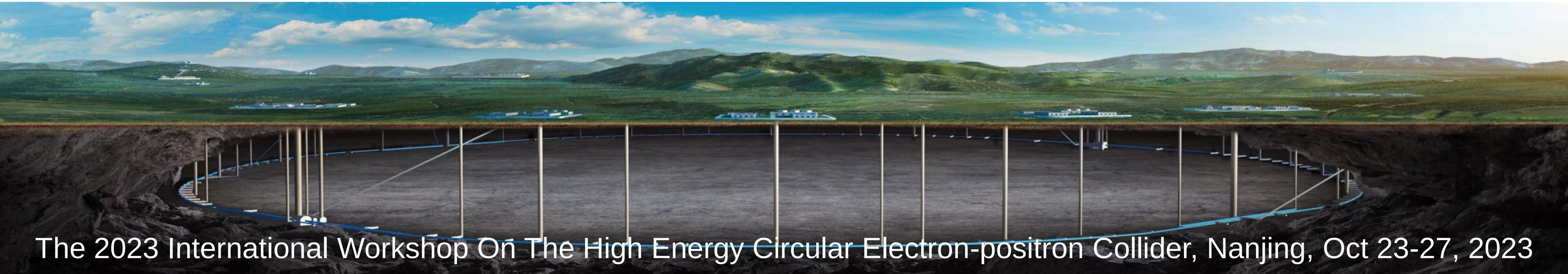
Institute of High Energy Physics
Chinese Academy of Sciences

# Orbit Correction And Error Analysis

BIN WANG
(ON THE BEHALF OF THE CEPC ERROR CORRECTION TEAM)
INSTITUTE OF HIGH ENERGY PHYSICS

2023.10.23



The 2023 International Workshop On The High Energy Circular Electron-positron Collider, Nanjing, Oct 23-27, 2023

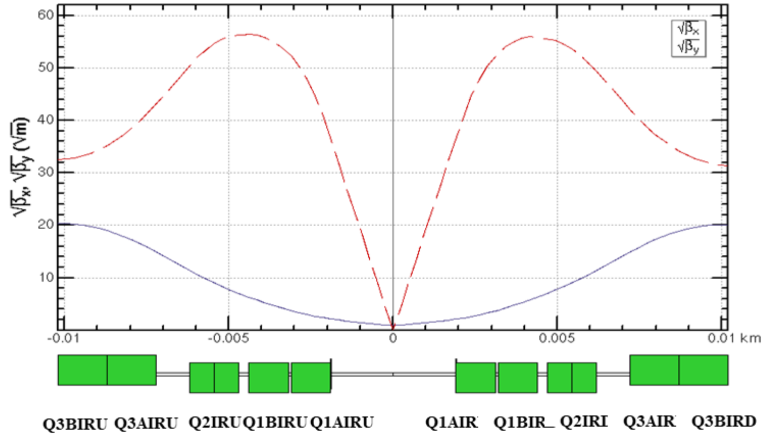
# Content

- Main parameters of four modes in CEPC TDR
- Error definition and challenges
- Correction scheme
- Correction performance
- Summary and To-do list

# Main parameters in TDR

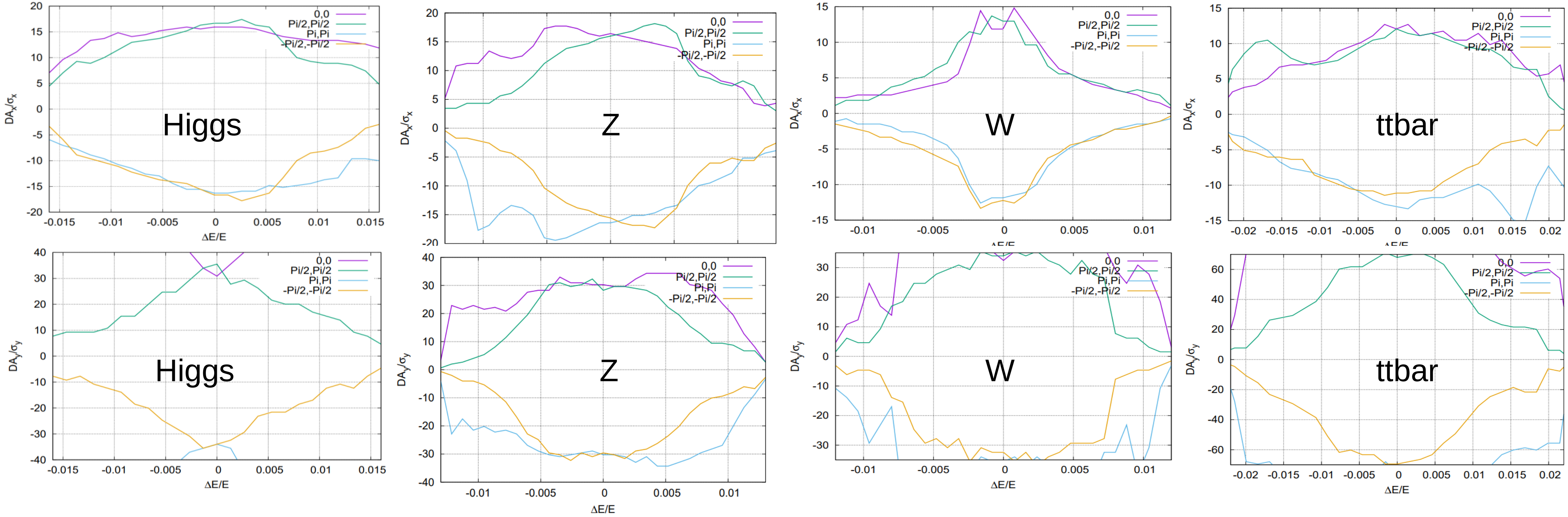
| | Higgs | Z | W | $t\bar{t}$ |
|---|---|---|---|---|
| Number of IPs | 2 | | | |
| Circumference (km) | **100.0** | | | |
| SR power per beam (MW) | **30** | | | |
| Half crossing angle at IP (mrad) | 16.5 | | | |
| Bending radius (km) | 10.7 | | | |
| Energy (GeV) | 120 | 45.5 | 80 | 180 |
| Energy loss per turn (GeV) | 1.8 | 0.037 | 0.357 | 9.1 |
| Damping time $\tau_x/\tau_y/\tau_z$ (ms) | 44.6/44.6/22.3 | 816/816/408 | 150/150/75 | 13.2/13.2/6.6 |
| Piwinski angle | 4.88 | 24.23 | 5.98 | 1.23 |
| Bunch number | 268 | 11934 | 1297 | 35 |
| Bunch spacing (ns) | 591 (53% gap) | 23 (18% gap) | 257 | 4524 (53% gap) |
| Bunch population ($10^{11}$) | **1.3** | **1.4** | **1.35** | **2.0** |
| Beam current (mA) | 16.7 | 803.5 | 84.1 | 3.3 |
| Phase advance of arc FODO (°) | 90 | 60 | 60 | 90 |
| Momentum compaction ($10^{-5}$) | 0.71 | 1.43 | 1.43 | 0.71 |
| Beta functions at IP $\beta_x^*/\beta_y^*$ (m/mm) | 0.3/**1** | 0.13/**0.9** | 0.21/**1** | 1.04/**2.7** |
| Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm) | **0.64**/1.3 | **0.27**/1.4 | **0.87**/1.7 | **1.4**/4.7 |
| Betatron tune $\nu_x/\nu_y$ | 445/445 | 317/317 | 317/317 | 445/445 |
| Beam size at IP $\sigma_x/\sigma_y$ (um/nm) | 14/36 | 6/35 | 13/42 | 39/113 |
| Bunch length (natural/total) (mm) | 2.3/4.1 | 2.5/8.7 | 2.5/4.9 | 2.2/2.9 |
| Energy spread (natural/total) (%) | 0.10/0.17 | 0.04/0.13 | 0.07/0.14 | 0.15/0.20 |
| Energy acceptance (DA/RF) (%) | **1.6**/2.2 | **1.0**/1.7 | **1.2**/2.5 | **2.0**/2.6 |
| Beam-beam parameters $\xi_x/\xi_y$ | 0.015/0.11 | 0.004/0.127 | 0.012/0.113 | 0.071/0.1 |
| RF voltage (GV) | 2.2 | 0.12 | 0.7 | 10 |
| RF frequency (MHz) | 650 | | | |
| Longitudinal tune $\nu_s$ | 0.049 | 0.035 | 0.062 | 0.078 |
| Beam lifetime (Bhabha/beamstrahlung) (min) | 39/40 | 82/2800 | 60/700 | 81/23 |
| Beam lifetime (min) | 20 | 80 | 55 | 18 |
| Hourglass Factor | 0.9 | 0.97 | 0.9 | 0.89 |
| Luminosity per IP ($10^{34}$ cm$^{-2}$ s$^{-1}$) | **5.0** | **115** | **16** | **0.5** |

