Imperfection and correction for CEPC

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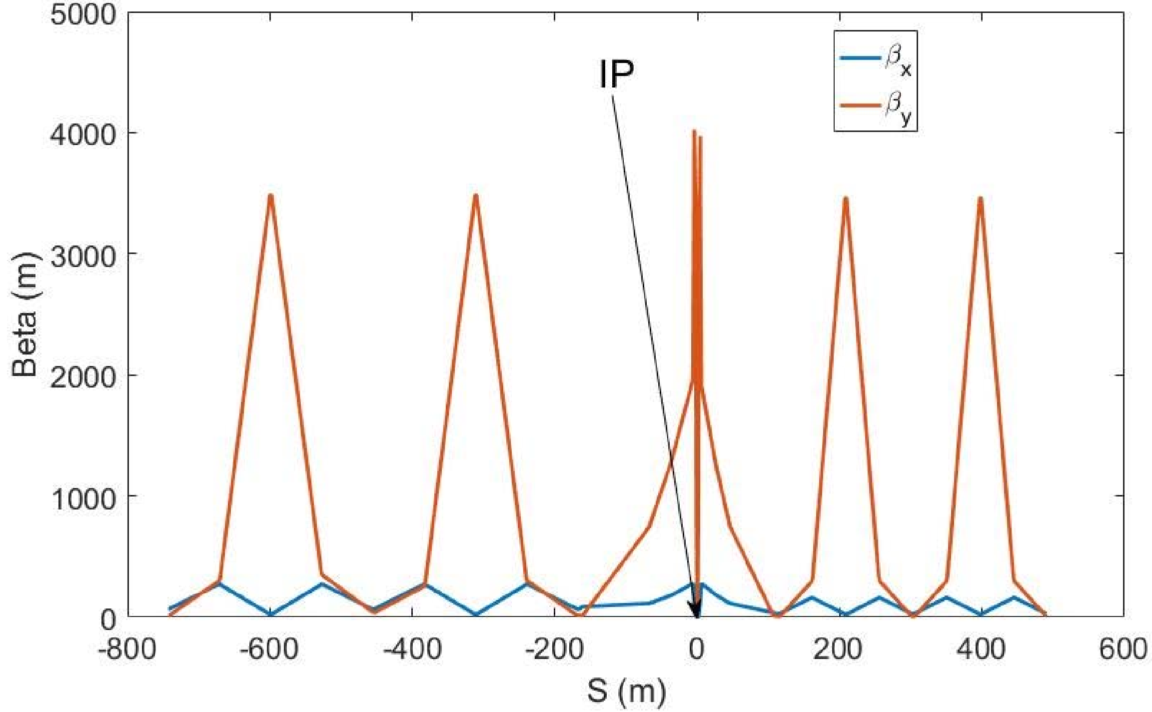
Lattice



