CEPC first tune operation required machine tuning

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(ON THE BEHALF OF THE CEPC ERROR CORRECTION TEAM)

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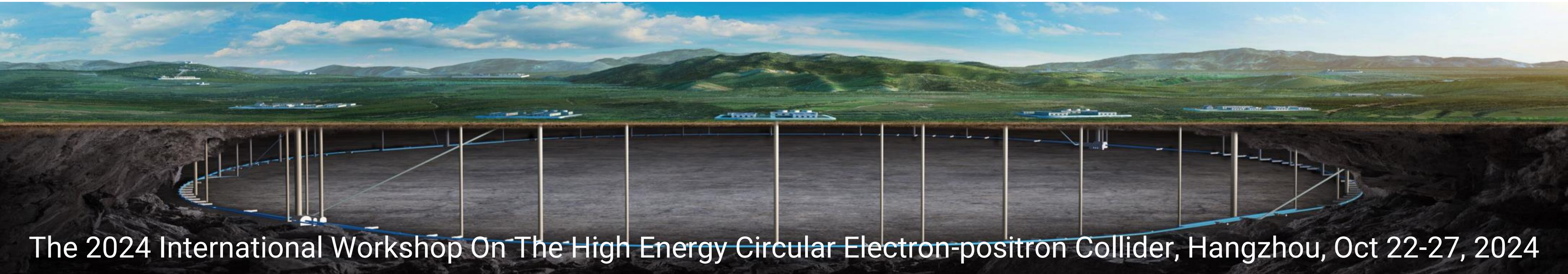

The 2024 International Workshop On The High Energy Circular Electron-positron Collider, Hangzhou, Oct 22-27, 2024

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Error assumptions

Component	Δx (mm)	Δy (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%

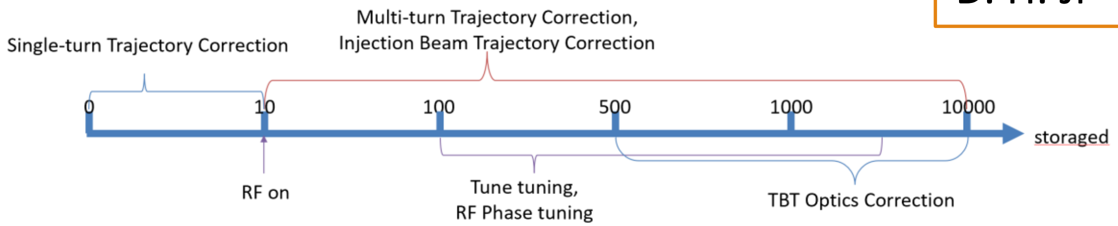
*implement beam-based alignment techniques to reach rms offsets in the order of 10 um with respect to the beam.

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

- Both BPM accuracy and offset w/o BBA are set to 100 μm.
- Other error settings are same as the error correction simulation in the TDR.
- The First turn Commissioning is performed based on the AT program.
- Using the response matrices of orbit and trajectory.