Y.W. Wang, CEPC collider ring lattice and dynamic aperture optimizations, 12-16. June. 2023, Hongkong, CEPC Accelerator TDR International Review.




- The beta function at the interaction point (IP) is extremely small, and the vertical beta function dramatically increases to 50m within a very short distance of ~5m. This poses a significant difficulty and challenge for error correction.
- The low emittance ratio requires a high correction performance for reducing the vertical dispersion and betatron coupling.

# Dynamic aperture and requirement




| DA requirement | Higgs | Z | W | ttbar |
|---|---|---|---|---|
| with on-axis injection | $8\sigma_x \times 20\sigma_y \times 1.6\%$ | - | - | - |
| with off-axis injection | $13.5\sigma_x \times 20\sigma_y \times 1.6\%$ | $11\sigma_x \times 23\sigma_y \times 1.0\%$ | $8.5\sigma_x \times 20\sigma_y \times 1.05\%$ | $11\sigma_x \times 16\sigma_y \times 2.0\%$ |

# Error assumptions

| Component | $\Delta x$ (mm) | $\Delta y$ (mm) | $\Delta\theta_z$ (mrad) | Field error |
|---|---|---|---|---|
| Dipole | 0.10 | 0.10 | 0.10 | 0.01% |
| Arc Quadrupole | 0.10 | 0.10 | 0.10 | 0.02% |
| IR Quadrupole | 0.10 | 0.10 | 0.10 | 0.02% |
| Sextupole | 0.10* | 0.10* | 0.10 | 0.02% |

*implement beam-based alignment techniques to reach rms offsets in the order of 10 um with respect to the beam.

- with a large beta* lattice
- with quadrupole coils in the sextupoles
- 10um is possible as O(BPM resolution)=1um

- Field errors of all magnets are included.
- Two BPMs and a pair of correctors (one each for horizontal and vertical) are installed in each cell. For the cells accommodating sextupoles, horizontal and vertical correctors are produced by the sextupole trims.
- Horizontal correctors were installed beside focusing quadrupoles and vertical correctors at defocusing quadrupoles.

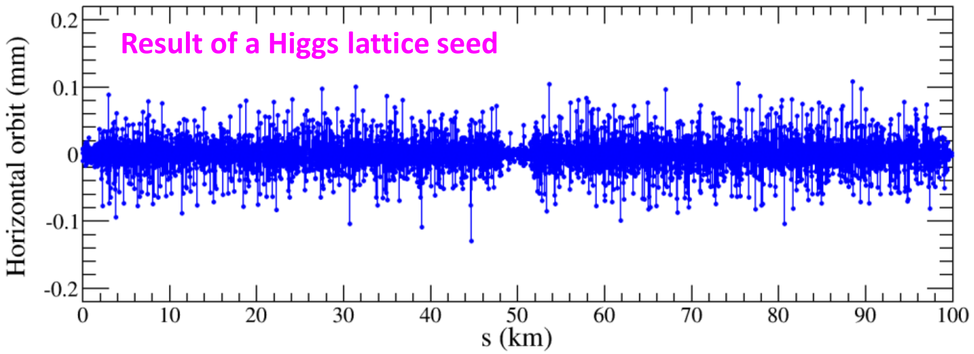
# Correction scheme

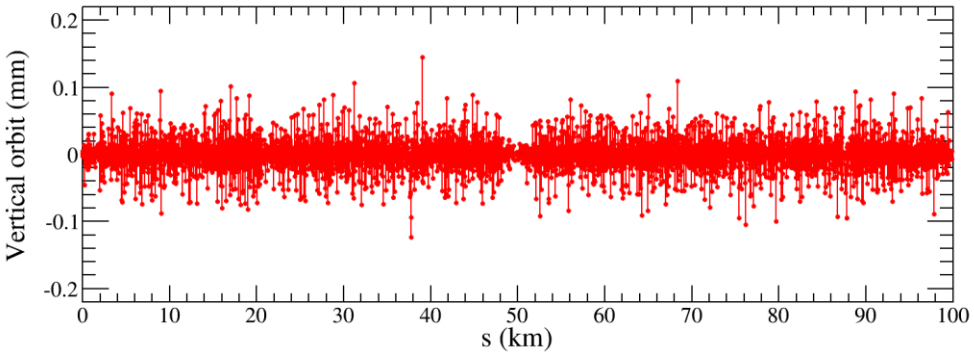
- Software: SAD and Matlab-based accelerator toolbox (AT)

1. Closed-orbit distortion (COD) correction was performed with sextupoles off, then the sextupoles were turned on and the COD correction repeated.
2. The dispersion correction and beta-beating correction are also used for optics correction.
3. The coupling and vertical dispersion correction are used to decrease the vertical emittance.
4. The above correction scheme is iterated until the emittance and tracking dynamic aperture satisfy the design requirements.

# COD correction

- The COD correction algorithm is based on the response matrix. By inverting the response matrix using singular value decomposition (SVD), the steering strengths can be derived to correct the distorted orbits.
- The maximum and RMS closed orbit is about 0.1 mm and 40 μm for both horizontal and vertical orbit, respectively.



# Dispersion correction

**Dispersion free steering principle (DFS):** $\boldsymbol{\theta}_c$

$$\vec{d} = \begin{pmatrix} (1-\alpha)\vec{u} \\ \alpha\vec{D}_u \end{pmatrix} \quad M = \begin{pmatrix} (1-\alpha)A \\ \alpha B \end{pmatrix} \quad \vec{d} + M\vec{\theta} = 0$$