- E=120GeV
- ν_x=363.11

  ν_y=365.22
- $\beta_x^* = 0.36$m

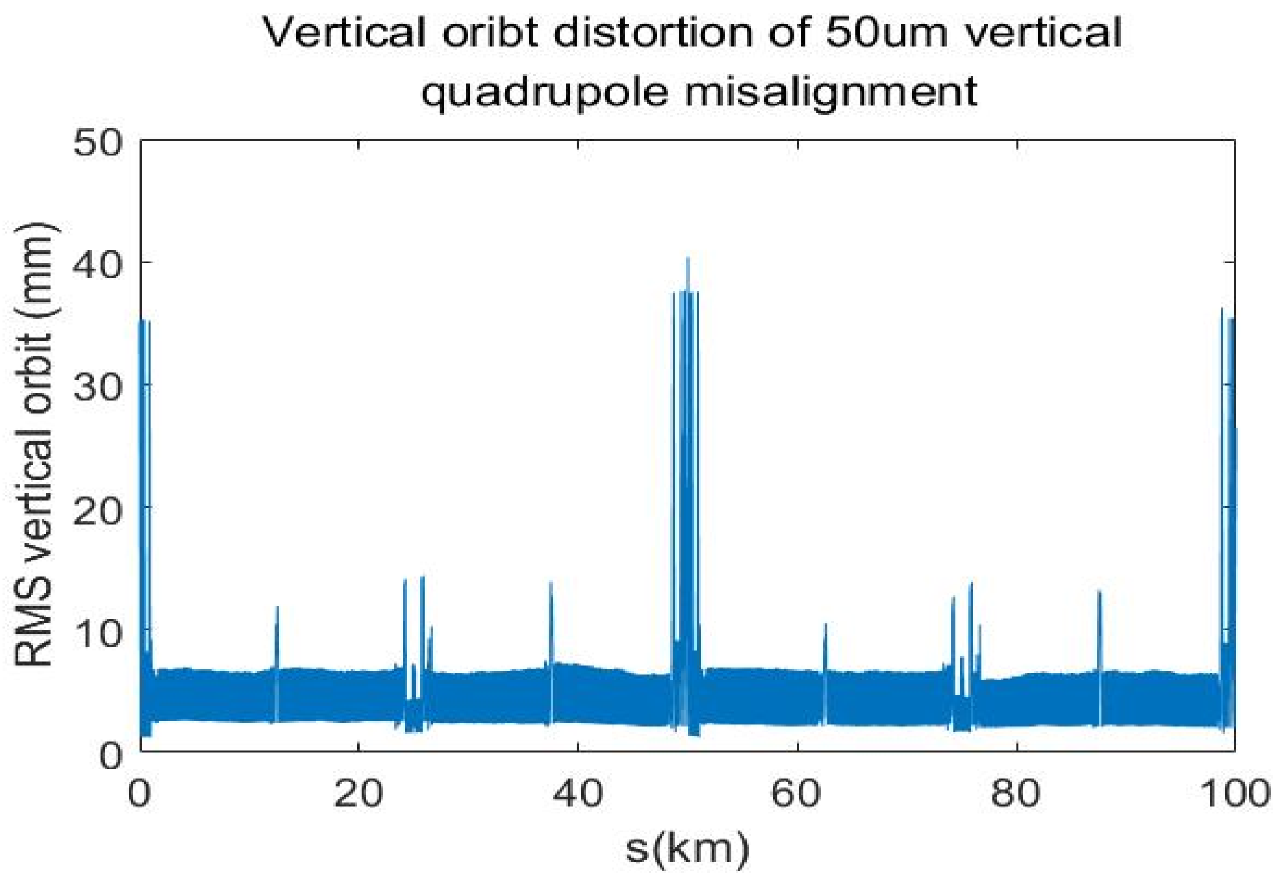
  $\beta_y^* = 0.0015$m

  $\beta_{x,max}$=599m

  $\beta_{y,max}$=4023m
- $\varepsilon_x = 1.21$nm

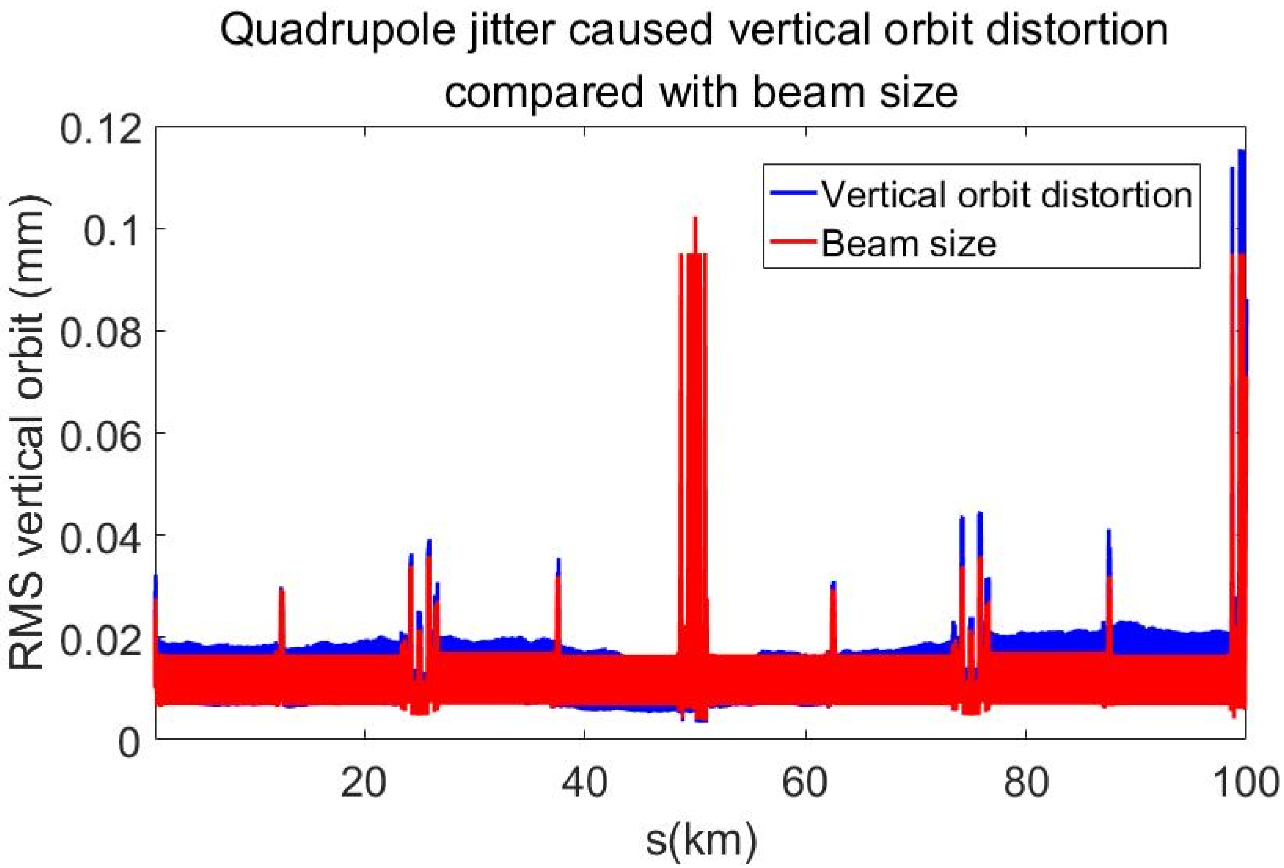
