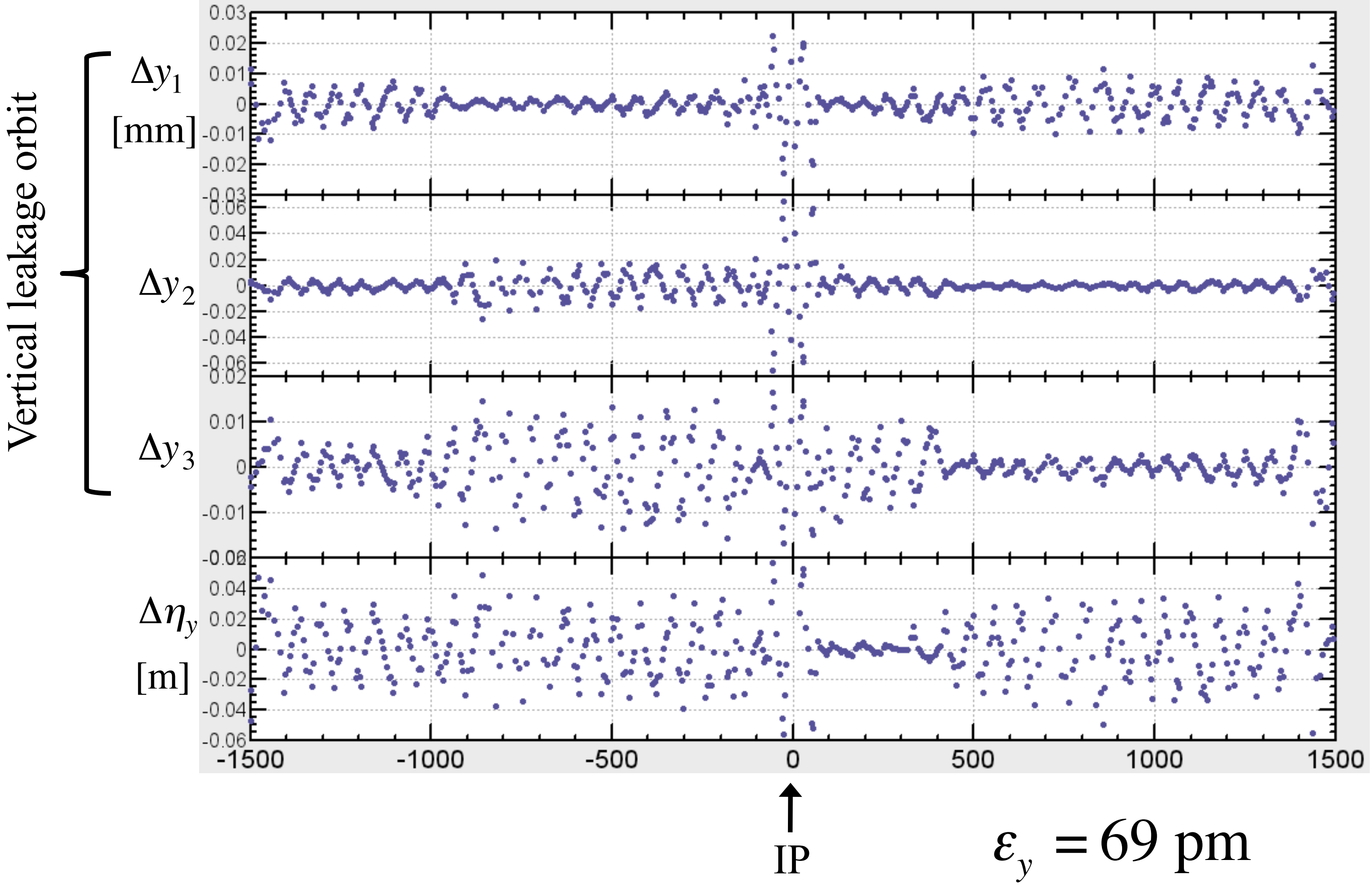
All errors are Gaussian distributed.

Skew correctors are adjusted by measured optics and response matrix of the model lattice with singular value decomposition.

Simulation Example

No BPM Jitter

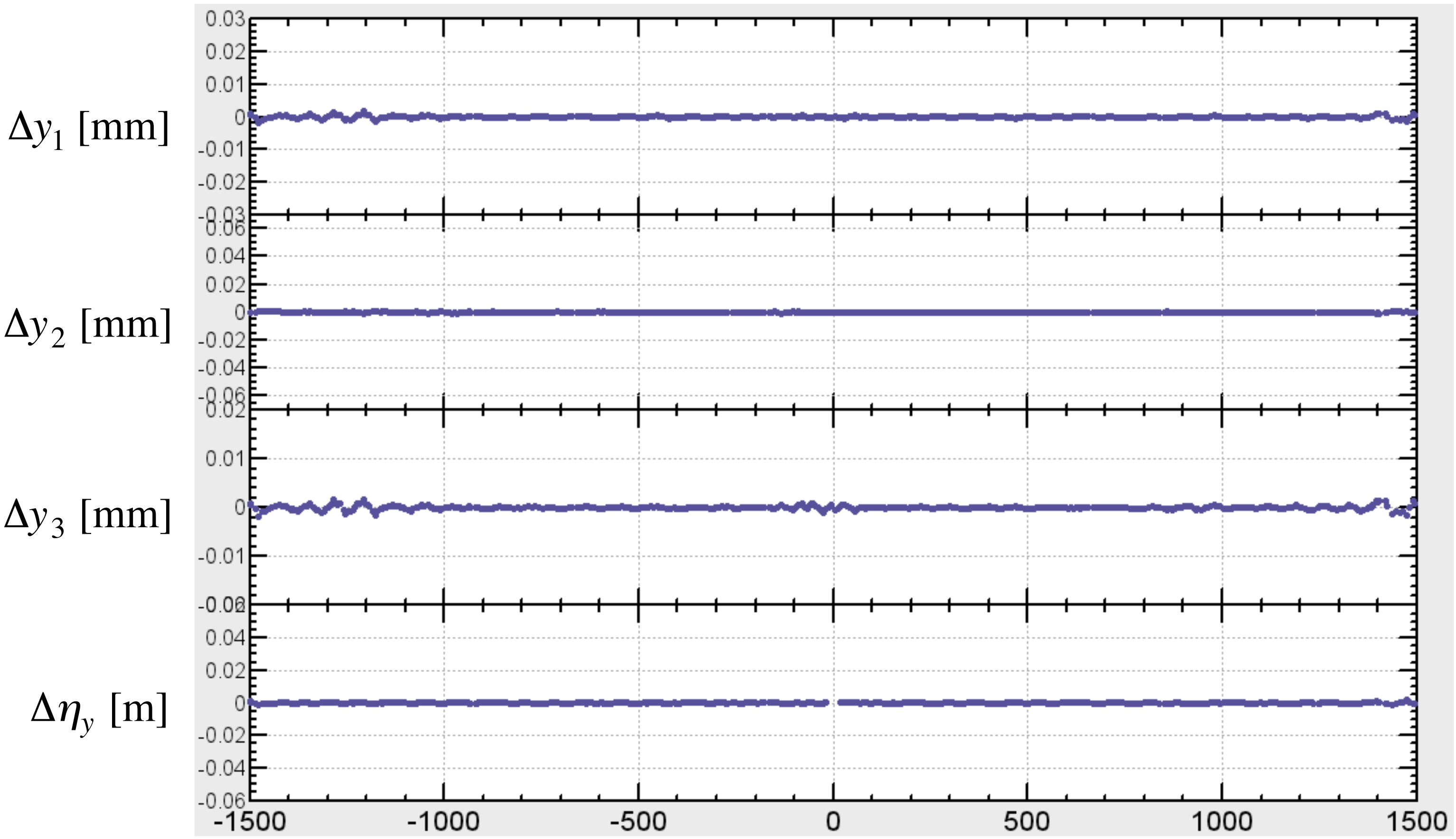
Before Correction



$$\varepsilon_y = 69 \text{ pm}$$

Simulation Example (No BPM Error)

