CEPC collider ring error analysis with detector dipole and anti-solenoid effects

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A.12 Studies of the tolerance to machine errors at all energies (Yiwei Wang, Bin Wang)

A.12.1 Comments

Simulations of tolerance to the machine errors, their effects on emittances and energy spread have been performed at different energies (from Z to ttbar). Misalignment errors of final-focus superconducting quadrupoles from 30 to 200 μm and other elements with 100 μm/μrad were studied. Standard correction algorithms were used. From 50 random seeds, all of them converged with 30 μm and only 11 with 200 μm. Beta-beating is below 1%. Dynamic aperture decreases insignificantly (about 20%). It is shown that optics, dispersion and coupling correction is more efficient in restoring emittance and energy spread than orbit correction. It is possible to obtain design value of vertical emittance at all energies. Conclusion is made that alignment errors of 100 μm/μrad are acceptable for all quadrupoles of the ring including the final-focus.

All the simulations were performed for a lattice without solenoids. This clearly can be useful for the very first stage of commissioning, however for a meaningful study the solenoids need to be included in the lattice. Also, the two solenoid compensations schemes need to be compared for machine error tolerance. This will help to make a choice between local and non-local compensation schemes.

After the solenoids are turned on, the final-focus quadrupoles might move due to the magnetic forces. This will affect coupling, beta beating, dispersion, vertical and horizontal emittances. The tolerable shifts and rotations of the final-focus quadrupoles need to be determined. A method to compensate the shifts of the FF quadrupoles need to be found. The HEPS experience will indeed be very valuable.

A.12.2 Recommendations

1. Study error tolerances with local and non-local solenoid compensation schemes;

2. Estimate vertical emittance growth and orbit distortion from seismic vibrations of magnetic elements. The ring is long, the number of magnets is large. In the light sources a special fast orbit feedback is used. Study how this will affect the luminosity.

Responses to the 2025 IARC EDR review report

■ **1. Study error tolerances with local and non-local solenoid compensation schemes;**

[Reply] This study is currently underway. We will analyze the correction and its performance of a lattice with solenoids by systematically scanning across different magnet error scenarios.

■ 2. Estimate vertical emittance growth and orbit distortion from seismic vibrations of magnetic elements. The ring is long, the number of magnets is large. In the light sources a special fast orbit feedback is used. Study how this will affect the luminosity.

[Reply] The vertical orbit distortion is mainly affected by two factors: the ground vibrations at the Interaction Points (IPs) and the ground motions in the arc region. With an estimated contribution of 4 nanometers from the ground vibrations at the IPs, based on the CERN vibration levels at the IP when situated 100 meters underground, and an additional 25 nanometers from the ground in the arc region—due to its length and the inevitable presence of mind-out areas even at a depth of 100 meters—the luminosity is expected to experience a reduction of approximately two percent. This is a roughly estimation. A multi-particle tracking initiative, including FOFB research, is set to commence.
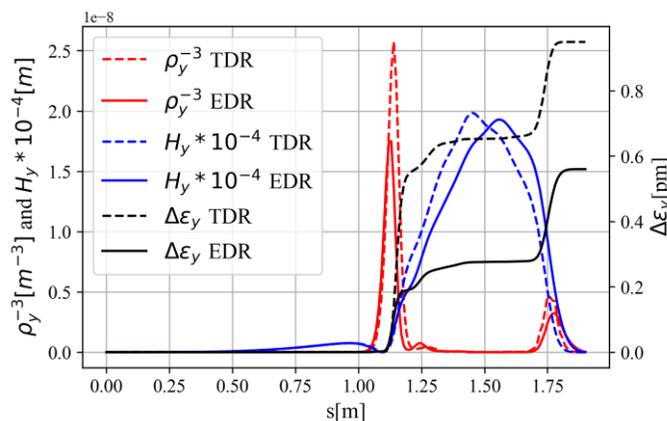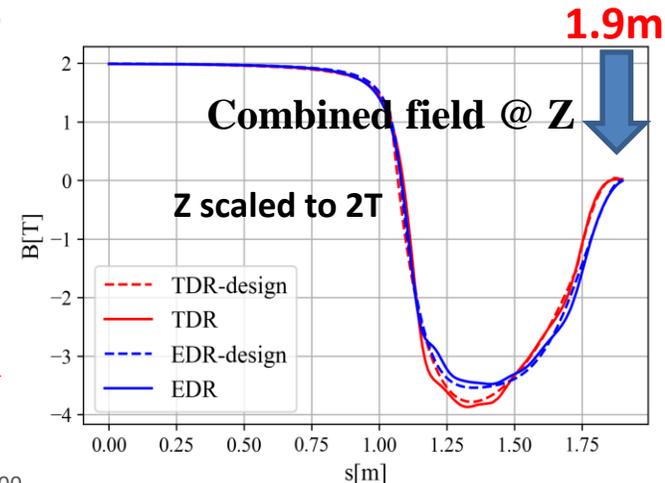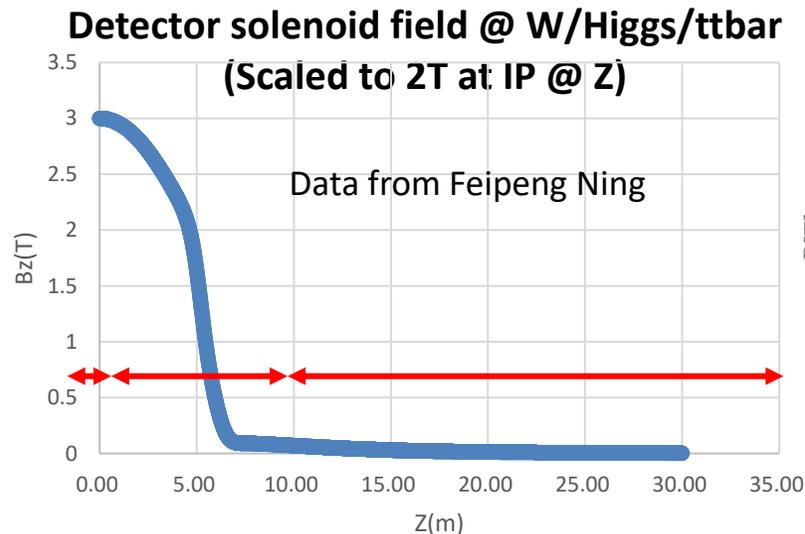
Content