  $\varepsilon_y = 2.4$pm

Orbit amplification factor



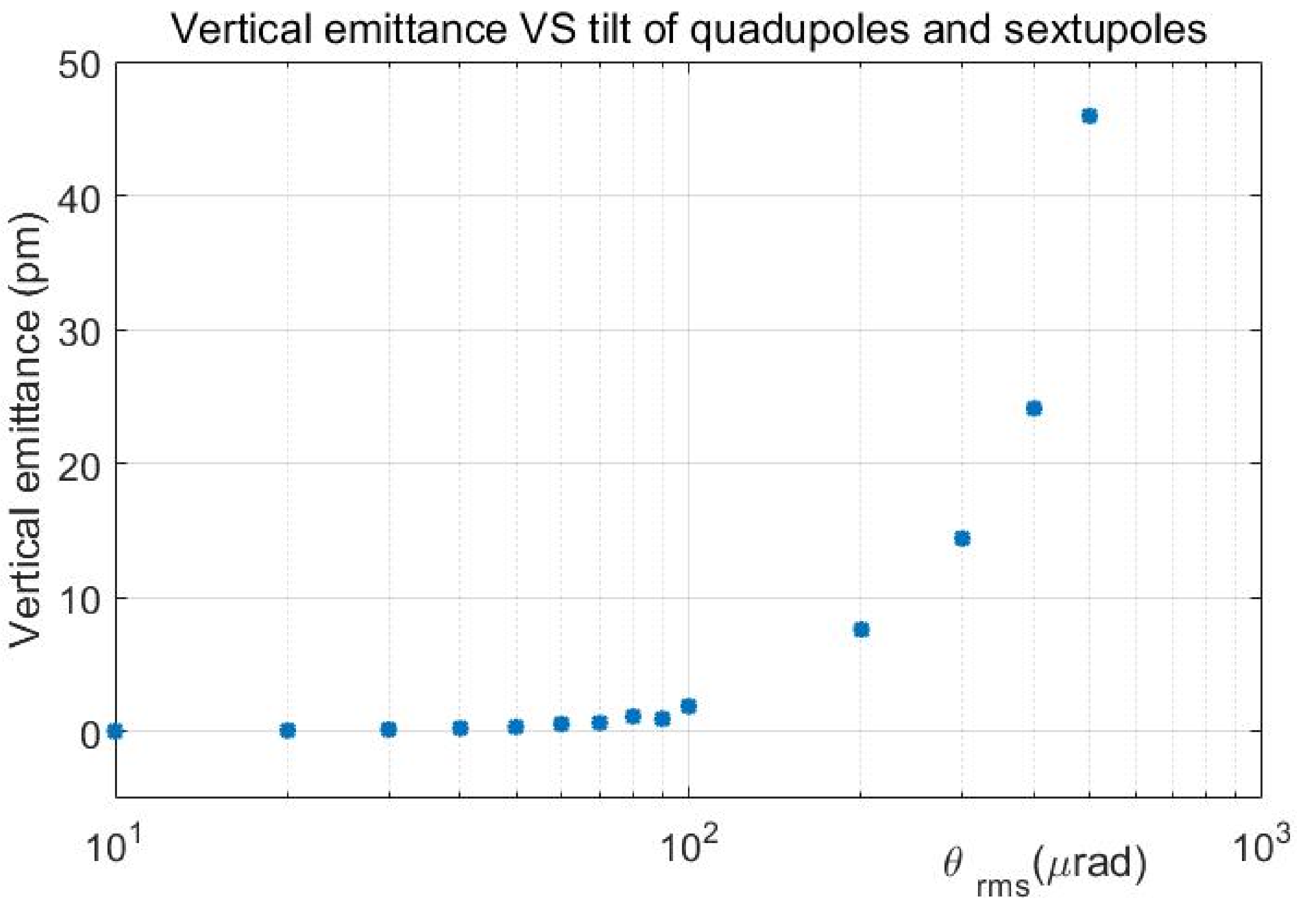
- $<\Delta y_{rms}>$ = 4.69mm
- Orbit amplification factor = 4.69/50e-3 = 94
- Turn off sextupoles and FF is left perfectly aligned.