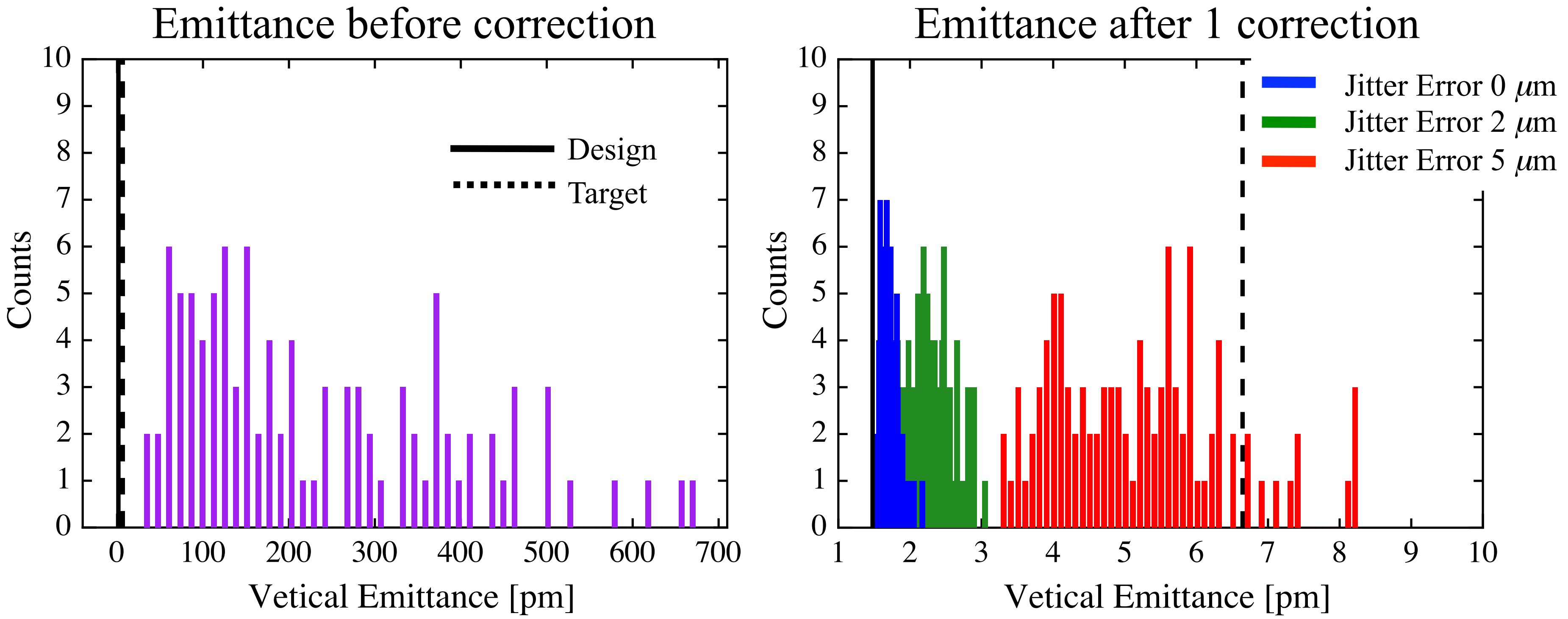
After Correction



$$\varepsilon_y = 69 \text{ pm} \longrightarrow \underline{\varepsilon_y = 1.5 \text{ pm}}$$

Vertical Emittance and BPM Jitter Error

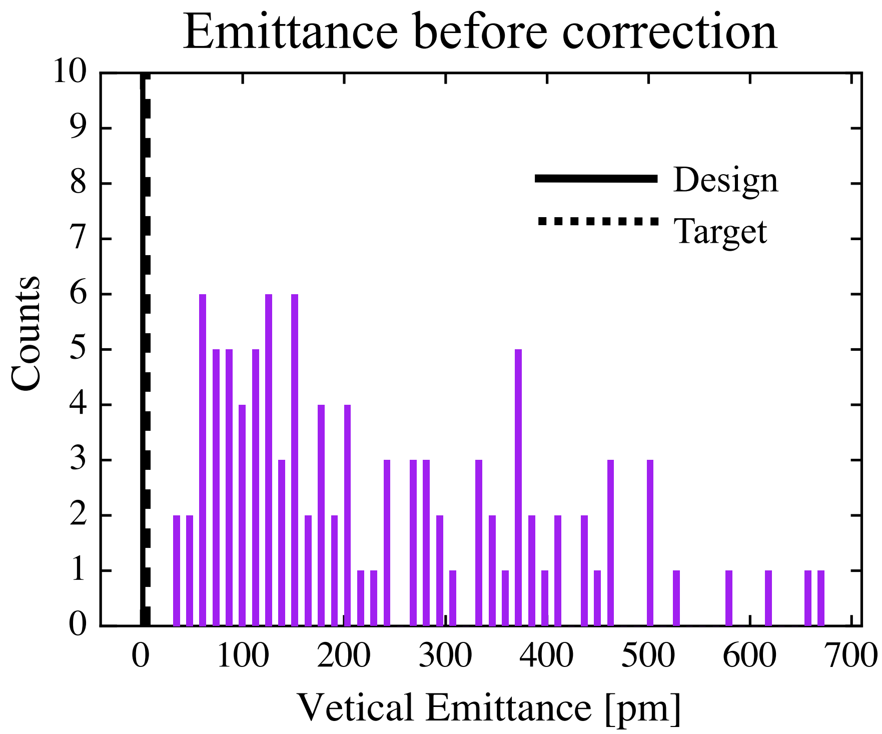
- 100 simulations with different seed of random numbers.