- **Introduction of the lattice with solenoid field compensation**

- **Status of the error correction team**

- **Progress of the correction to the Higgs lattice with solenoid**

- **Summary and to do list**

Solenoid field compensation in CEPC TDR and update

Ande MA, Yiwei Wang, Yingshun Zhu et al

- The detector solenoid are compensated **locally** with anti-solenoids

- From IP to the entrance of Q1A (0 to 1.9m):

  – ∫Bzdz cancled between the IP and the entrance of final quadrupole with strong anti-solenoid field in 1.1m to 1.9m.
  – Field configuration optimized to get emittance minimum and iterate with anti-solenoid technical constraints

- From the entrance of Q1A to Q3(1.9m to 10.55m)

  – Bz keep fully cancellation along this region

- From the Q3 to the last bend (farer than 10.55m)

  – ∫Bzdz from detector only < 0.5 T*m.
  – Along beam line (not z), fully cancelation in Q3 and pre-cancelation in some extension region (with length of 1m) for the long tail of the detector solenoid field

Detector solenoid field @ W/Higgs/ttbar (Scaled to 2T at IP @ Z)

1.9m

Data from Feipeng Ning

Combined field @ Z

Z scaled to 2T

Legend:
- TDR-design
- TDR
- EDR-design
- EDR

Emittance contribution from the from IP to the entrance of Q1A

	$t\bar{t}$ 3T	Higgs 3T	W 3T	Z 2T
Nominal ϵ_y[pm]	4.7	1.3	1.7	1.4
Solenoid contributed ϵ_y[pm](TDR)	0.04	0.36	1.20	0.95
Solenoid contributed ϵ_y[pm] (Update)	0.02	0.21	0.71	0.56

Plot legend:
- ρ_y^{-3} TDR
- ρ_y^{-3} EDR
- $H_y * 10^{-4}$ TDR
- $H_y * 10^{-4}$ EDR
- $\Delta\epsilon_y$ TDR
- $\Delta\epsilon_y$ EDR

Solenoid effect on dynamic aperture

- The anti-solenoid cancel the ∫Bzdz between the IP and the faces of the final quadrupole.

- The Twiss function distortion due to solenoid field was corrected with final quadrupoles.