Quadrupole jitter sensitivity



- The RMS vertical orbit distortion caused by 0.15μm quadrupole jitter is equal to beam size at 2.4pm vertical emittance.
- Turn off sextupoles and FF is left perfectly aligned.

Quadrupoles and sextupoles tilt sensitivity



- 100 μ**rad** rotation ~ 2pm vertical emittance

Misalignment sensitivity

	Super *B* LER	Super *B* HER	ILC DRs	KEK ATF	CEPC
Vertical emittance (pm)	4	4	2	4.5	2.4 0.2%coupling)
Orbit amplification factor	46	44	32	21	94
Quadrupole jitter sensitivity (nm)	209	217	221	227	150
Sextupole alignment sensitivity (μm)	95	87	70	50	16
Quadrupole tilt sensitivity (μrad)	166	183	79	800	100 (sextupoles included)

Misalignment and field errors

Component	Δx (μm)	Δy (μm)	$\Delta\theta_z$ (μrad)
Arc quadrupole	100	100	100
IR Quadrupole w/o FF	50	50	50
Sextupole	100	100	100

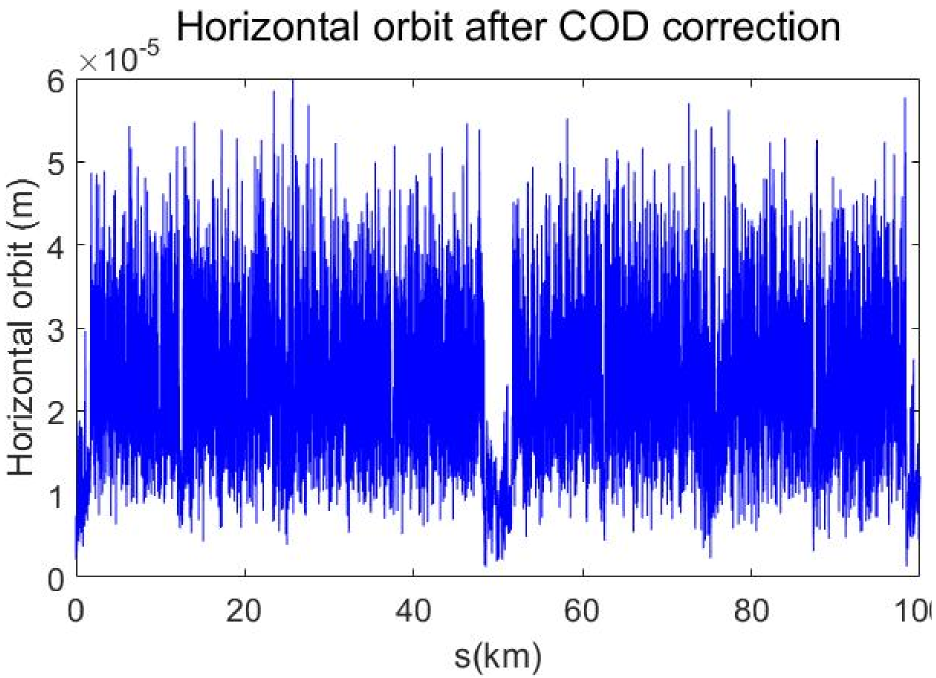
Component	Field error
Dipole	0.01%
Arc Quadrupole	0.02%