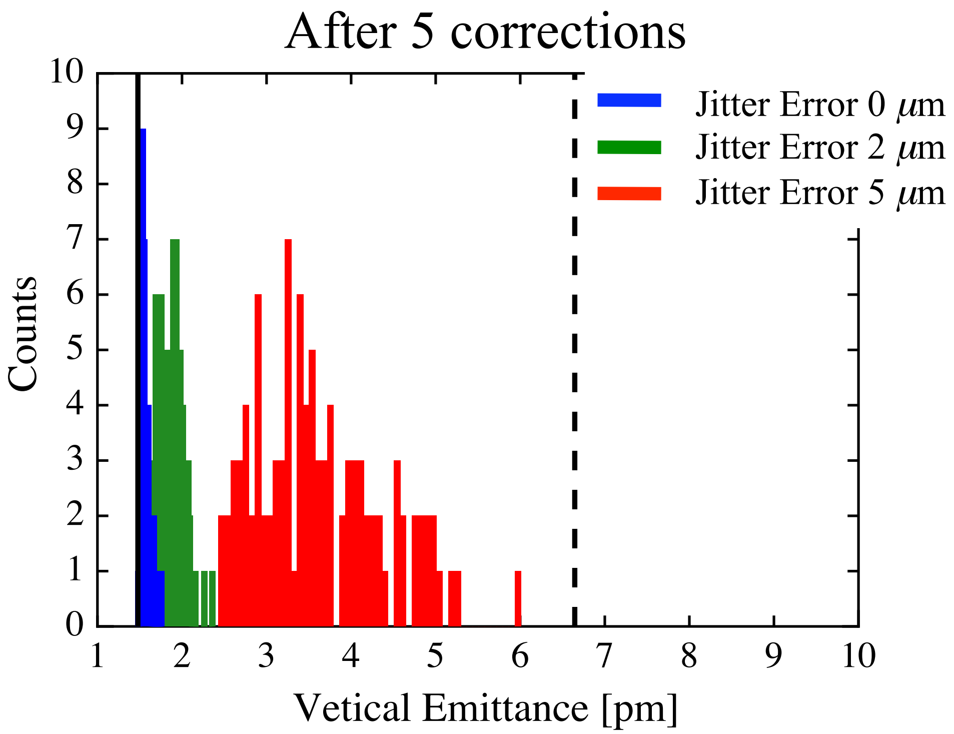
- Corrections of XY-coupling and vertical dispersion effectively reduce vertical emittance.

Vertical Emittance and BPM Jitter Error

- 100 simulations with different seed of random numbers.