First Turn Commissioning

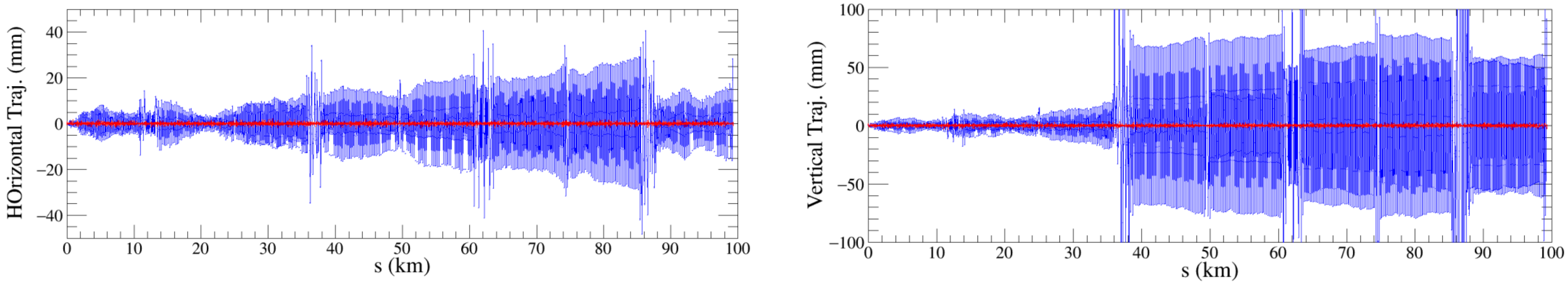
D. H. Ji



- Single turn trajectory correction:
  - Turn off the sextupoles and multipole magnets;
  - Select the TBT data where the BPM signals are clear enough (ignore the last five BPM info), so that the beam trajectory tends to approach the center and can be transmitted as far as possible.
  - Combine the newly added BPM information and continue the correction iteration using the same method to ultimately complete the first turn injection.
- multi-turn trajectory correction:
  - After the beam completes the first turn correction, we use the BPM signals for the second turn as independent new BPMs, and continue with the first turn correction until the multi-turn beam trajectory is obtained.

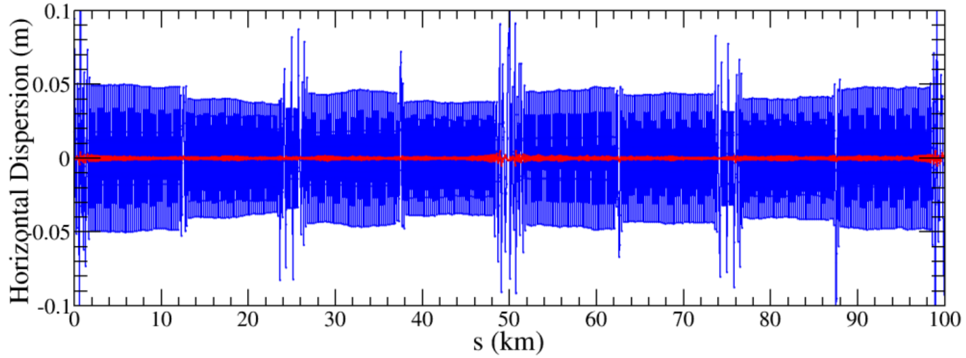
First Turn Commissioning

- The beam can survive for 10 turns after correction, and the beam trajectory of these 10 turns is used to approximate the closed orbit for the error correction wit BPM noise.
- Other first turn commissioning program is still ongoing, such as the RF parameters adjustment, Injection beam trajectory correction, Tune adjustment, and so on.
- We assume the BPM resolution is 0.1 μm after first turn commission.

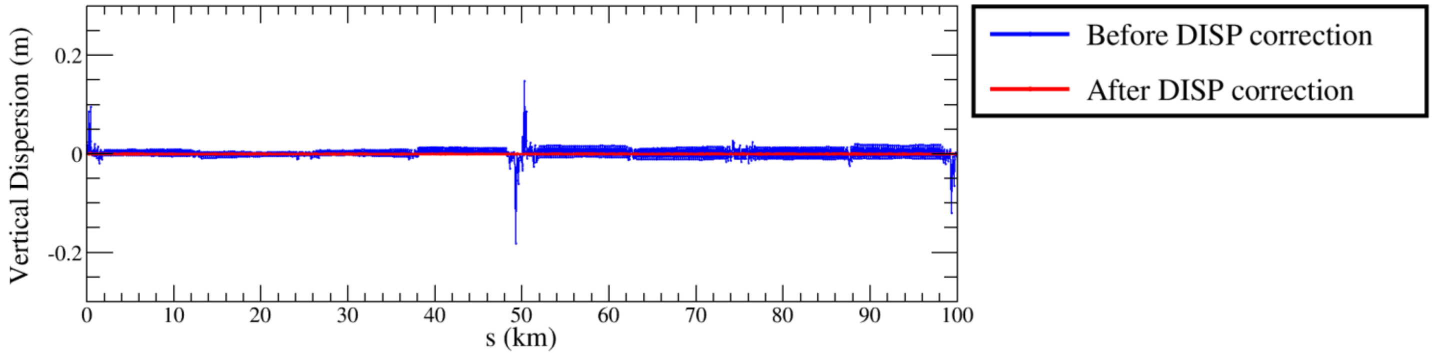


The blue curves are trajectory before correction, the red curves are the trajectory after multi-turn trajectory correction.