$\vec{u}$: Orbit vector

$\vec{D}_u$: Dispersion vector

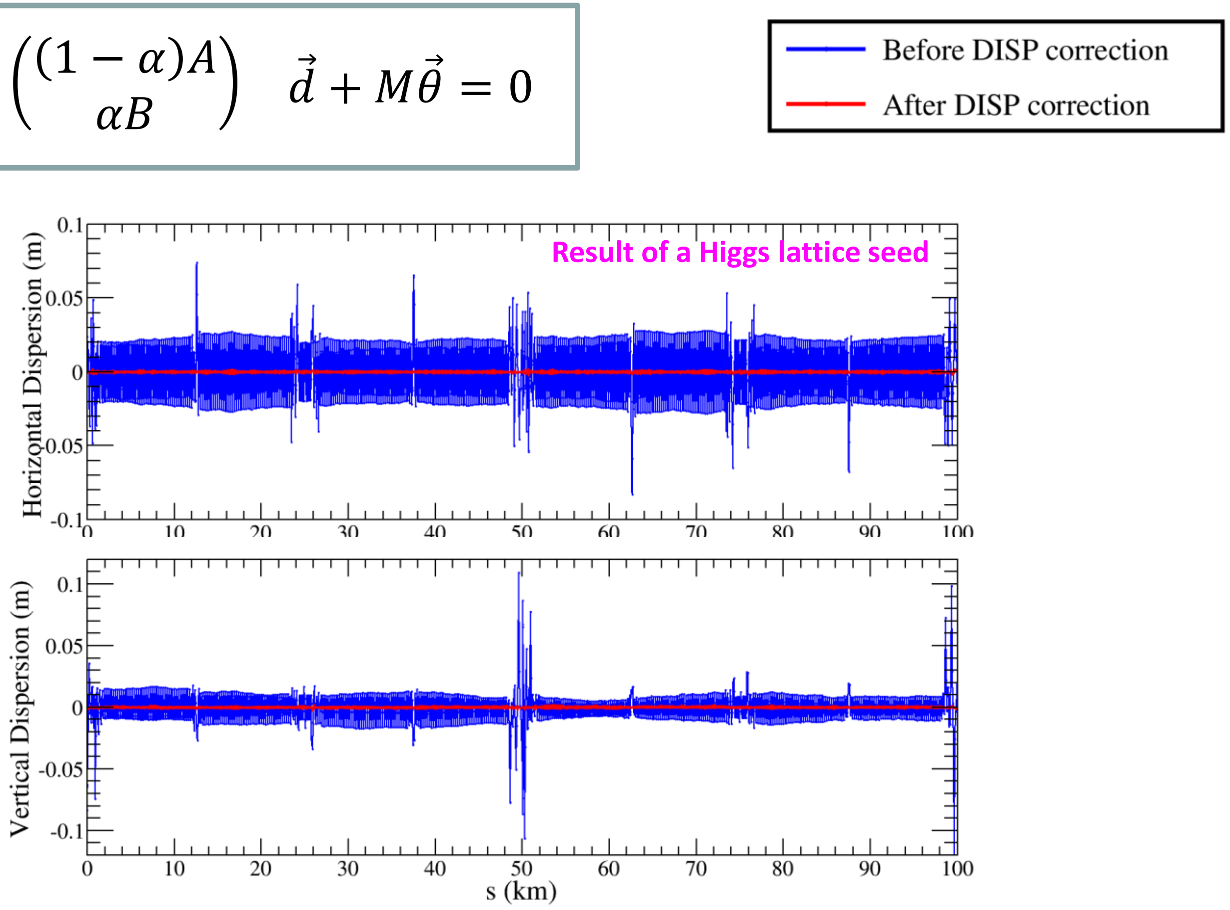
$\vec{\theta}$: Corrector strengths vector

$\alpha$: Weight factor

$A$: Orbit response matrix

$B$: Dispersion response matrix

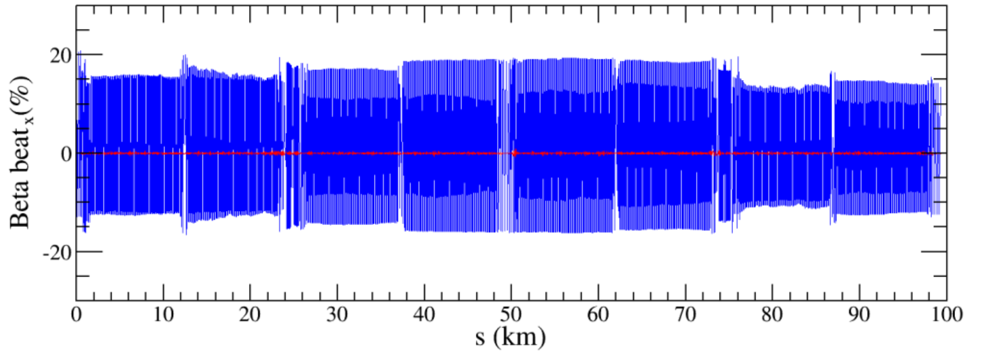
The dispersion is corrected well, the RMS dispersion is about 1mm for all lattice seeds.

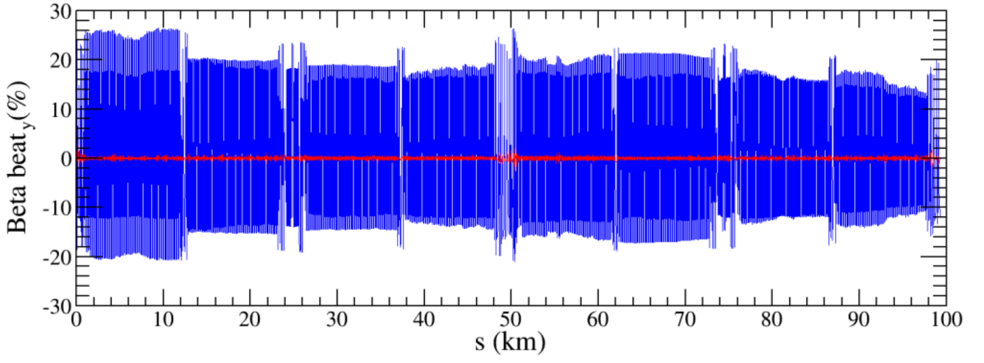


# Beta-beating correction

- Correct the beta functions with sextupoles on.
- 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:
  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
  - Fit the dispersion at the same time.
  - Application to correct beta-beating, dispersion and coupled response matrix.

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

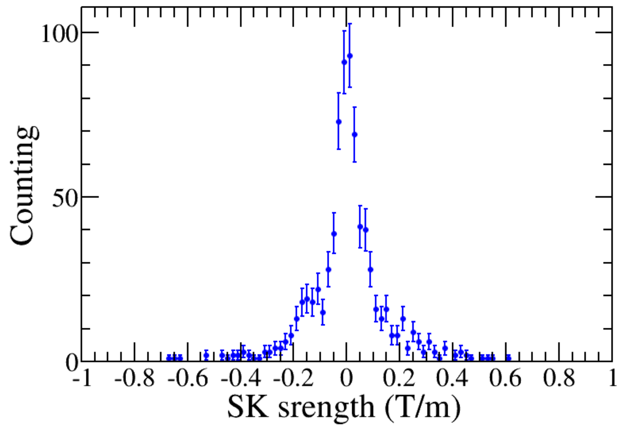



$\Delta\beta/\beta_{rms} < 3\%$

# Coupling correction

- Neglecting beam-beam effects $\varepsilon_y = \varepsilon_{y0} + \kappa\varepsilon_x + \gamma E^2 (D_y^{rms})^2$
- Local coupling parameter matching was developed for BEPCII.
- Both coupling and vertical dispersion are controlled.
- 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:

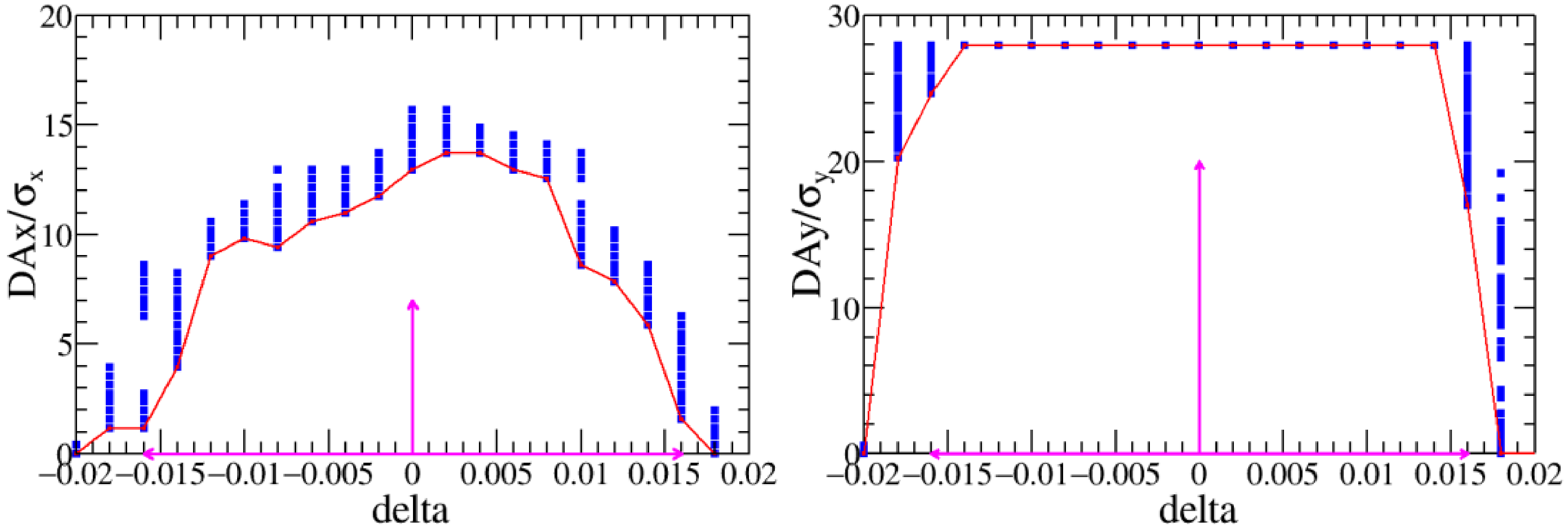
$$\frac{\Delta y_{cod}}{\Delta x_{cod}} = \bar{c}_{b,22}k_1 + \bar{c}_{b,12}k_2 + \bar{c}_{c,11}k_3 + \bar{c}_{c,12}k_4$$