- **The solenoid effect on the dynamic aperture is small.**

Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole
Solenoid
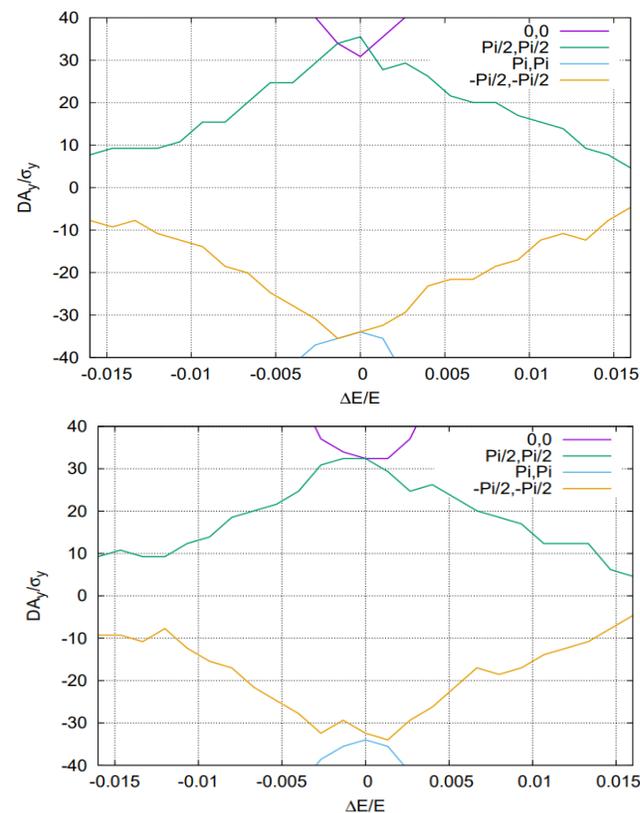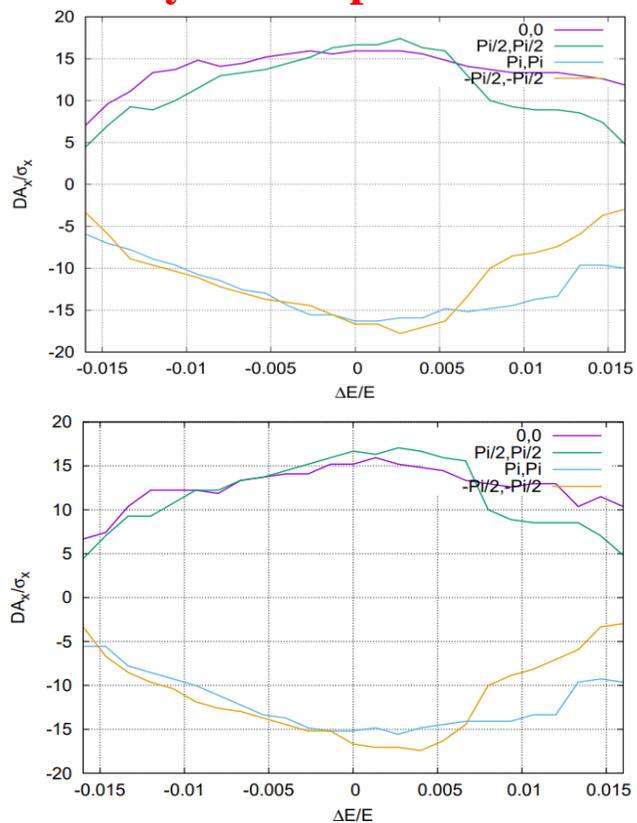
Higgs without solenoid

Higgs with solenoid

Status of the error correction team

- From the end of December, the "CEPC Beam Dynamics Meeting" was formed to hold weekly discussions on error correction with solenoid.

- The weekly meeting also included discussions on the other optimization of the collider ring lattice, including IP tuning (Wei Yuanyuan), vibration influence (Yan Fang), lattice optimization (Wang Yiwei), etc.

Error Correction to the Higgs lattice

- 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 (DISP) 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.

- The correction target is 50 μm for COD correction, 2mm for DISP correction and 3% for beta beating correction. Taking the Higgs mode correction as an example.

Misalignment and field error requirements.

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Quadrupole	0.10	0.10	0.10	0.02%
Sextupole	0.10	0.10	0.10	0.02%

Correction performance for lattices without solenoid.

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

Closed-orbit distortion correction (Higgs mode)

- The Lattice starts at the injection point.

- 100 random **Higgs lattice** seeds are generated, there are 85 lattice seeds have convergent solutions.

- **Correction target:** The green line is marked with the correction target (50 μm), corresponding to the correction performance without solenoid.