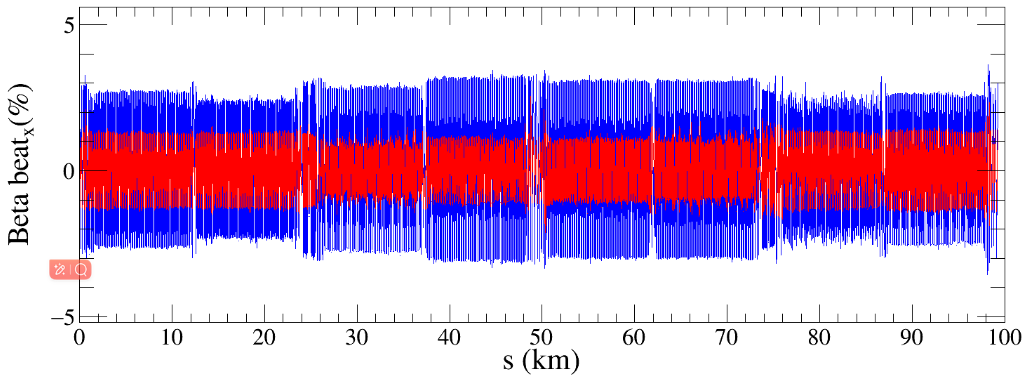
Error Correction with BPM error

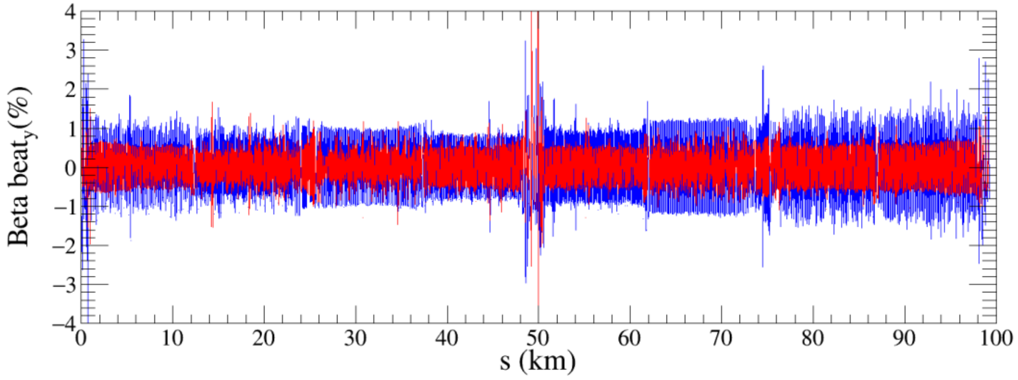


$\Delta D_{x,rms}$ decreased from 27.9 mm to 0.5 mm



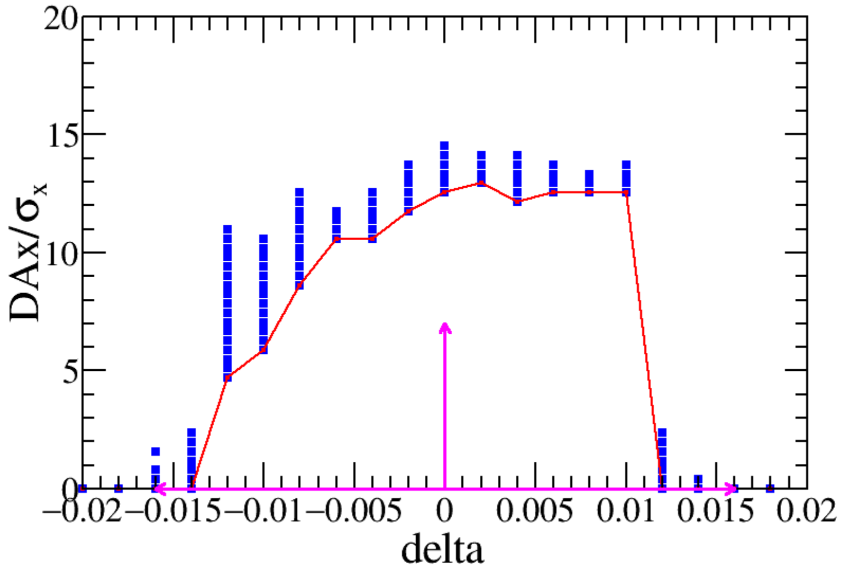
$\Delta D_{y,rms}$ decreased from 10.3 mm to 0.4 mm