$k_1, k_2, k_3, k_4$ : only related to the decoupled linear optics $M_c$: $\bar{c}_{b,12}$ response matrix

$\bar{c}_{b,22}, \bar{c}_{b,12}, \bar{c}_{c,11}, \bar{c}_{c,12}$: local coupling parameters, $\bar{c}_{b,12} = M_c\overrightarrow{ks}$ $\overrightarrow{ks}$ : skew-quadrupole vector

The emittance correction is evaluated to be $\epsilon_x$ = 0.666 nm and $\epsilon_y$ = 0.209 pm, the emittance ratio ($\epsilon_y/\epsilon_x$) is 0.03%, which satisfies the design requirement.

# Dynamic aperture tracking



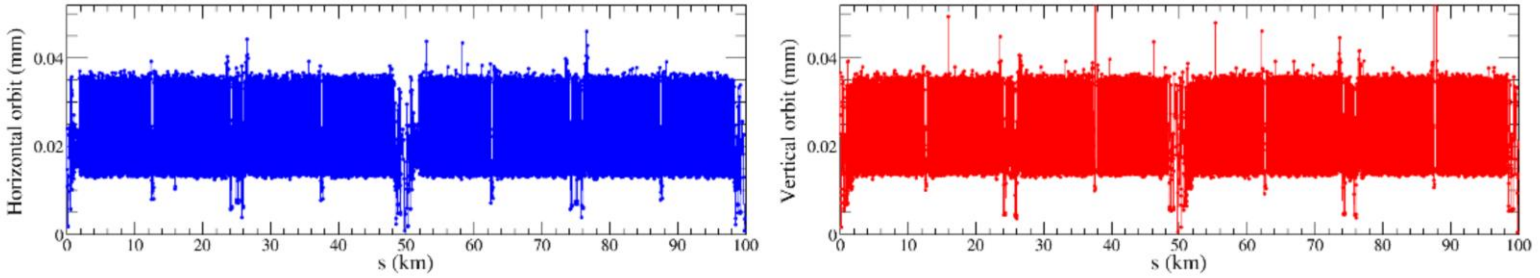

- The dynamic aperture in Higgs mode is tracked over 145 turns, about one damping time.
- The DA with error correction are tracked and satisfy the on-axis injection requirement, $8\sigma_x \times 20\sigma_y$ & $0.016$.

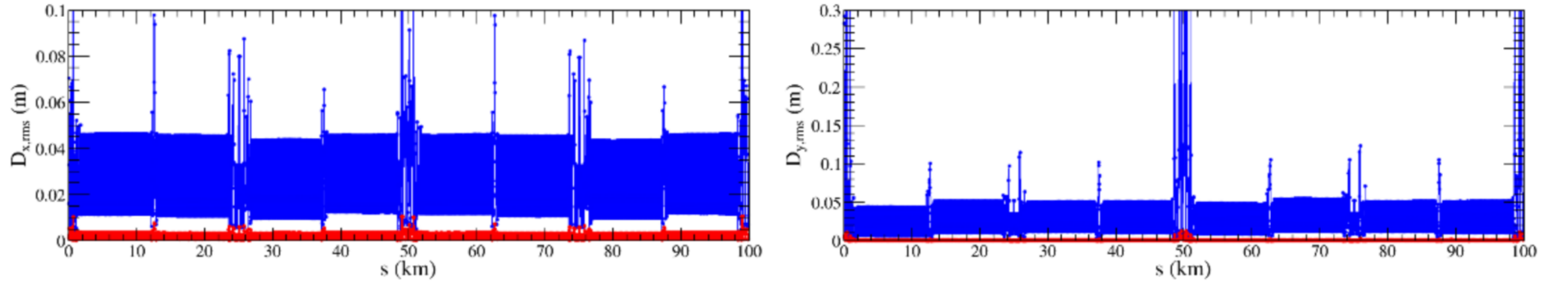
# Correction performance

- To reduce the statistical fluctuation, 100 random lattices seeds with errors are generated for correction, all error sources follow a Gaussian distribution truncated at $\pm 3\sigma$.
- The above correction scheme is adjusted (such as the iteration times, the step size, the size of response matrix, and so on) and iterated until getting the converged correction result and the tracking dynamic aperture satisfy the design requirements.

| RMS | Higgs | Z | W | $t\bar{t}$ |
|---|---|---|---|---|
| Orbit (μm) | $< 50$ | $< 50$ | $< 50$ | $< 50$ |
| Dispersion (mm) | 1.8/0.9 | 2.8/1.4 | 2.7/1.8 | 0.6/0.3 |
| Beta-beating (%) | 1.0/2.8 | 2.0/3.0 | 0.5/2.5 | 1.1/1.2 |

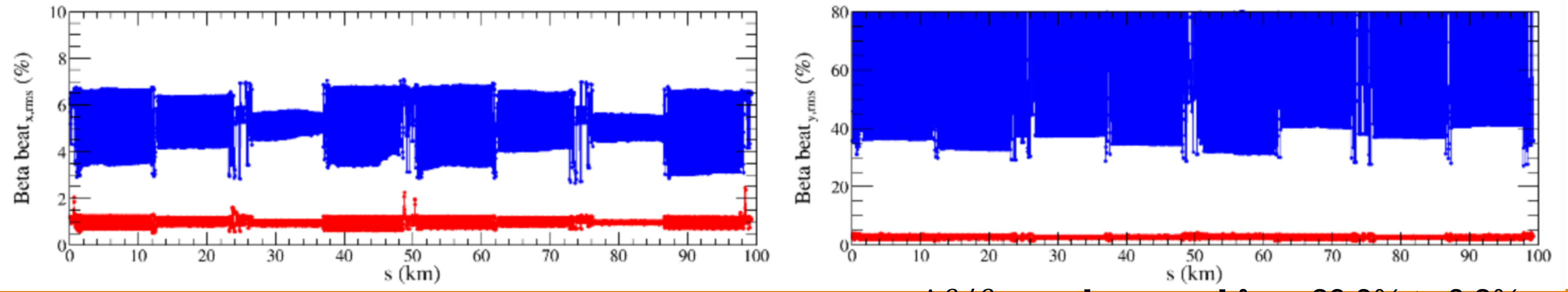
# Correction performance (Higgs mode)