- **Correction result (one seed):** Most horizontal and vertical orbits are within 50 μm, while some points near IP are significantly larger, exceeding 200 μm.
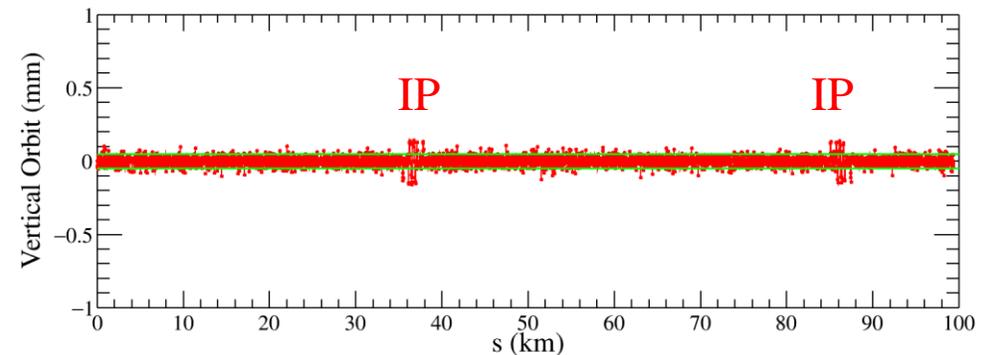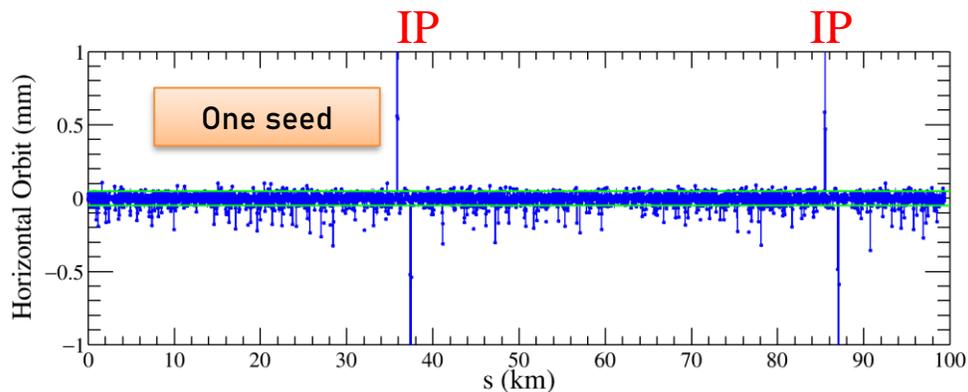
# Closed-orbit distortion correction (Higgs mode)

85 seeds

- The Lattice starts at the injection point.

- 100 random **Higgs lattice** seeds are generated, there are 85 lattice seeds have convergent solutions.

- **Correction target:** The green line is marked with the correction target (50 µm), corresponding to the correction performance without solenoid.

- **Correction result (85 seeds):** Most of the RMS values for horizontal and vertical orbits are within 50 µm, while some orbits near the IP are significantly larger, exceeding 200 µm.

- **Conclusion:** Move to the next dispersion correction, which also include the **orbit adjustment**.
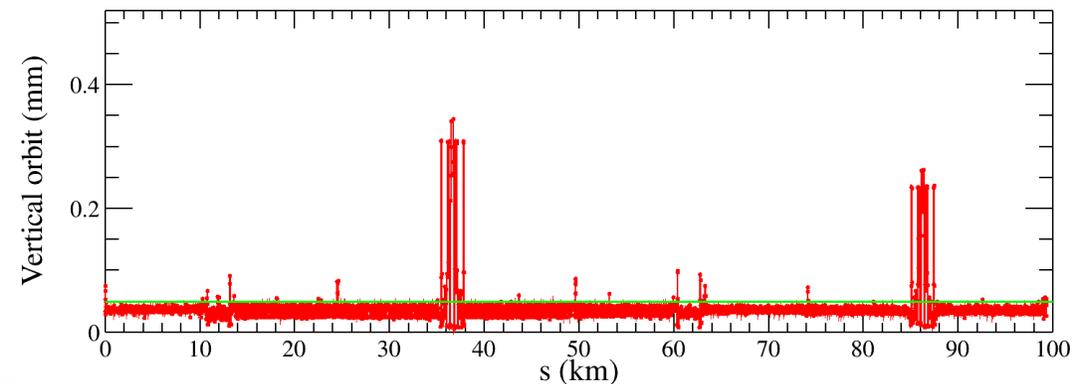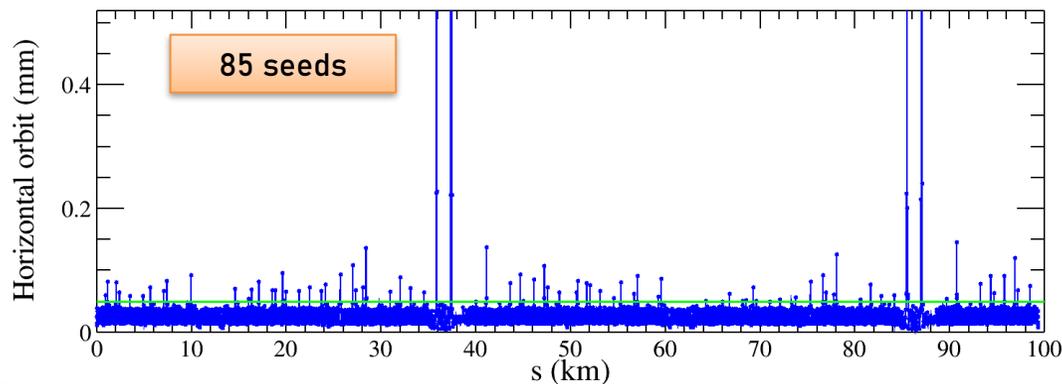
Dispersion correction (Higgs mode)

- **85 Higgs lattice seeds** with COD correction are used to do the dispersion correction.

- **Correction target:** The green line is marked with the correction target (2 mm), corresponding to the correction performance without solenoid.