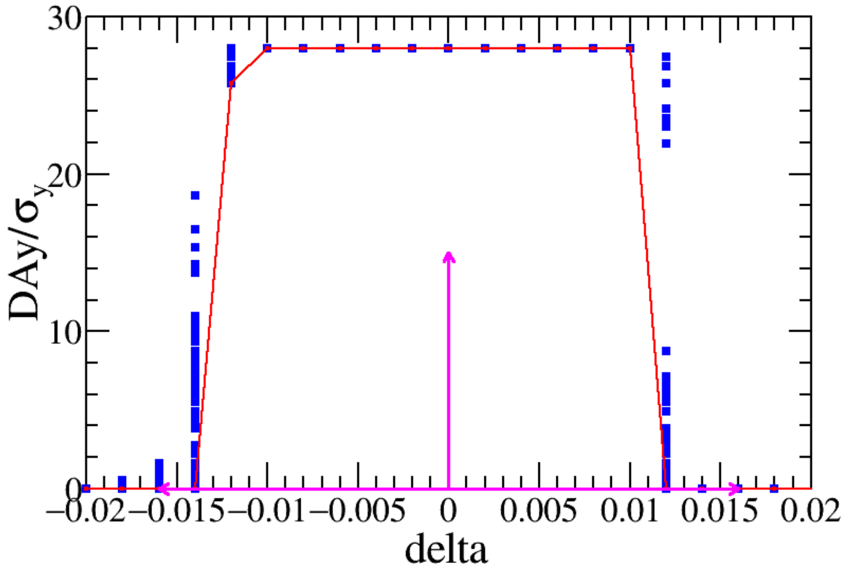




$\Delta\beta/\beta_{rms}$ < 3%

Error Correction with BPM error

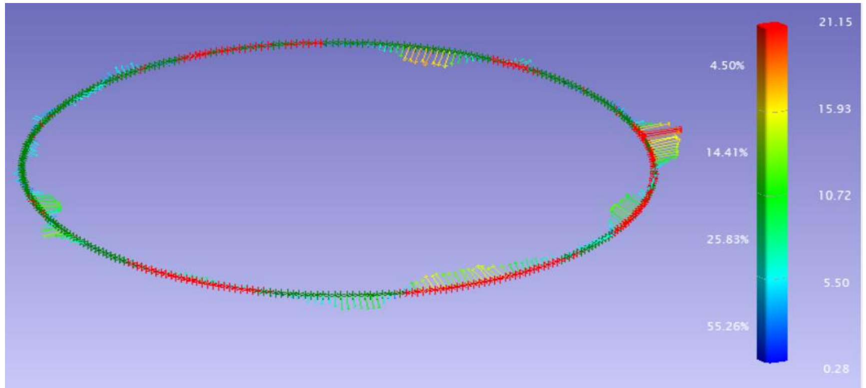


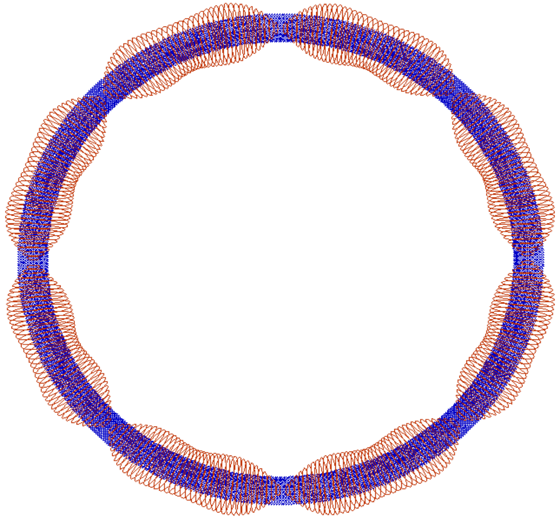


- The dynamic aperture after correction can not fulfill the requirement of on axis top-up injection $8\sigma_x \times 20\sigma_y \times 1.6\%$.