Emittance before correction

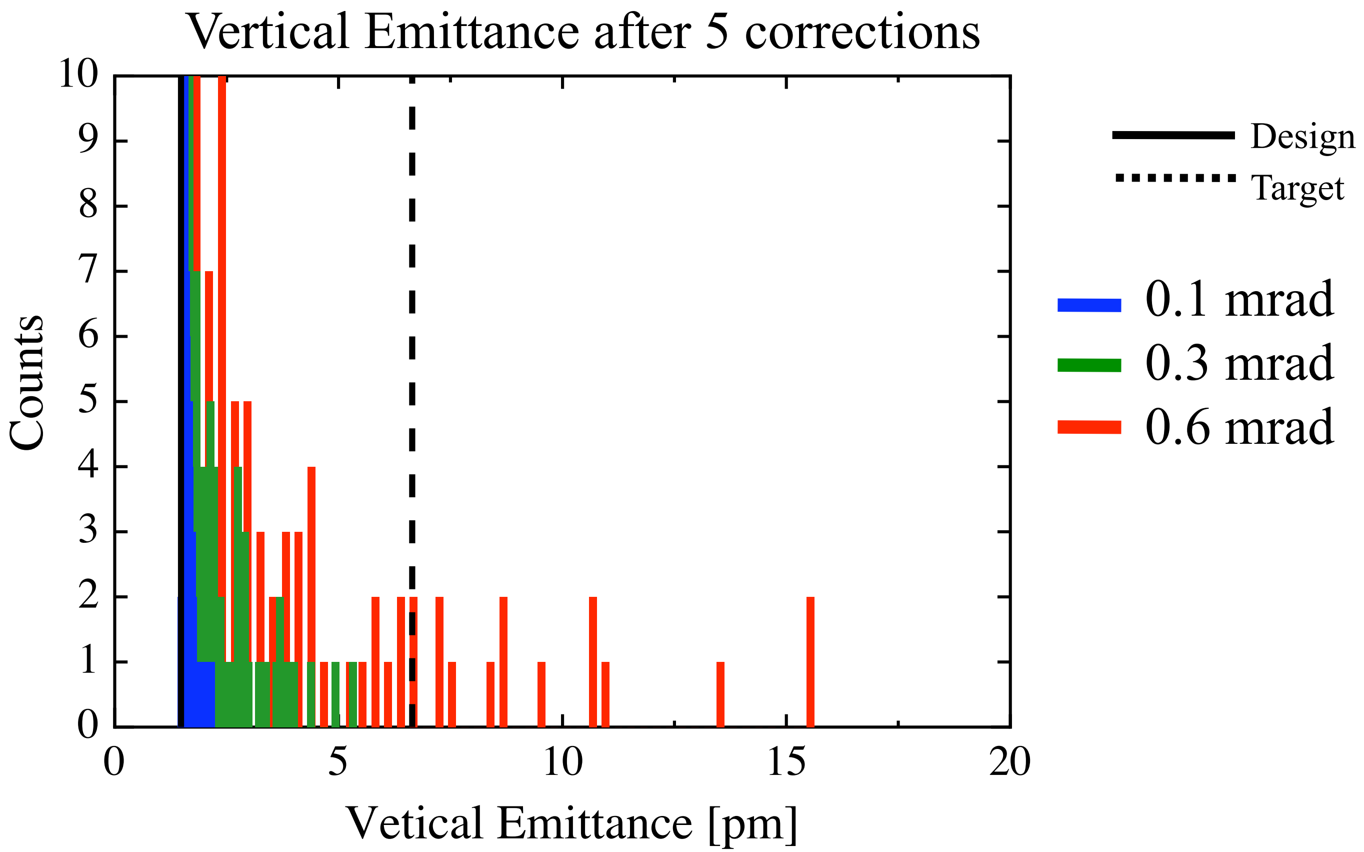


After 5 corrections

- Iterative correction is effective especially when BPM jitter error is large

Vertical Emittance and BPM Rotation Error

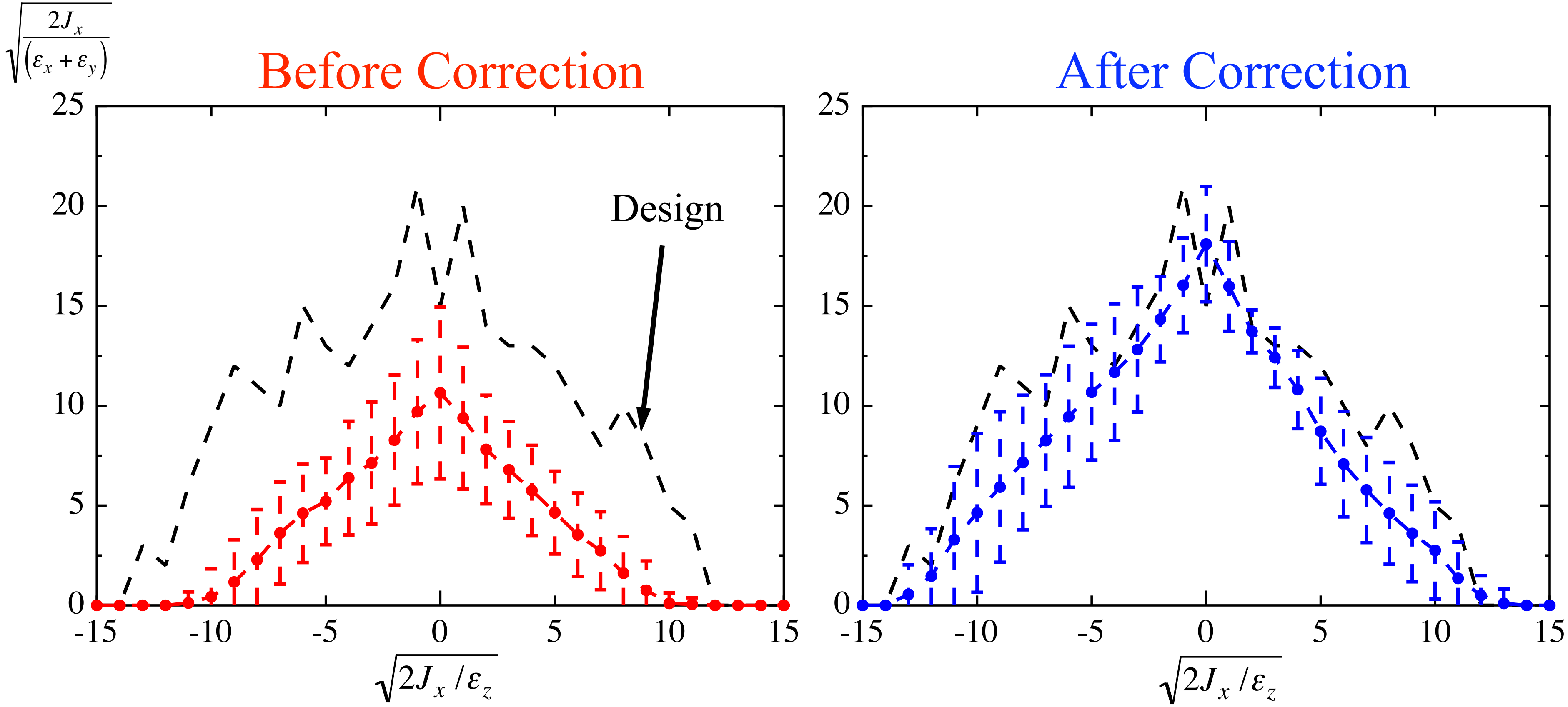
- 100 simulations with different seed of random numbers.



- BPM rotation error should be less than 0.5 mrad for the target vertical emittance.

Dynamic Aperture (DA)

- 100 simulations with different seed of random numbers.



- DA is dramatically improved by the optics correction.

Betatoron Function

Beta Measurement

Ref. A. Morita *et al*, PRSTAB **10**, 072801 (2007)

- Analyze CODs induced by steering kicks.
- COD at the *i* th BPM induced by *j* th steering kick in two forms.

$$\Delta x_i^j = \underbrace{\frac{\Delta k_j}{2\sin\pi\nu_x}\left(\cos\pi\nu_x X_j^S - S_{ij}\sin\pi\nu_x Y_j^S\right)X_i^M + \left(\cos\pi\nu_x Y_j^S + S_{ij}\sin\pi\nu_x X_j^S\right)Y_i^M}_{F\left(X_i^M, Y_i^M\right) \quad \cdots \quad \text{Form 1}}$$

$$= \underbrace{\frac{\Delta k_j}{2\sin\pi\nu_x}\left(\cos\pi\nu_x X_i^M - S_{ij}\sin\pi\nu_x Y_i^M\right)X_j^S + \left(\cos\pi\nu_x Y_i^M - S_{ij}\sin\pi\nu_x X_i^M\right)Y_j^S}_{G\left(X_j^S, Y_j^S\right) \quad \cdots \quad \text{Form 2}}$$

$$X_i^{M\ S} \equiv \sqrt{\beta_i^{M,S}}\cos\phi_i^{M,S}$$

$$Y_i^{M,S} \equiv \sqrt{\beta_i^{M,S}}\sin\phi_i^{M,S}$$

$$S_{ij} \equiv \mathrm{sign}\left(\phi_i^M - \phi_j^S\right)$$

- Find $\left\{X_i^M, Y_i^M\right\}$ and $\left\{X_j^S, Y_j^S\right\}$

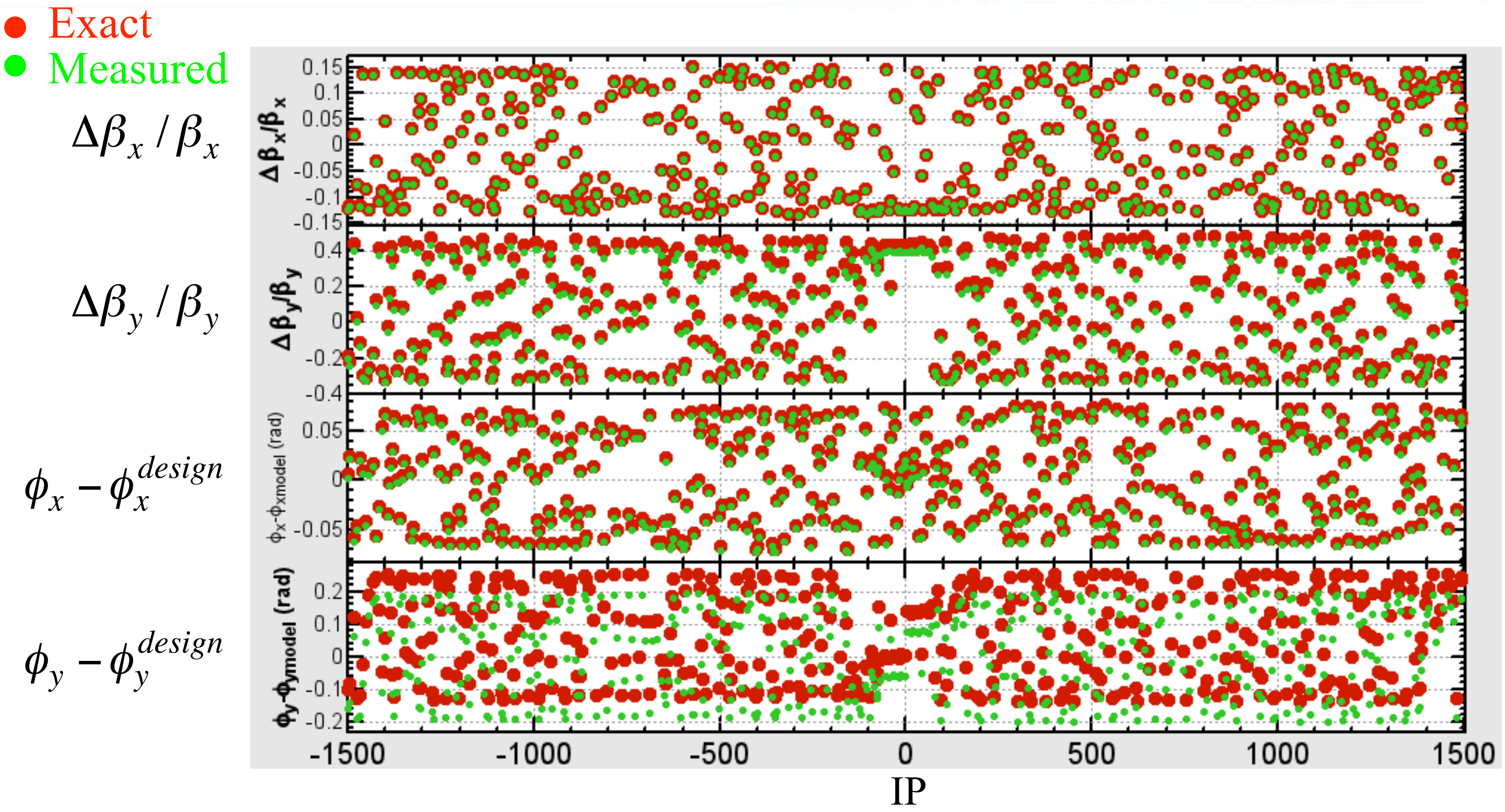
  which reproduce measured beam positions $\left\{\Delta x_{i\ meas}^j\right\}$