- **Correction result:** Both horizontal and vertical dispersion deviation after correction are lower than the correction target, 2mm. The application of the DISP correction resolved the large fluctuations in the vertical dispersion near the IP.

One seed
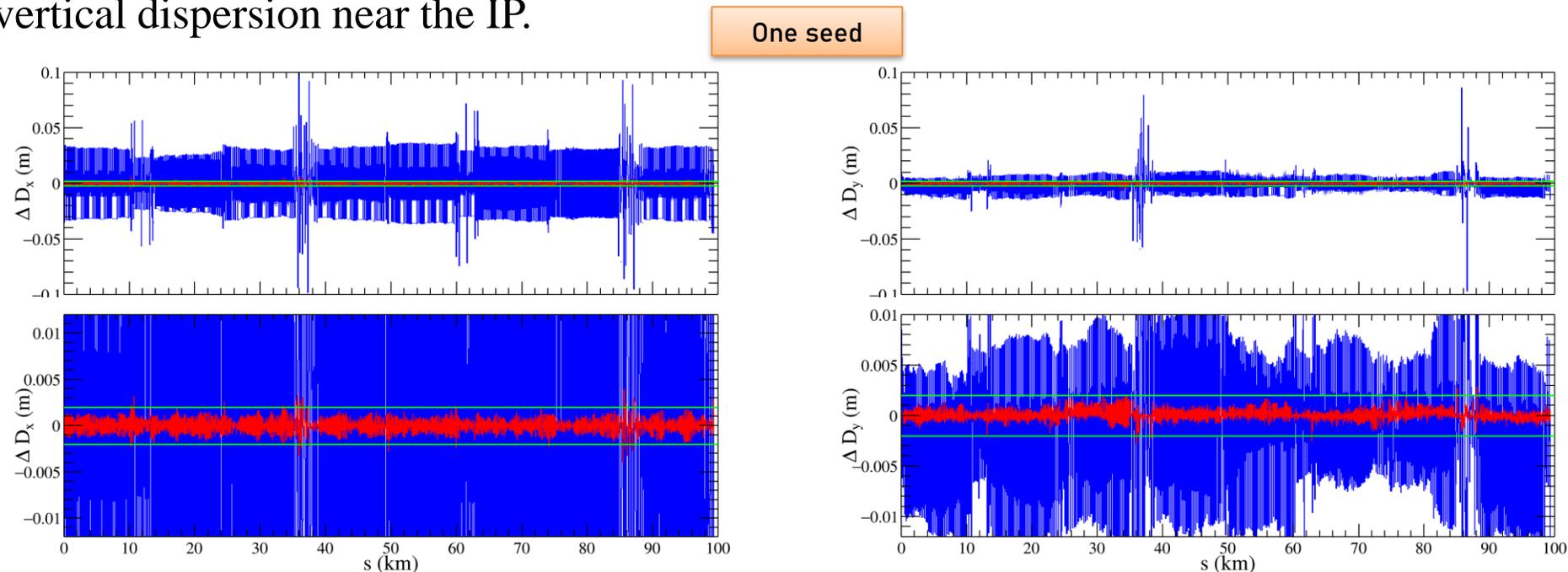
Blue: before DISP correction

Red: After DISP correction

Closed orbit after dispersion correction (Higgs mode)

- **Correction result:** The large fluctuation of closed orbit is also corrected.

- **Explanation**: During the DISP/DFS correction, the closed orbit deviations are used as weighting factors in the response matrix inversion to prioritize correcting dispersion errors where the orbit is most distorted.

Dispersion free steering principle (DFS): θ_c

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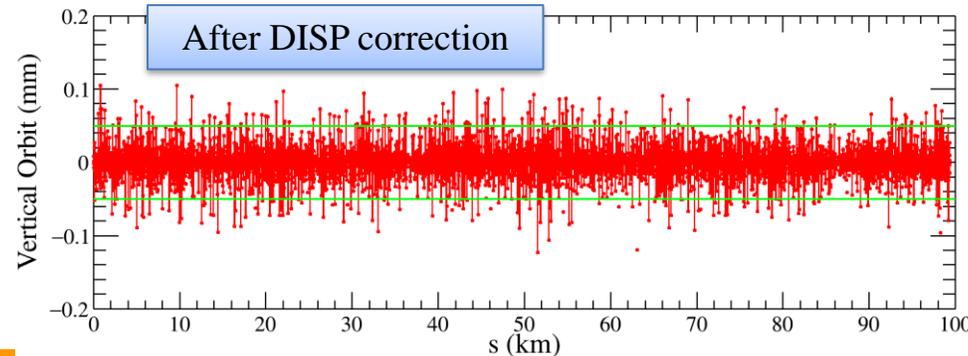
$\vec{u}$: Orbit vector