- Correction wit more lattice seeds is ongoing, other additional correction methods are necessary.

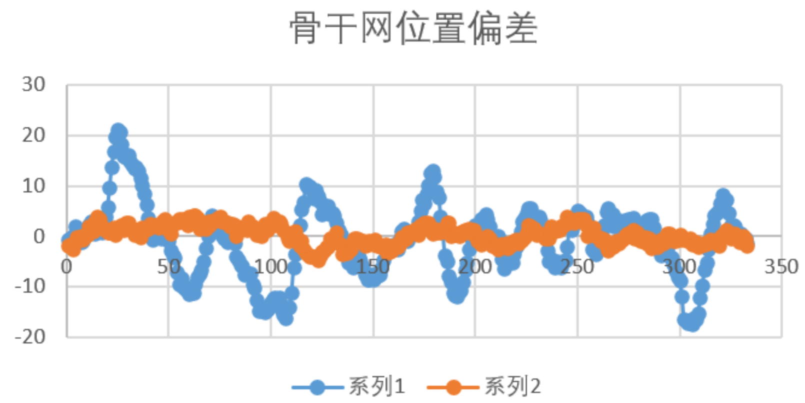
Long range alignment tolerances

X. L. Wang





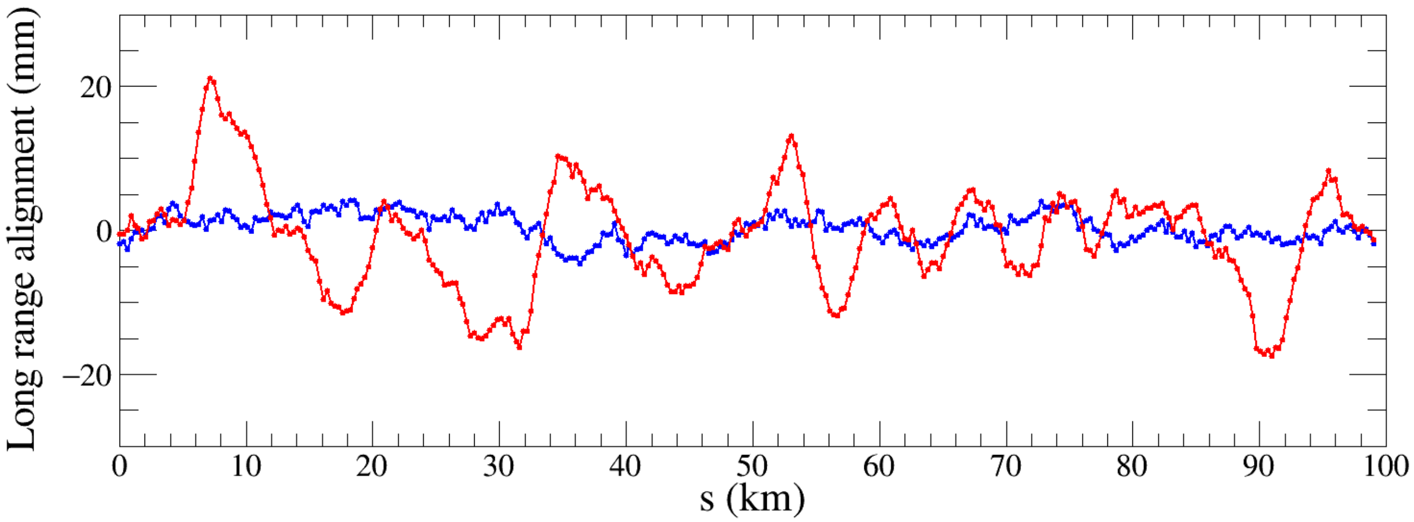
95%标准偏差Standard Deviations			
	X/mm	Y/mm	Z/mm
MAX	7.511	7.491	19.581
MIN	0	0	0
标准偏差	4.550611	4.538313	16.03869