$\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm

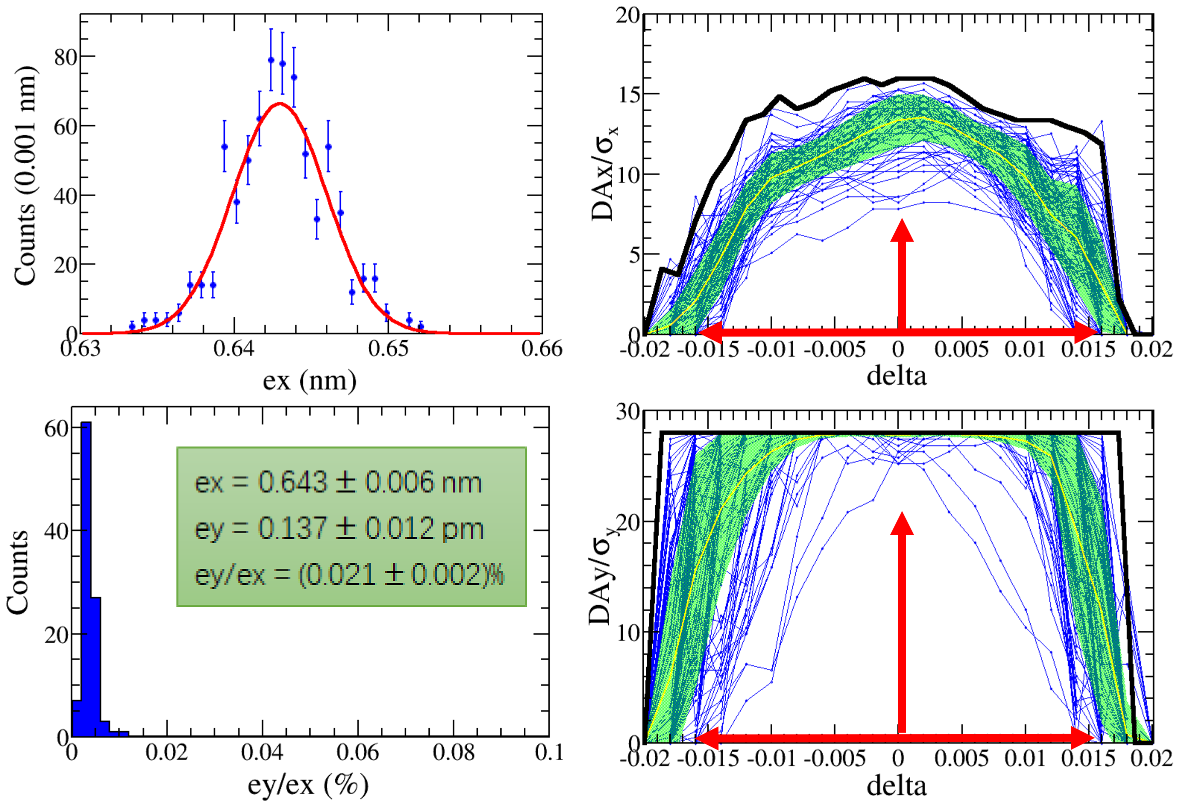
$\Delta D_{y,rms}$ decreased from 31.9 mm to 0.9 mm




$\Delta\beta/\beta_{x,rms}$ decreased from 5.2% to 1.0%

$\Delta\beta/\beta_{y,rms}$ decreased from 83.2% to 2.8%

# Dynamic aperture tracking (Higgs mode)




—w/o error

—mean value

—statistic errors

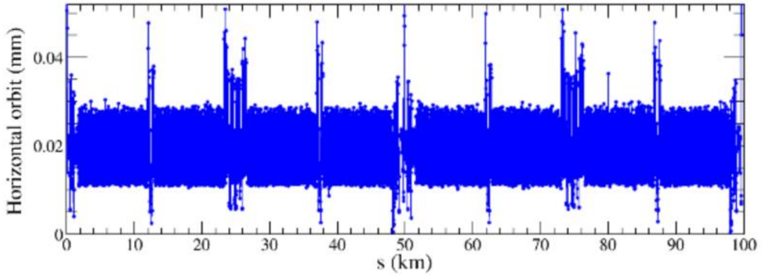
—seeds

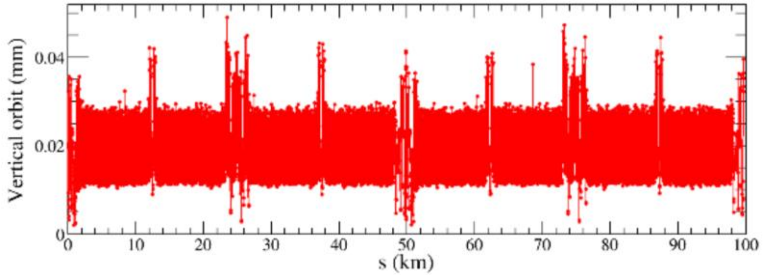
—requirement

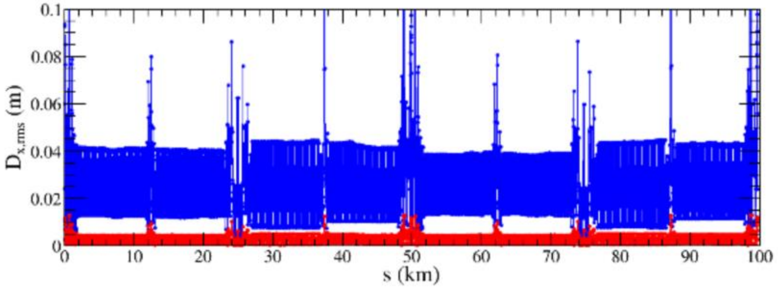
| Effects included in tracking |
|---|
| Synchrotron motion |
| Radiation loss in all magnets |
| Tapering |
| Crab waist sextupole |
| Maxwellian fringes |
| Kinematic terms |
| Finite length of sextupole |

- The emittance coupling fulfill the requirement (<0.2%).
- 100 lattice seeds with errors are corrected.
- **>90% lattice seeds with error correction fulfill the requirement of on axis top-up injection $8\sigma_x \times 20\sigma_y \times 1.6\%$.**

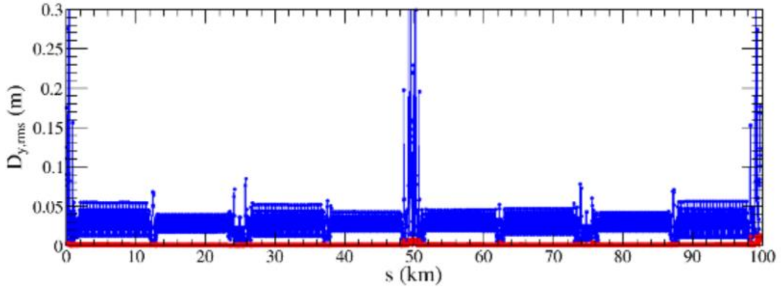
# Correction performance (Z mode)