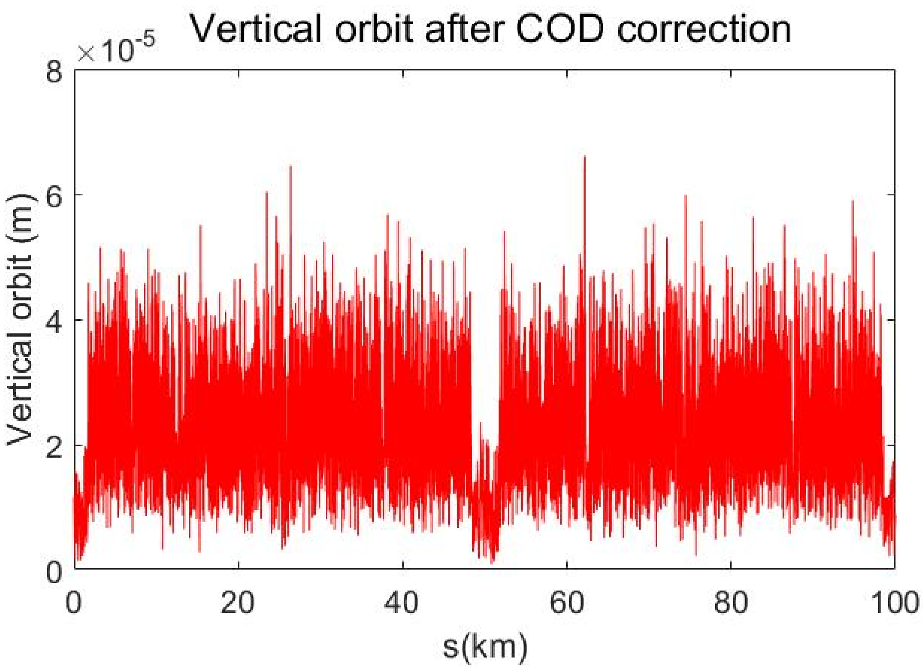
Correction scheme

- COD correction with sextupoles off (the misalignment of FF is not included)
- Turn on the sextupoles and perform COD correction again.
- Dispersion correction (DFS)
- Beta beating correction (LOCO)
- Coupling and vertical dispersion correction (Local coupling parameter correction）.

COD after correction

- BPMs placed at quadrupoles (~1500, 4 per betatron wave)
- Horizontal correctors placed beside focusing quadrupoles（~1500）
- Vertical correctors placed beside defocusing quadrupoles（~1500）





Distortion $RMS_{COD} <$ 0.1 mm after orbit correction

Dispersion correction

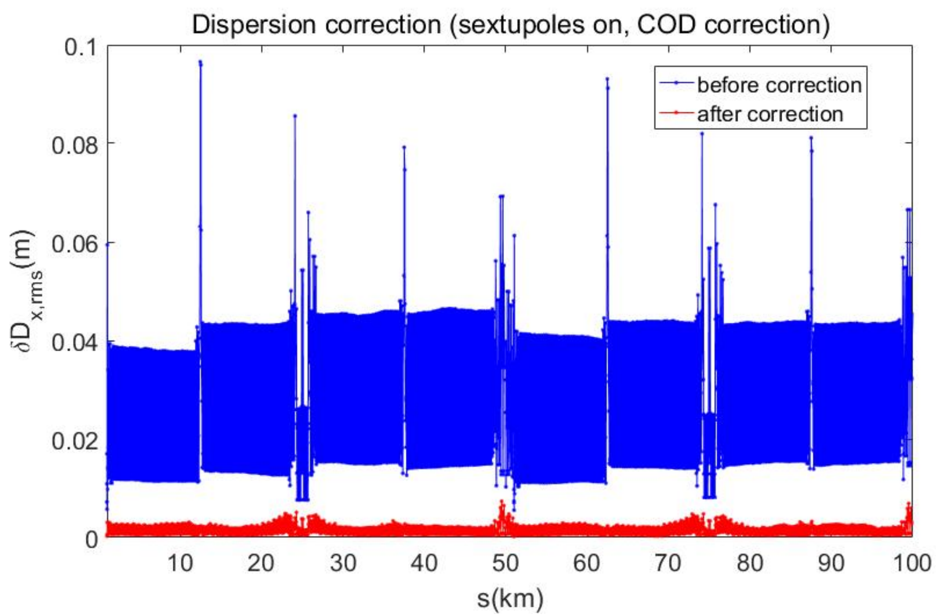
- Dispersion free steering principle (DFS): orbit manipulation by knob correctors.