- There are eight ground network control points with random errors ranging from 0 to 7 mm.
- There are 333 stations, and the RMS values of position deviation are also in the range of several tens of millimeters.
- Ten samples have been provided by Xiaolong Wang for error analysis.

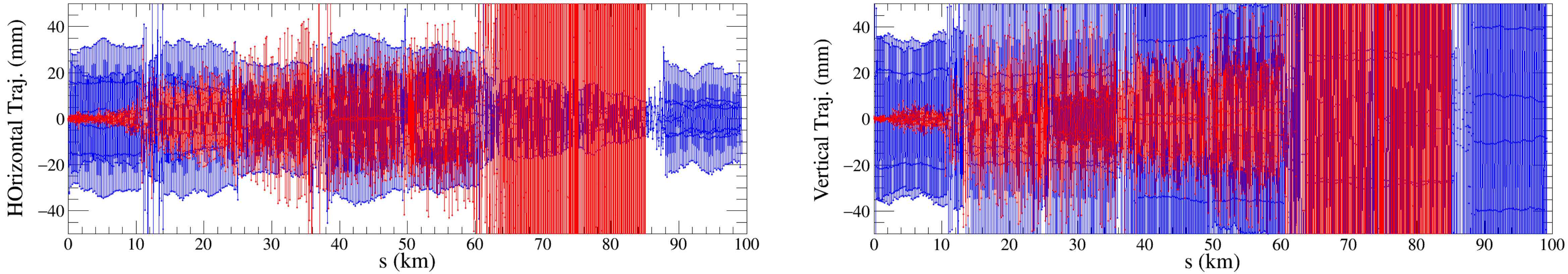
Long range alignment tolerances

- Using linear interpolation to calculate the long-range errors of all magnetic components, and then superimposing their respective alignment errors.
- The first turn commissioning is conducted initially to achieve a closed orbit.



First turn trajectory correction

- Using linear interpolation to calculate the long-range errors of all magnetic components, and then superimposing their respective alignment errors.
- The first turn commissioning is conducted initially to achieve a closed orbit.
- Only about 10 km of beam trajectory can be found, after which the beam will be lost due to exceeding the aperture limit. We are currently investigating the cause.



Summary and To-do list

- The first turn and multi-turn trajectory corrections have been completed, while other aspects of the first turn commissioning are still in progress.
- Preliminary results of the error correction with BPM noise are presented, while the dynamic apertures after correction need further optimized.
- The error analysis with long-range alignment tolerances is being initiated, and the first turn and multi-turn trajectory corrections are currently underway.