- The solution is obtained by iteratively minimize two quadratic functions.

$$S_1\left(X_i^M, Y_i^M\right) \equiv \sum_{i,j}\left|\Delta x_{i\ meas}^j - F\left(X_i^M, Y_i^M\right)\right|^2 \qquad S_2\left(X_j^S, Y_j^S\right) \equiv \sum_{i,j}\left|\Delta x_{i\ meas}^j - G\left(X_j^S, Y_j^S\right)\right|^2$$

Beta Measurement @ SuperKEKB HER

No BPM Jitter



- This scheme inevitably has two ambiguous.

1. Scaling of beta function

$$\left\{\beta_i^M\ ,\ \beta_j^S\right\} \mapsto \left\{\lambda\beta_i^M\ ,\ \lambda^{-1}\beta_j^S\right\}$$

2. Phase origin

$$\left\{\phi_i^M\ ,\ \phi_j^S\right\} \mapsto \left\{\phi_i^M + \delta,\ \phi_j^S + \delta\right\}$$

Beta Measurement @ SuperKEKB HER

No BPM Jitter

● Exact

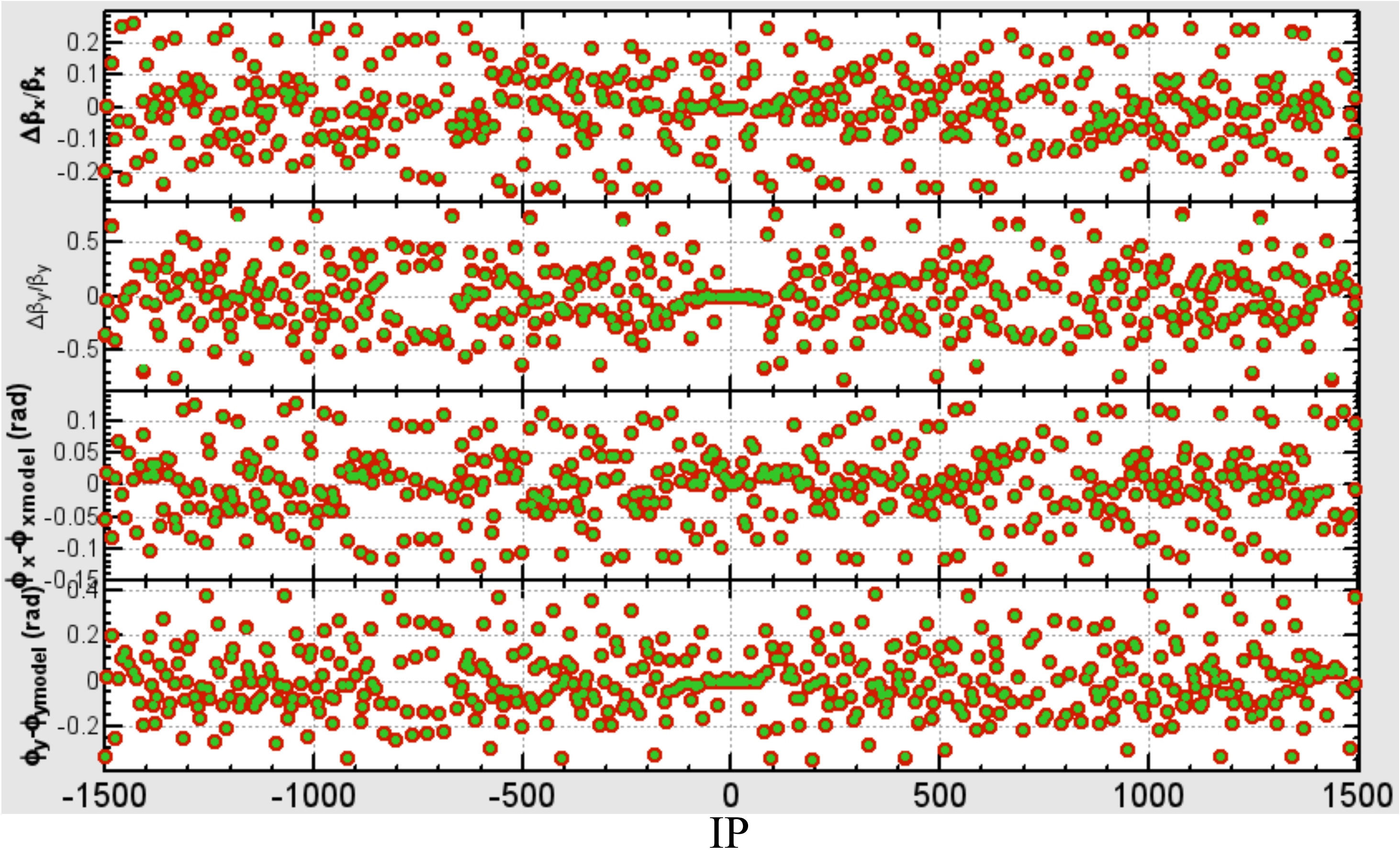
● Measured

$\delta\left(\Delta\beta_x / \beta_x\right)$

$\delta\left(\Delta\beta_y / \beta_y\right)$

$\delta\left(\phi_x - \phi_x^{design}\right)$

$\delta\left(\phi_y - \phi_y^{design}\right)$



- To avoid the ambiguous
  we use difference between neighborhood BPMs in the optics correction.

Simulation of Beta Correction

- Assumptions
  - No orbit drift in time.
  - Zero-current (ignore intra-beam scatteringin emittance calculation).
  - No error source in the IR region.
  - Exact values of perturbed tunes are known.