$\vec{D}_u$: Dispersion vector

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

α: Weight factor

A: Orbit response matrix

B: Dispersion response matrix

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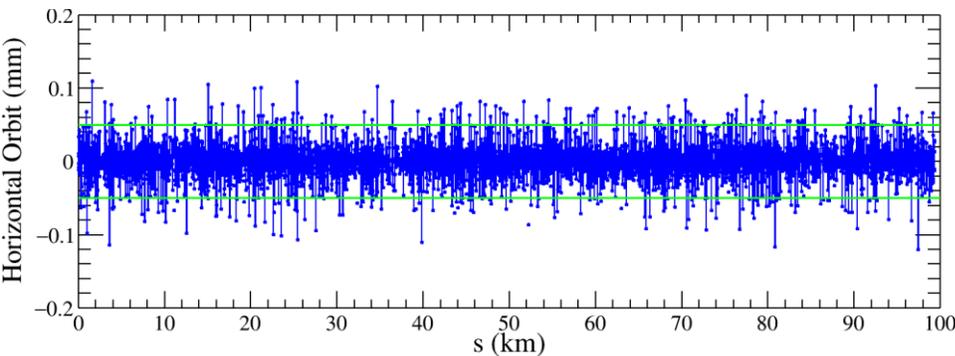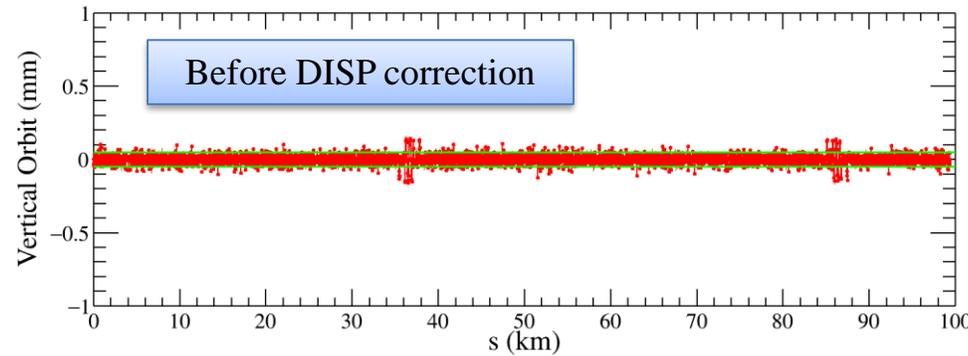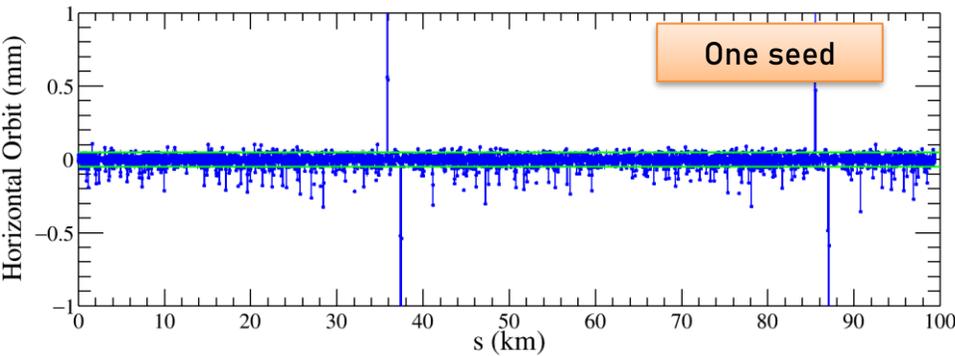
Dispersion correction (85 seeds)

- **Correction result:** All **85 seeds** are converged, the horizontal dispersion RMS value is reduced from 15.6 mm to 0.6 mm, and the vertical dispersion RMS value is reduced from 3.5 mm to 0.2 mm. The RMS horizontal and vertical orbits are lower than 50 μm.

- **Conclusion:** After DISP correction, closed orbit and dispersion deviation are lower than those correction targets, respectively. We move to the next beta beating correction.