Thank you for your attention

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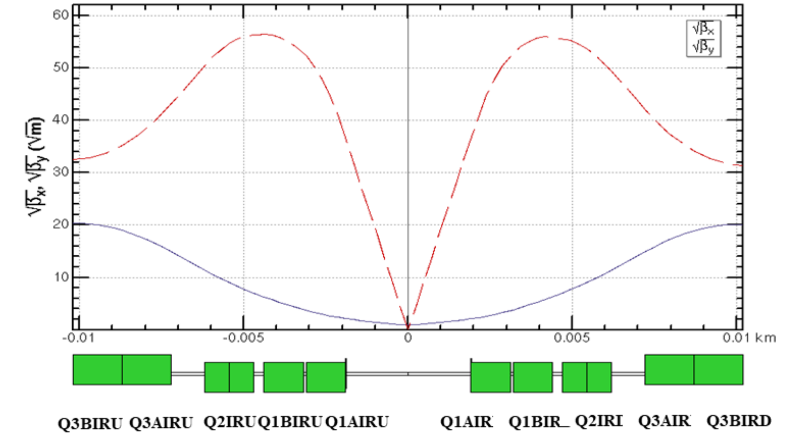
Main parameters in TDR

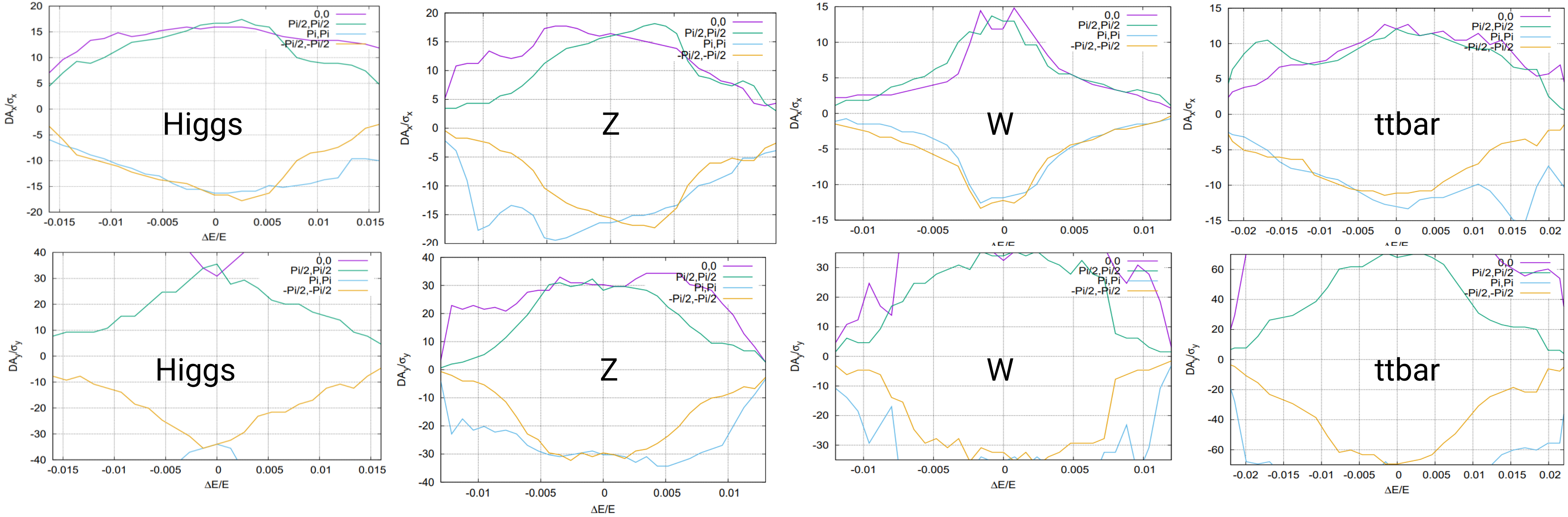
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	**100.0**			
SR power per beam (MW)	**30**			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	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 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	**1.2**/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 (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	$13.5\sigma_x \times 20\sigma_y \times 1.6\%$	$11\sigma_x \times 23\sigma_y \times 1.0\%$	$8.5\sigma_x \times 20\sigma_y \times 1.05\%$	$11\sigma_x \times 16\sigma_y \times 2.0\%$

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.