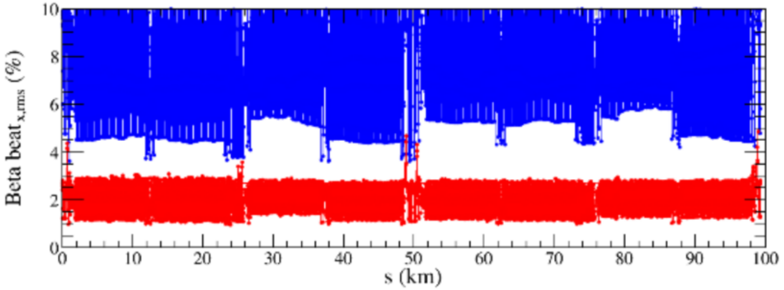



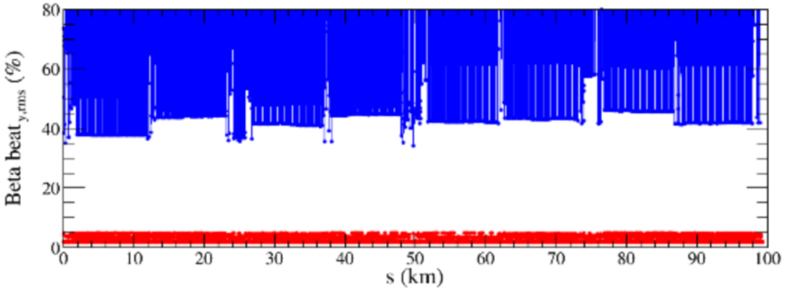

$\Delta D_{x,rms}$ decreased from 25.4 mm to 2.8 mm




$\Delta D_{y,rms}$ decreased from 30.5 mm to 1.4 mm

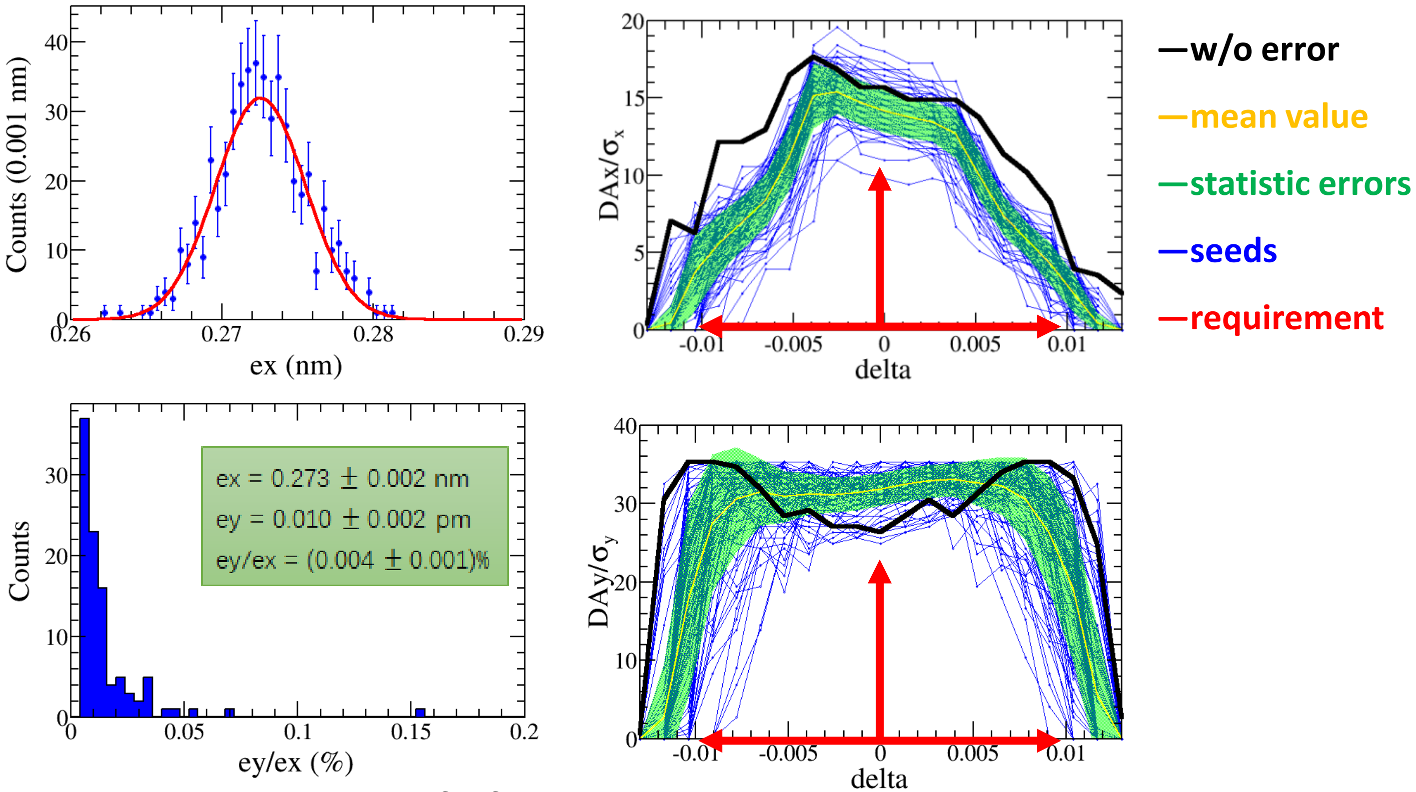



$\Delta\beta/\beta_{x,rms}$ decreased from 7.5% to 2.0%




$\Delta\beta/\beta_{y,rms}$ decreased from 148.8% to 3.0%

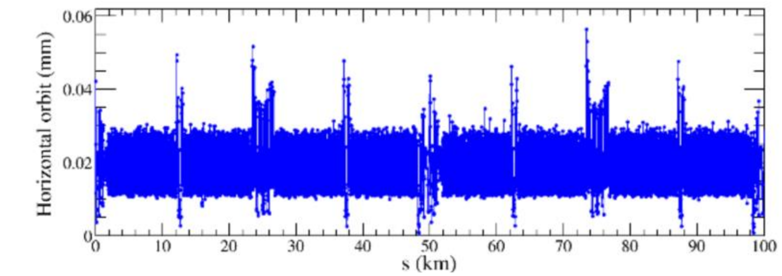
# Dynamic aperture tracking (Z mode)

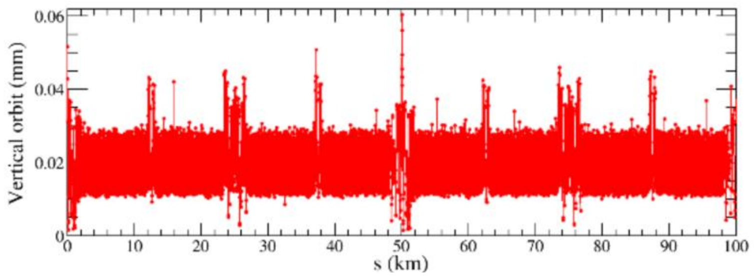


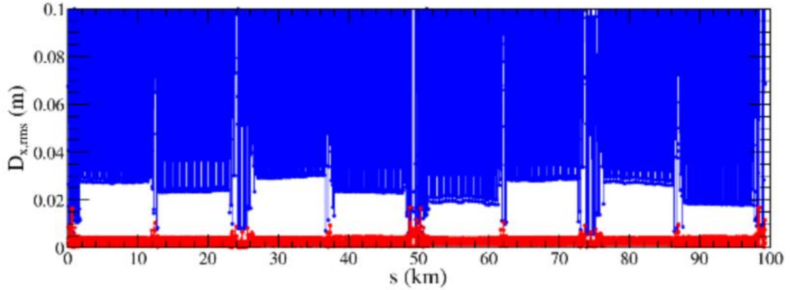

| Effects included in tracking |
|---|
| Synchrotron motion |
| Radiation loss in all magnets |
| Tapering |
| Crab waist sextupole |
| Maxwellian fringes |
| Kinematic terms |
| Finite length of sextupole |

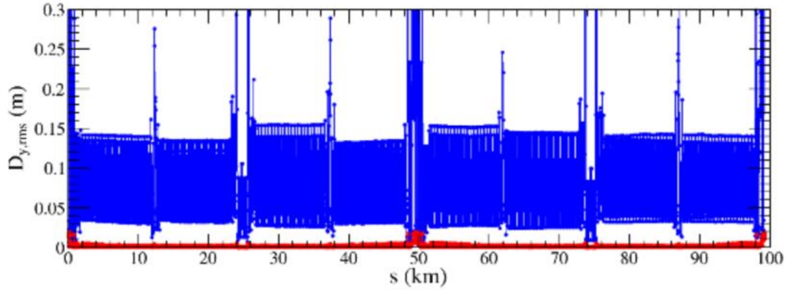
- The emittance coupling fulfill the requirement (<0.5%).
- 100 lattice seeds with errors are corrected.
- **>90% lattice seeds with error correction fulfill the requirement of on axis top-up injection $11\sigma_x \times 23\sigma_y \times 1.0\%$.**