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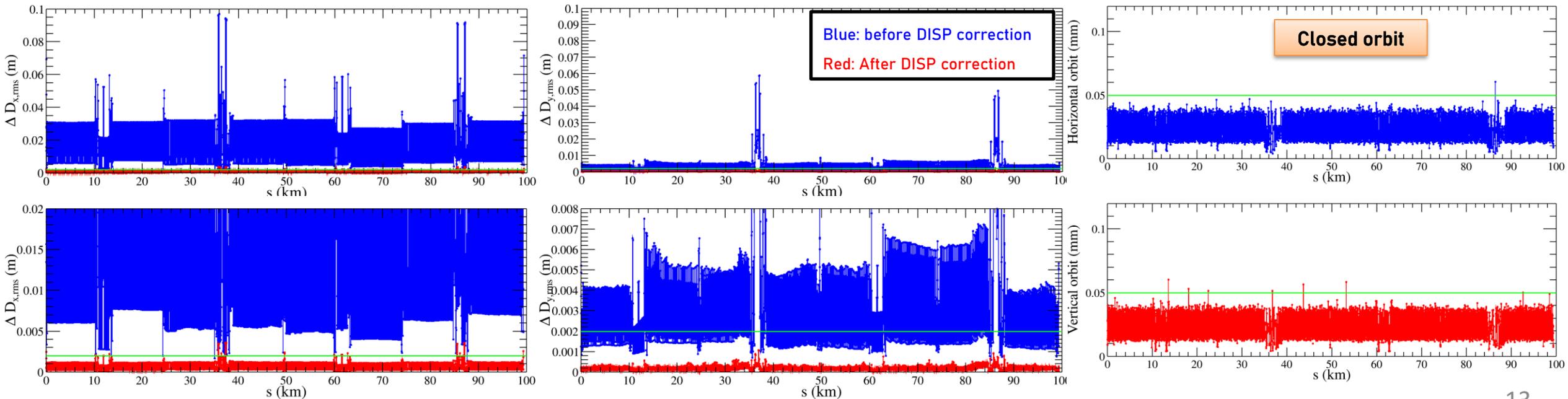
Beta-beating correction (on going)

- Correct the beta functions with sextupoles on.

- Based on **AT LOCO**: model based correction

    – Establish lattice model Mmod, multi-parameter fit to the orbit response matrix Mmeas 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.

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

    – Application to correct beta-beating, dispersion and coupled response matrix.

- We are working on the lattice debug based on the MATLAB softer ware.

Beat beating and DA after dispersion correction

- **We check the relative beta beating, emittance and dynamic aperture (DA) before beta beating.**

- Beta beating: the rms horizontal and vertical relative beat beating are **4.4%** and 2.4%. The horizontal relative beta beating is higher than the correction target.

- Emittance: emitx=0.667 nm, emity=0.34 pm, etmiy/emitx = 0.05%；[satisfied]

- DA: $1.2\% \times 11\sigma_x \times 20\sigma_y$, the momentum acceptance is lower than that of the on-axis injection requirement.

- **Conclusion:** After orbit and dispersion corrections, the DA has improved but still fails to meet the on-axis injection requirement. **Further improvement in DA is expected once beta-beating is addressed.**

The green arrow indicates the Dynamic Aperture requirement for on-axis injection.
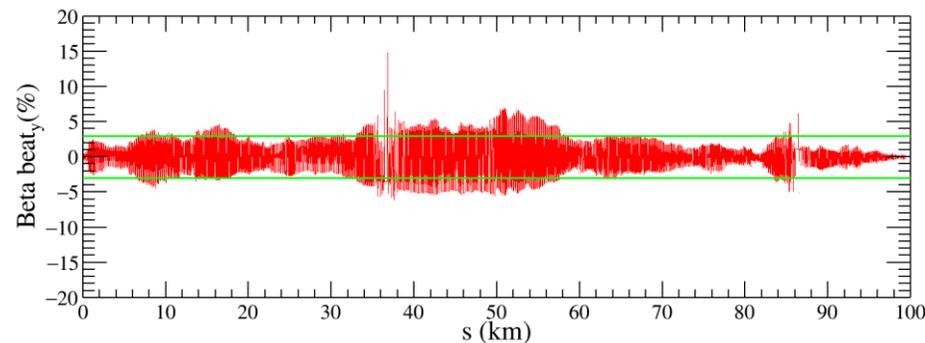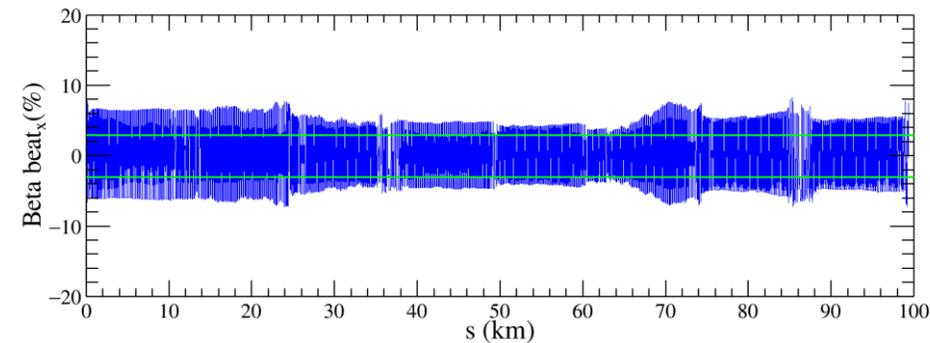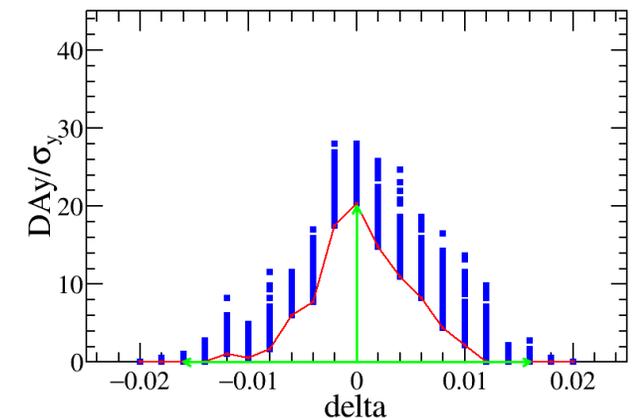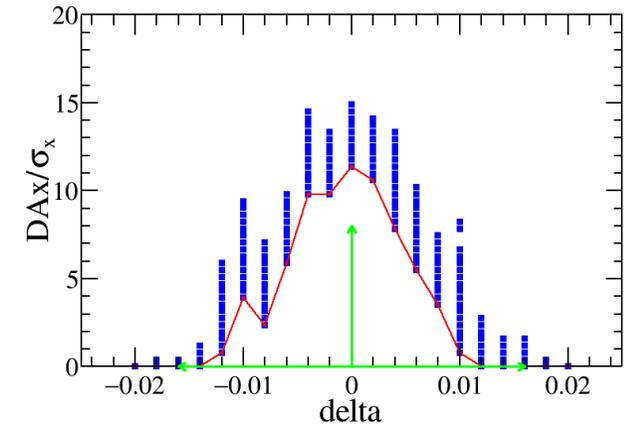
Summary and to do list