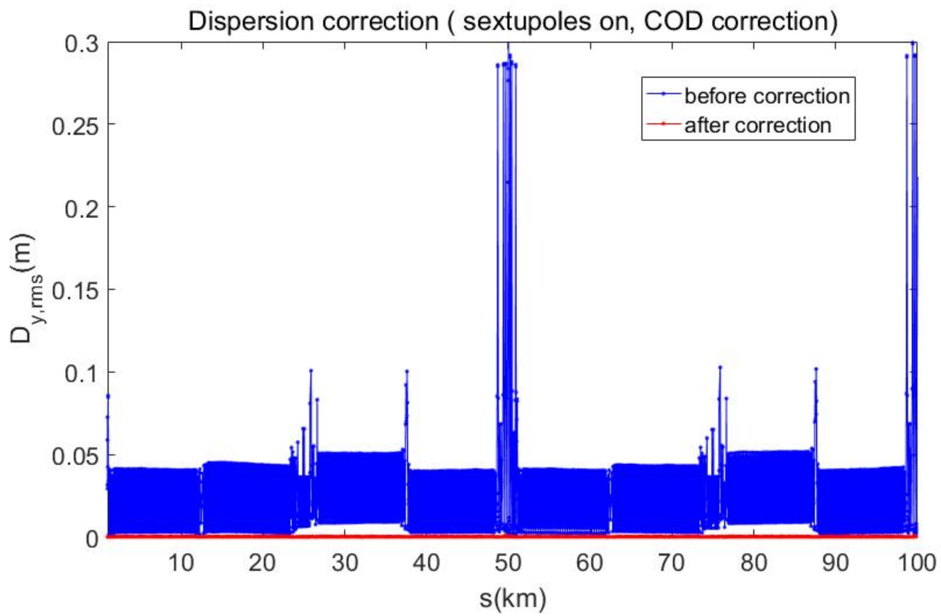
$$\vec{d} = \begin{pmatrix} (1-\alpha)\vec{u} \\ \alpha \vec{D}_u \end{pmatrix} \qquad M = \begin{pmatrix} (1-\alpha)A \\ \alpha B \end{pmatrix}$$

$$\vec{d} + M\vec{\theta} = 0$$

$\vec{u}$: Orbit vector
$\vec{D}_u$: Dispersion vector
$\vec{\theta}$: Corrector strengths vector
α: Weight factor
A: Orbit response matrix
B: Dispersion response matrix

Dispersion correction





$\Delta D_{x,rms}$ decreased from 30mm to 1.7mm
Factor 20 improvement

$D_{y,rms}$ decreased from 40mm to 0.2mm
Factor 200 improvement

Beta-beating correction

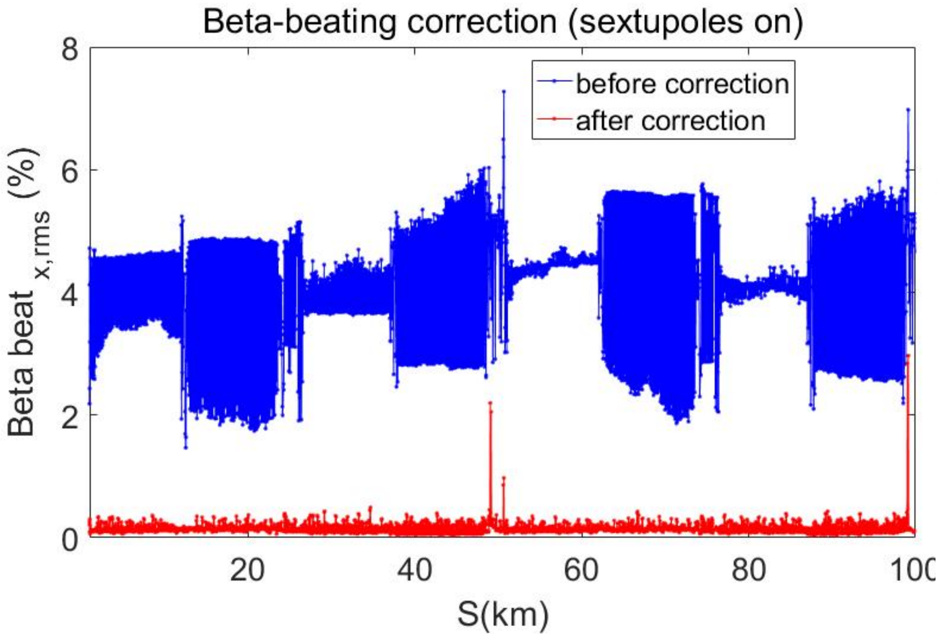
- Based on AT LOCO: model based correction
  - Establish lattice model $\boldsymbol{M}_{mod}$, multi-parameter fit to the orbit response matrix $\boldsymbol{M}_{meas}$ to obtain calibrated model:

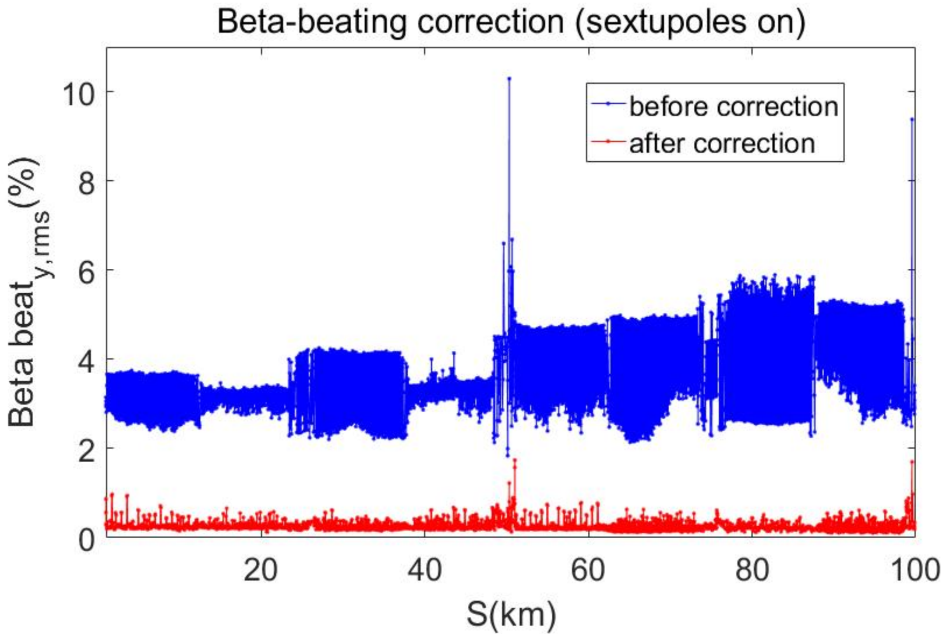
$$\chi^2 = \sum_{i,j} \frac{(M_{\mathrm{mod},ij} - M_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2$$

  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
  - Application to correct beta-beating, dispersion and coupled response matrix.

Beta-beating correction

- 1/5 quadrupole (~600 out of 3000 quadrupoles) strengths are changed to restore beta functions along the ring.





$\Delta\beta/\beta_{x,rms}$ decreased from 3.1% to 0.25%

$\Delta\beta/\beta_{y,rms}$ decreased from 3.7% to 0.3%

Coupling correction

- Neglecting beam-beam effects

$$\varepsilon_y \simeq \varepsilon_{y0} + \kappa\varepsilon_x + rE^2(D_y^{\mathrm{rms}})^2$$

- Local coupling parameter matching was developed for BEPCII.
- Both coupling and dispersion can be corrected.
- Using the trim coils of the sextupoles (~1000), which providing skew-quadrupole field, to perform emittance tuning for CEPC.
- The vertical orbit distortion due to a horizontal deflection at a BPM is:

$$\boxed{\frac{\Delta y_{cod}}{\Delta x_{cod}} = \bar{c}_{b,22}k_1 + \bar{c}_{b,12}k_2 + \bar{c}_{c,11}k_3 + \bar{c}_{c,12}k_4}$$

k_1, k_2, k_3, k_4 : only related to the decoupled linear optics

$\bar{c}_{b,22}, \bar{c}_{b,12}, \bar{c}_{c,11}, \bar{c}_{c,12}$: local coupling parameters

$$\boxed{\bar{c}_{b,12} = M_c\overrightarrow{ks}}$$

M_c: $\bar{c}_{b,12}$ response matrix

$\overrightarrow{ks}$: skew-quadrupole vector

Emittance tuning

Component	Δx (um)	Δy (um)	$\Delta\theta_z$ (urad)
Arc quadrupole	100	100	100
IR Quadrupole w/o FF	50	50	50
Sextupole	100	100	100

Component	Field error
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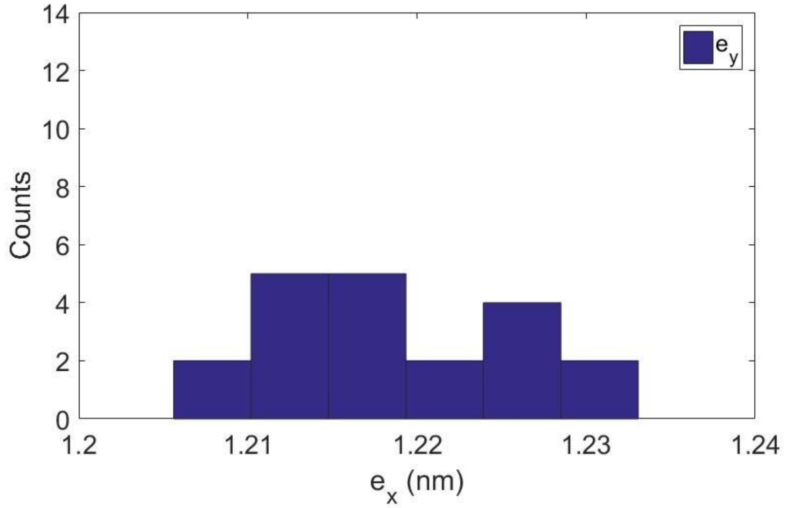