- Error Source (Gaussian distributed)

  $\frac{\Delta K_1}{K_1} = 5 \times 10^{-4}$ All normal quadrupoles

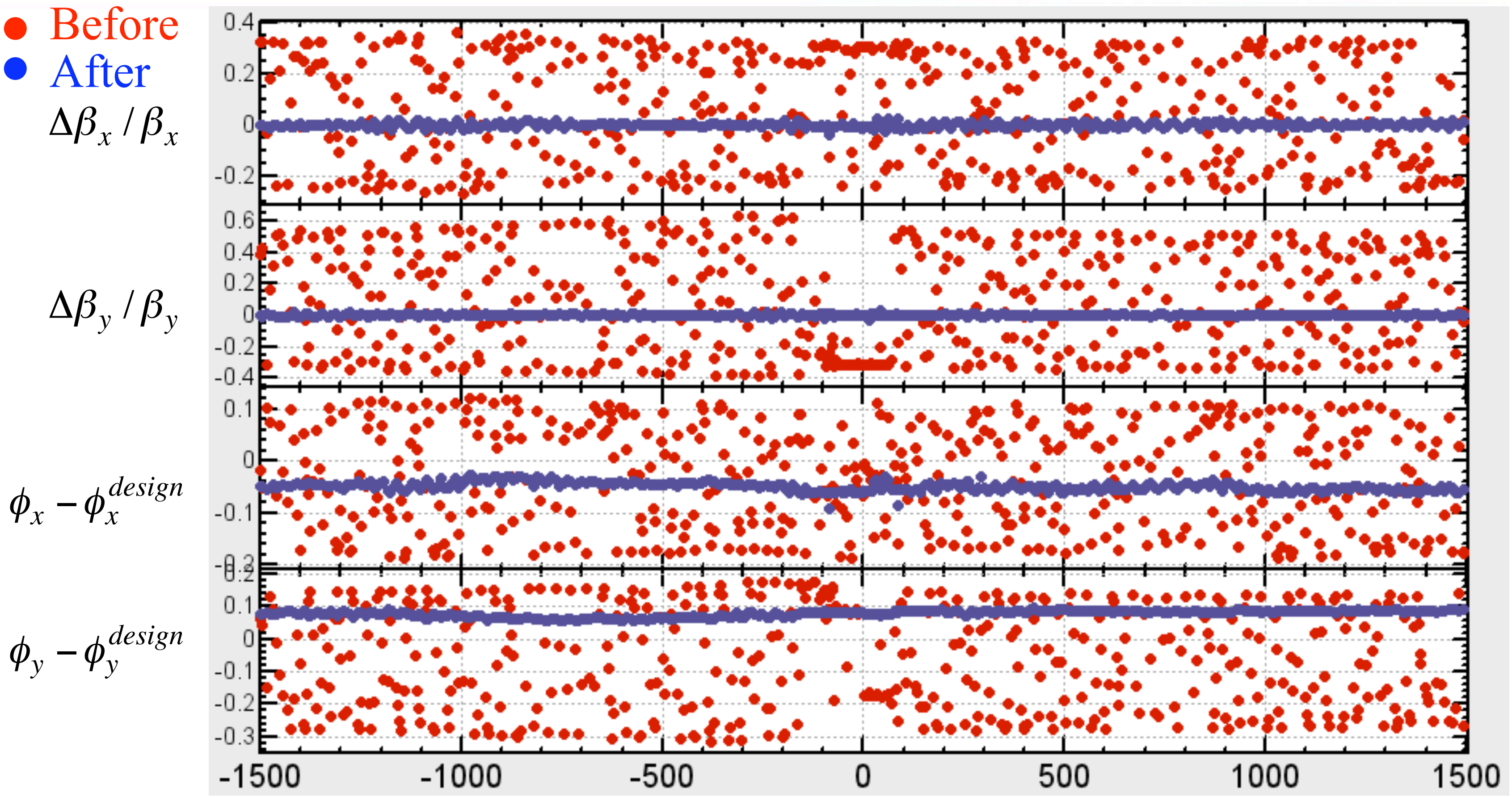
- Beta Measurement
  - Use 6 horizontal and 6 vertical orbit kicks.
  - Orbit amplitude at Arc section is about < 1mm.

- Corrector

  all quadrupoles (fudge factor of the electric power supplies)

Beta Correction @ SuperKEKB HER

No BPM Jitter



Before

$$\frac{\Delta\beta_x}{\beta_x} \approx 22\% \qquad \frac{\Delta\beta_y}{\beta_y} \approx 33\%$$

$$\Delta\nu_x = -6.5 \times 10^{-3} \qquad \Delta\nu_y = 4.1 \times 10^{-2}$$

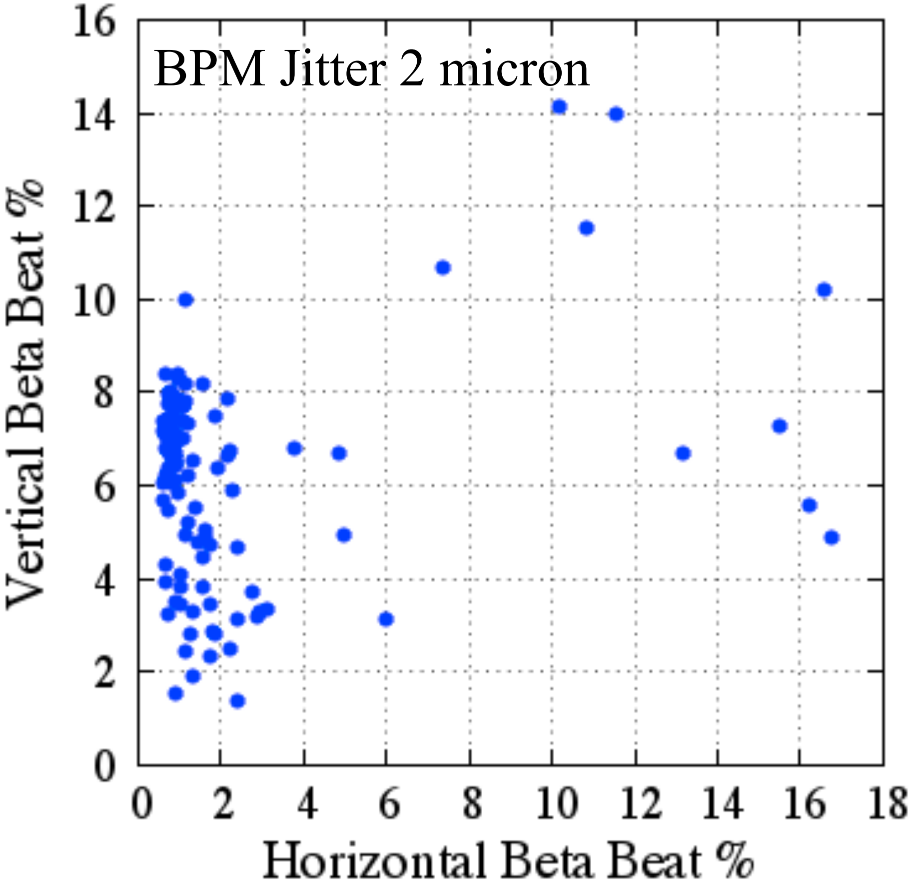
After

$$\frac{\Delta\beta_x}{\beta_x} \approx 0.9\% \qquad \frac{\Delta\beta_y}{\beta_y} \approx 0.5\%$$

$$\Delta\nu_x = -1.3 \times 10^{-4} \qquad \Delta\nu_y = 8.2 \times 10^{-4}$$

Global Beta Beat After Correction (SuperKEKB HER)

- 100 simulations with different seed of random numbers.