- Error correction with solenoid is mainly promoted.

- After weekly discussions and updates, the closed orbit correction and dispersion correction are carried out effectively, and the correction performance is comparable to that of the correction without solenoid.

- The beta beating correction is currently ongoing.

Thank you for your attention!

backup

CEPC Design Parameters

	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)	**576.9**	**23.1**	**253.8**	**4523.1**
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 β_x^*/β_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 ν_x/ν_y	445/445	317/317	317/317	445/445
Beam size at IP σ_x/σ_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	**1.05**/2.5	**2.0**/2.6
Beam-beam parameters ξ_x/ξ_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 ν_s	0.049	0.035	0.062	0.078
Beam lifetime (min)	**18**	**77**	**22**	**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**

- $\beta y*$ and emittance chosen for luminosity
- adequate bunch population Ne for the luminosity and the achievable energy acceptance for lattice design
- Number of bunches Nb is adjusted to keep the beam current
- Updated bunch spacing for the requirement from detector (D. Wang, Aug 2024, CEPC day)

Dynamic aperture requirement

■ The dynamic aperture requirement comes **from the injection parameters,** beam lifetime for the top-up injection.

Operation mode	On-axis injection	Off-axis injection
$t\bar{t}$	-	$11\sigma_x \times 16\sigma_y \times 2.0\%$
Higgs	$8\sigma_x \times 20\sigma_y \times 1.6\%$	$13.5\sigma_x \times 20\sigma_y \times 1.6\%$
W	-	$8.5\sigma_x \times 20\sigma_y \times 1.05\%$
Z	-	$11\sigma_x \times 23\sigma_y \times 1.0\%$

Considering: 3 sigma injection beam from booster (nominal booster emittance x and energy spread, 1% coupling for emittance x), 4 sigma circulated beam in collider, beam jitter due to kicker strength jitter are usually limit at the order of 10% sigma for circular accelerators.

All the particles from injection will survival w/ error, w/ jitter, w/o beam-beam as the particles located within the dynamic aperture.

E (GeV)	emitx_b (nm)	emitx_c (nm)	emity_b (pm)	emity_c (pm)
45.5	0.19	0.27	1.9	1.4
80	0.56	0.87	5.6	1.7
120	1.26	0.64	12.6	1.3
180	2.83	1.4	28.3	4.7

Coupling correction

➡ Neglecting beam-beam effects $\varepsilon_{\mathrm{y}} = \varepsilon_{\mathrm{y}0} + \kappa\varepsilon_x + \gamma E^2 (D_y^{rms})^2$

➡ 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

Error assumptions and correction schemes

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

A. Closed-orbit distortion (COD) correction is performed with sextupoles off, then the sextupoles were turned on and the COD correction repeated.

B. The dispersion correction using dispersion free steering principle (DFS).

C. beta-beating correction (LOCO), coupling and vertical dispersion correction

- The vertical emittance is calculated in each step of correction, and **only auto-corrected seeds were included in the performance evaluation**.

- Taking the Higgs mode correction as an example.

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Quadrupole	**0.10**	**0.10**	**0.10**	0.02%
Sextupole	0.10*	0.10*	0.10	0.02%