# Correction performance (W mode)



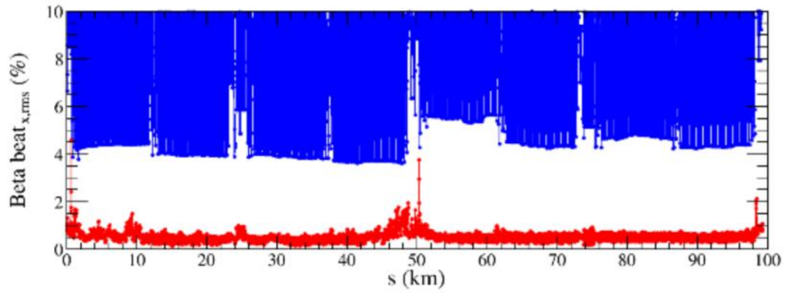



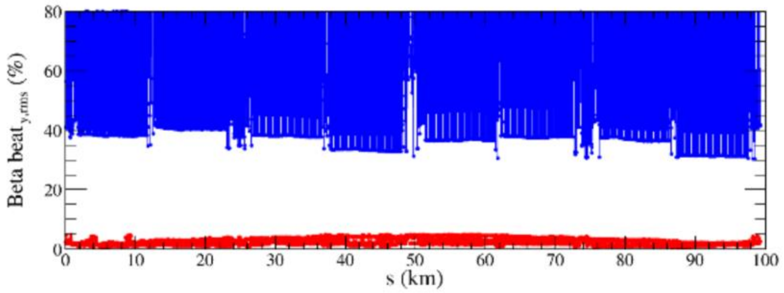




$\Delta D_{x,rms}$ decreased from 85.0 mm to 2.7 mm

$\Delta D_{y,rms}$ decreased from 92.4 mm to 1.8 mm

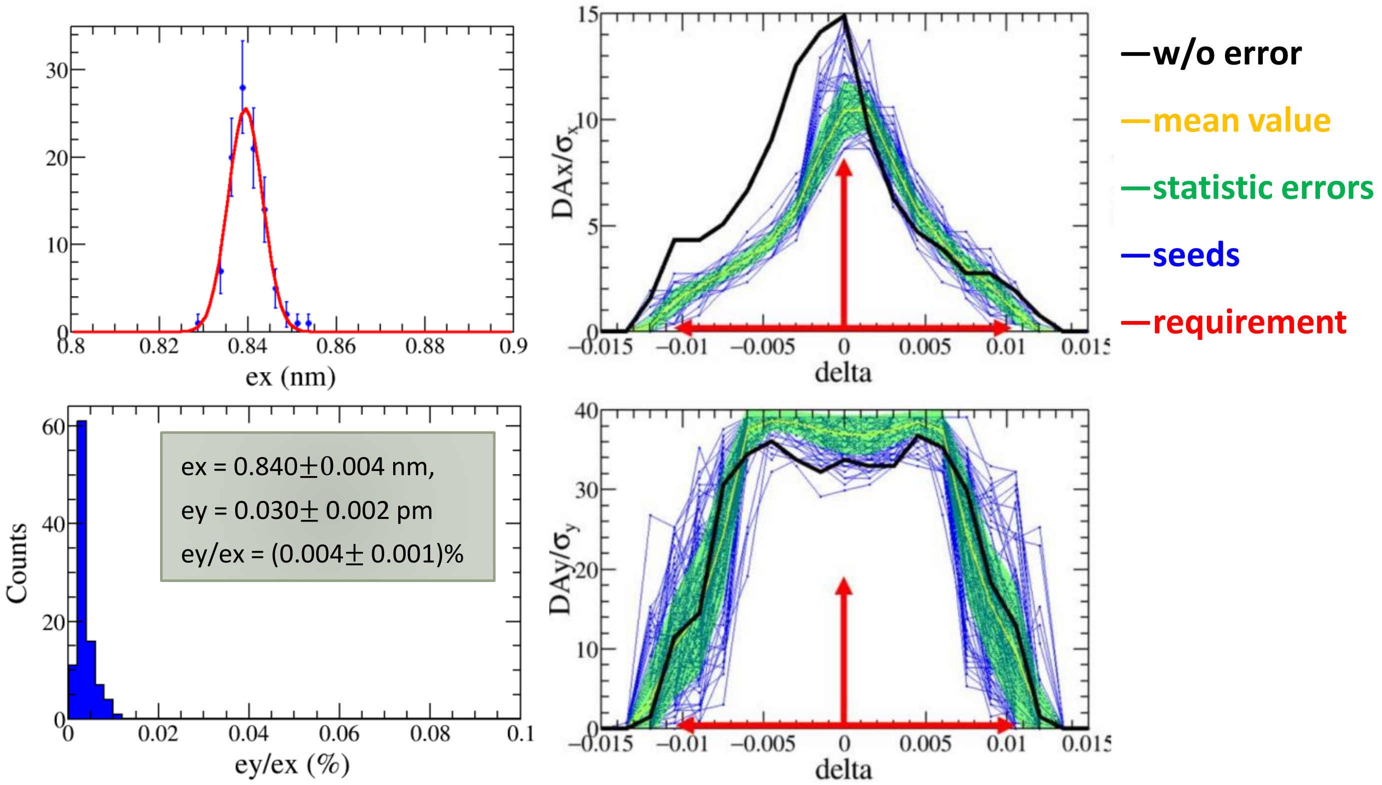



$\Delta\beta/\beta_{x,rms}$ decreased from 8.1% to 0.5%

$\Delta\beta/\beta_{y,rms}$ decreased from 106.8% to 2.5%

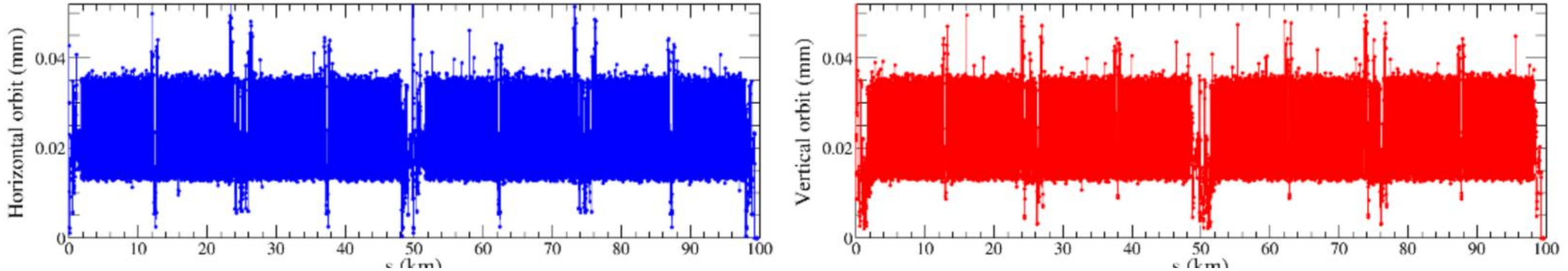
# Dynamic aperture tracking (W mode)

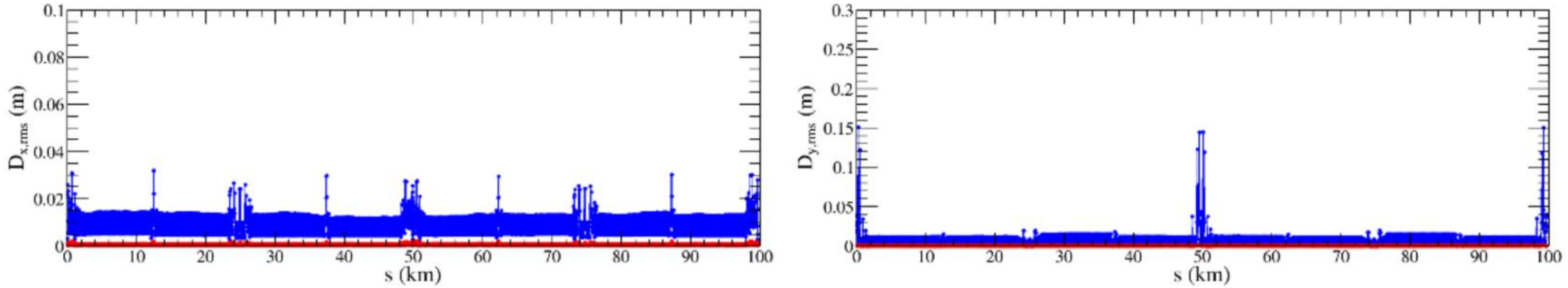



| Effects included in tracking |
|---|
| Synchrotron motion |
| Radiation loss in all magnets |
| Tapering |
| Crab waist sextupole |
| Maxwellian fringes |
| Kinematic terms |
| Finite length of sextupole |