- Typically, global beta beat for 2 micro bpm jitter is within ~5% for horizontal and within ~10% for vertical betatron motion.

Full Optics Correction

Measurement Method and Corrector Knob

- All measurements are based on COD or its response.

	Measurement Method	Corrector Knob
COD	BPM reading	Horizontal/Vertical Steerings
XY Coupling	COD response associated with horizontal steering kick	Skew winding of sextupoles
Vertical Dispersion	COD response associated with RF frequency change	Skew winding of sextupoles
Betatron Function&Phase	COD response associated with steering kick	quadrupole (fudge factor)
Horizontal Dispersion	COD response associated with RF frequency change	Horizontal mover of focusing sextupoles

Simulation Condition

Error Source

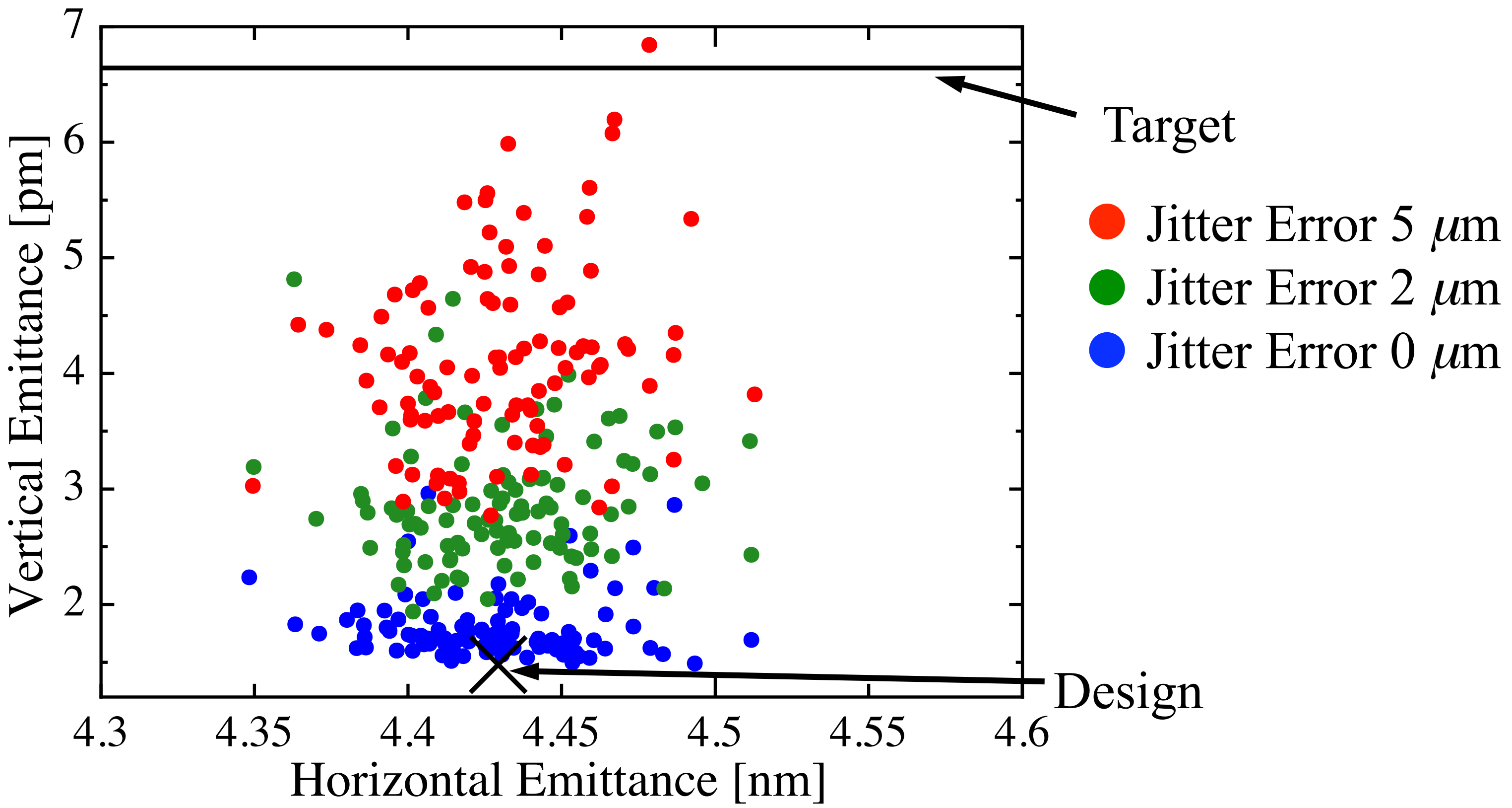
	Horizontal misalignment [μm]	Vertical misalignment [μm]	Rotation error [μrad]	ΔK/K
Quadrupoles	100	100	100	$2.5*10^{-4}$
Sextupoles	100	100	0	0

- Assumptions
  - No orbit drift in time.
  - Zero-current (ignore intra-beam scattering in emittance calculation).
  - No error source in the IR region.
  - Exact values of perturbed tunes are known.

- Beam optics is unstable if we introduce the error sources at once.
- Thus, we gradually increase the error amplitude with the optics corrections.

Emittance

- 100 simulations with different seed of random numbers.