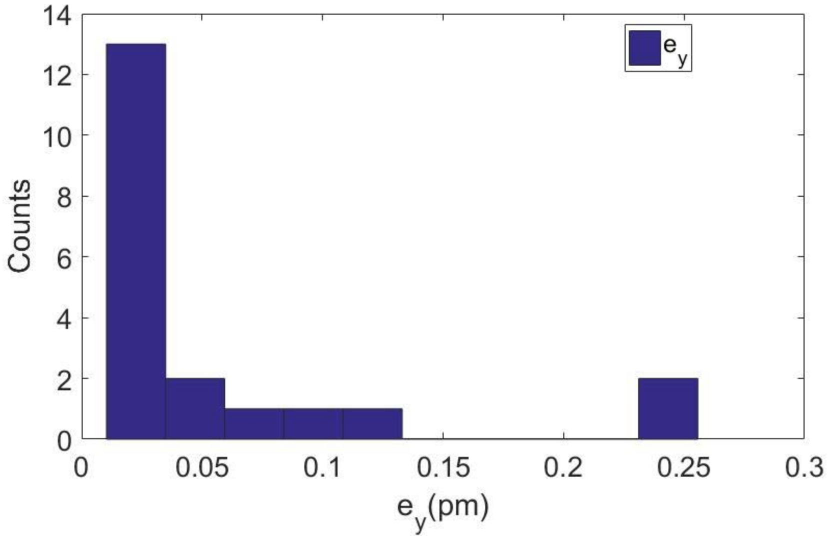

ε_x=1.22 +/- 0.008 nm

ε_y=0.09 +/- 0.07 pm

$\varepsilon_y/\varepsilon_x$= 0.007 %

DA and MA

Component	Δx (um)	Δy (um)	$\Delta\theta_z$ (urad)
Arc quadrupole	100	100	100
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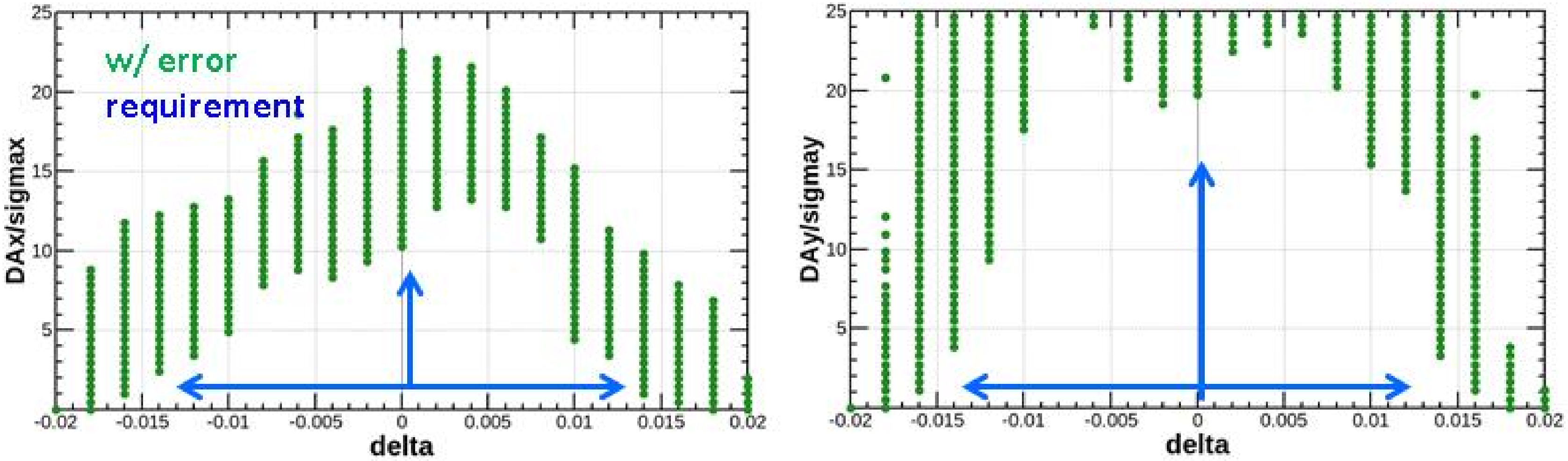

Requirement with on-axis injeciotn $8\sigma_x \times 15\sigma_y$ & 0.0135

Tracking done by Y.W.Wang

Conclusions

- CEPC lattice is sensitive to the imperfections. Therefore, the optics correction is very challenging.
- CEPC optics correction procedure was demonstrated to be effective.
- With the abovementioned imperfections, both DA and MA after correction are acceptable.

Towards TDR

- Study whether the tolerance of the imperfections can be relaxed.
- Optimize the correction strategy to achieve finer tuning of optics.
- Include imperfection of final focus (FF) quadrupoles.
- Include more types of imperfections.

Thanks for you attention