- The emittance coupling fulfill the requirement (<0.2%).
- 100 lattice seeds with errors are corrected.
- **>90% lattice seeds with error correction fulfill the requirement of on axis top-up injection $8.5\sigma_x \times 20\sigma_y \times 1.05\%$.**

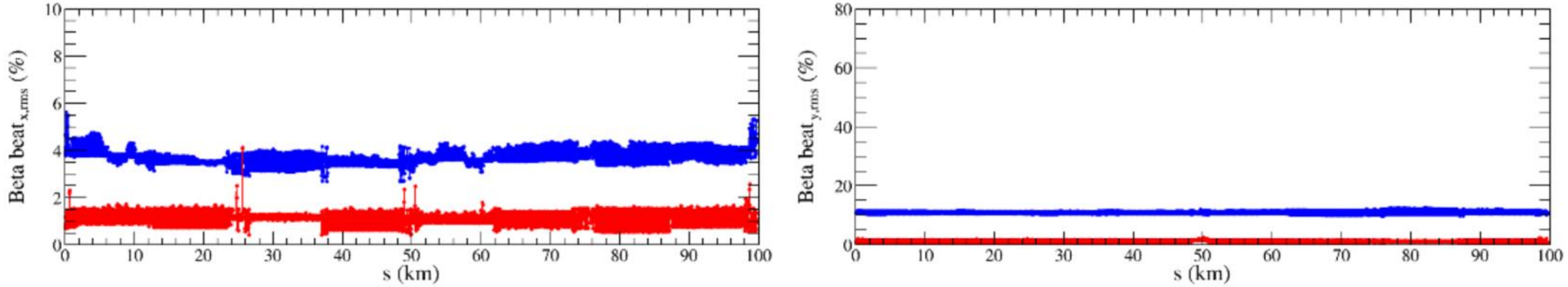
# Correction performance (ttbar mode)




$\Delta D_{x,rms}$ decreased from 8.8 mm to 0.6 mm

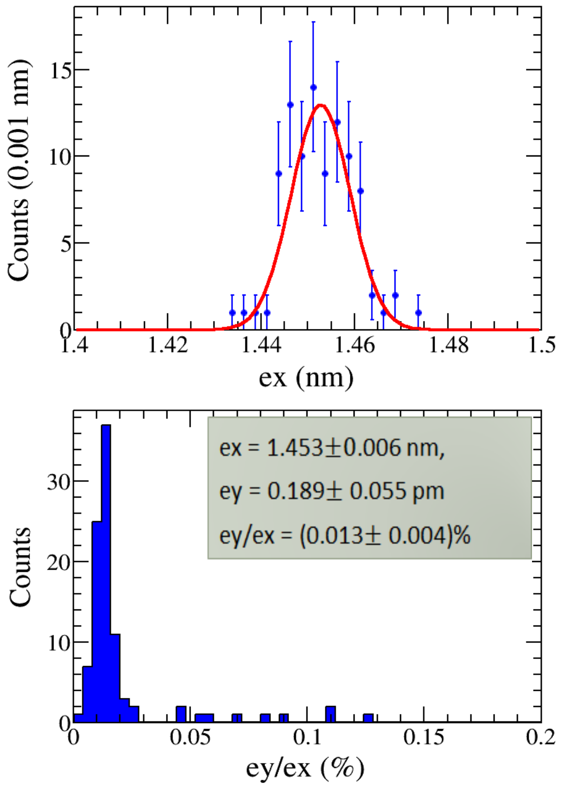
$\Delta D_{y,rms}$ decreased from 7.7 mm to 0.3 mm

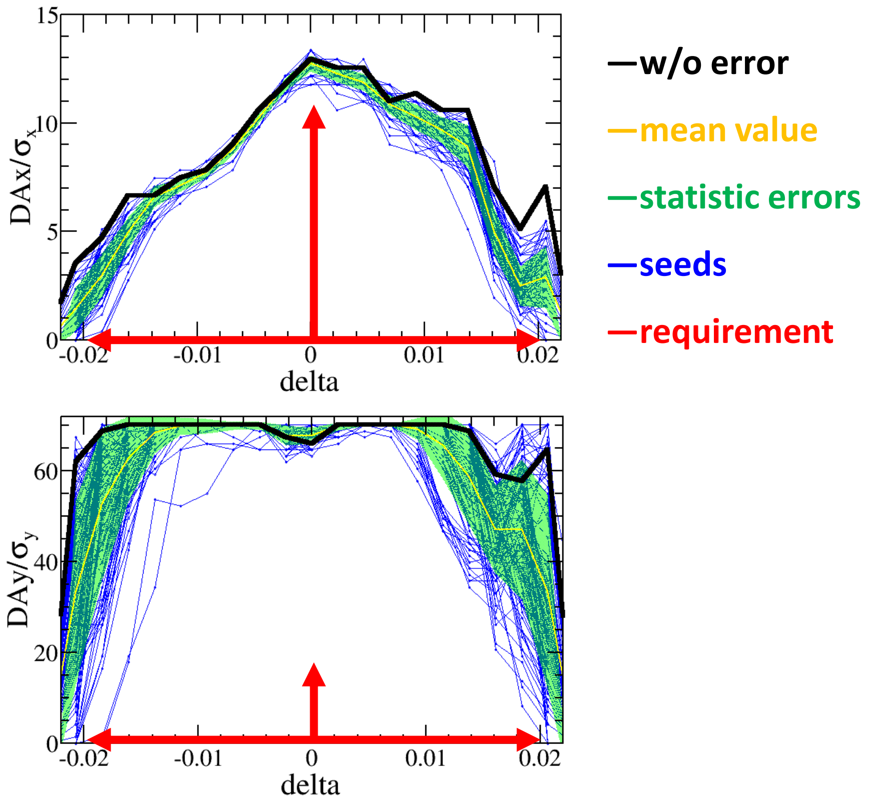



$\Delta\beta/\beta_{x,rms}$ decreased from 3.7% to 1.1%

$\Delta\beta/\beta_{y,rms}$ decreased from 11.1% to 1.2%

# Dynamic aperture tracking (ttbar mode)




| **Effects included in tracking** |
|---|
| Synchrotron motion |
| Radiation loss in all magnets |
| Tapering |
| Crab waist sextupole |
| Maxwellian fringes |
| Kinematic terms |
| Finite length of sextupole |

- The emittance coupling fulfill the requirement (<0.34%).
- 100 lattice seeds with errors are corrected.
- **>90% lattice seeds with error correction fulfill the requirement of on axis top-up injection $11\sigma_x \times 16\sigma_y \times 2.0\%$.**

# Summary and To-do list

- ➢ The error correction to lattice with all four modes (Higgs, Z, W, and ttbar) are achieved in this year.
- ➢ The dynamic apertures after correction are tracked and meet the injection requirement with a success rate of >90%.
- ☐ Include more types of imperfections.
- ☐ Working on fine-tuning IP tuning, includes local orbits, optics functions, and couplings is ongoing.

# Thank you for your attention

E-mail:
wangbin@ihep.ac.cn