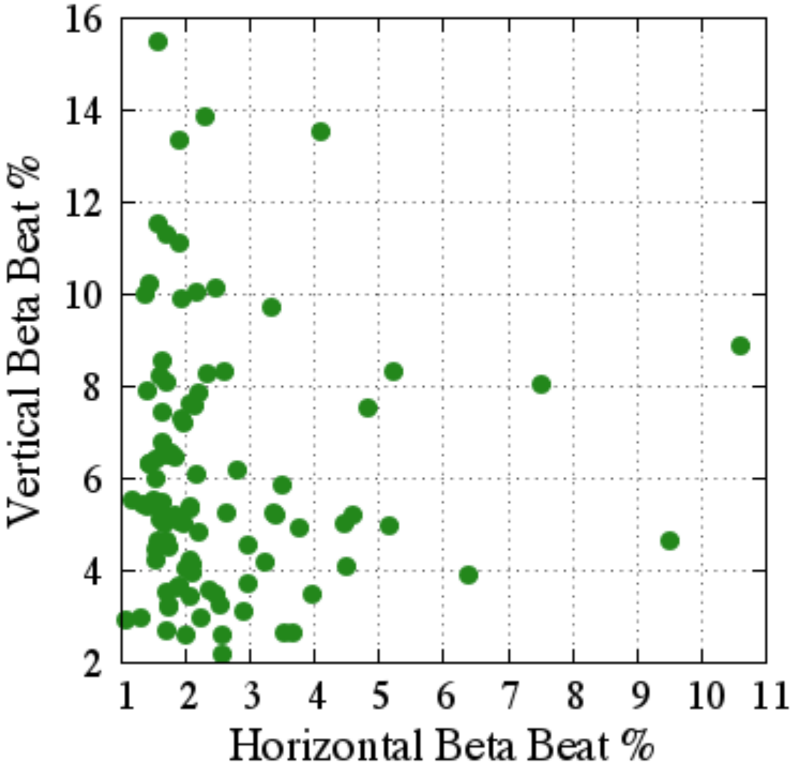


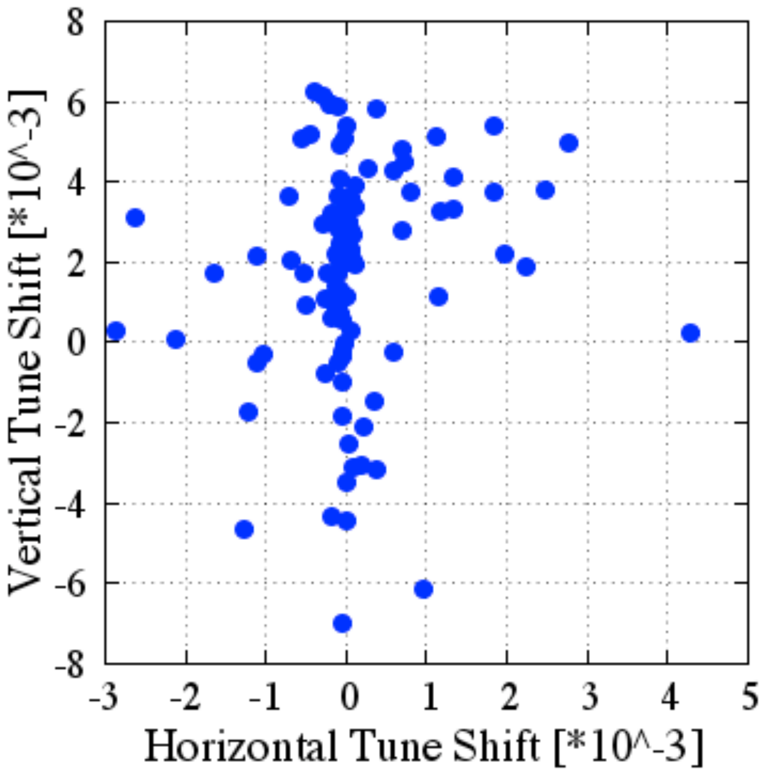
- Iterative correction with adjusting correction parameters is necessary to improve vertical emittance.
- Reached vertical emittance is sensitive to the correction parameters especially when BPM jitter is large.

Beta Beat After Optics Correction

2 micro BPM Jitter

- 100 simulations for different random seeds.

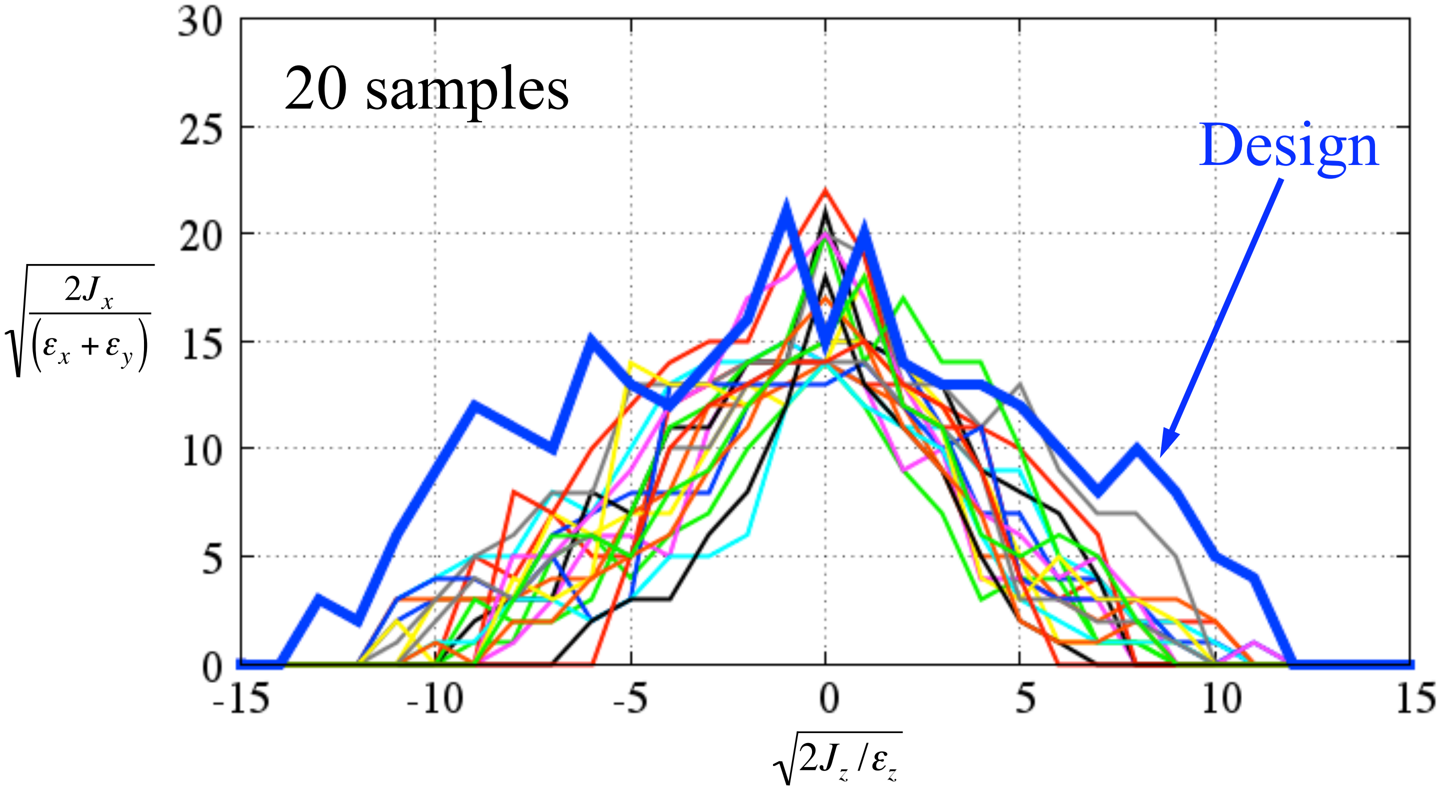




- Vertical beta beat is typically within ~10%, and ~5% for horizontal direction.

Dynamic Aperture

2 micro BPM Jitter



- On-momentum aperture is improved to the design level.
- Optimization of higher order multipole magnets is necessary to improve off-momentum aperture (in progress)

Summary and …

- COD based scheme is applied to SuperKEKB HER lattice.
  - Iterative corrections is necessary to reduce vertical emittance.
  - BPM rotation should be less than 0.5 mrad for the target vertical emittance.
  - In typical case, global beta beat is within ~5% for horizontal and within ~10% for vertical betatron motion.
  - After full optics corrections, we can reach the target vertical emittance.
  - Achieved vertical emittance is sensitive to the correction parameters especially when BPM error is large.
  - On-momentum DA is improved to the design level.
  - As for off-momentum DA, it is expected to be improved by tuning higher order multipole fields, but not confirmed yet.

- To be studied
  - More detailed study on optics measurement using single-pass BPM.
  - Error source in IR region.
  - Orbit drift

and so on…

Thank you for listening!