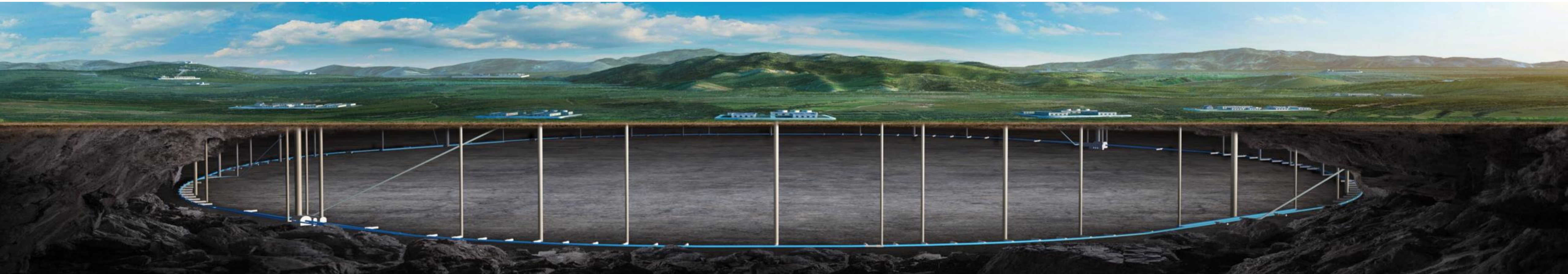
Institute of High Energy Physics
Chinese Academy of Sciences

CEPC first tune operation required machine tuning (including orbit corrections and sextupoles) and luminosity ramping scenarios

Bin Wang
On behalf of the error correction team

2024.05.20



Content

- Progress of error correction with BPM error
- Progress of the first turn correction
- Summary and To do list

CEPC EDR Plan

Yiwei Wang, CEPC Accelerator physics EDR plans, CEPC Day, 2024.03.15

- 建立首圈注入、调谐、运行和不同模式切换等算法。
- 研究更加完整的静态误差效应及全局误差校正
  - 基于束流的准直、长程准直误差、高阶场误差、BPM、双孔径二极铁两孔径场系统误差
- 研究各种动态误差效应和可能的反馈（工作点、轨道，快轨道反馈）
  - 各种抖动源、选址有关的地面运动、潮汐效应等
- 建立调束和运行的工具。
- 研究束束作用在机器误差、束流光学非线性、阻抗及其他集体效应下对亮度的影响。

一、关于 BPM 测量精度需求。季大恒、王斌、王毅伟从加速器物理的角度做了初步分析和说明，与会人员经过讨论，建议物理系统先做误差分析，然后提出合理且明确的测量精度要求，并反馈给束测系统，束测系统根据该需求设计 BPM 测量系统，在此基础上提出 BPM 测量系统对参考时钟抖动性能的要求。高杰指出，BPM 测量精度需求只是一个起点，另需要考虑纵向（高频）、轨道反馈等因素，形成一张完整的参数表，逐步完善。

2024年3月26日CEPC前端设计和通用讨论会会议纪要

Progress of error correction with BPM error

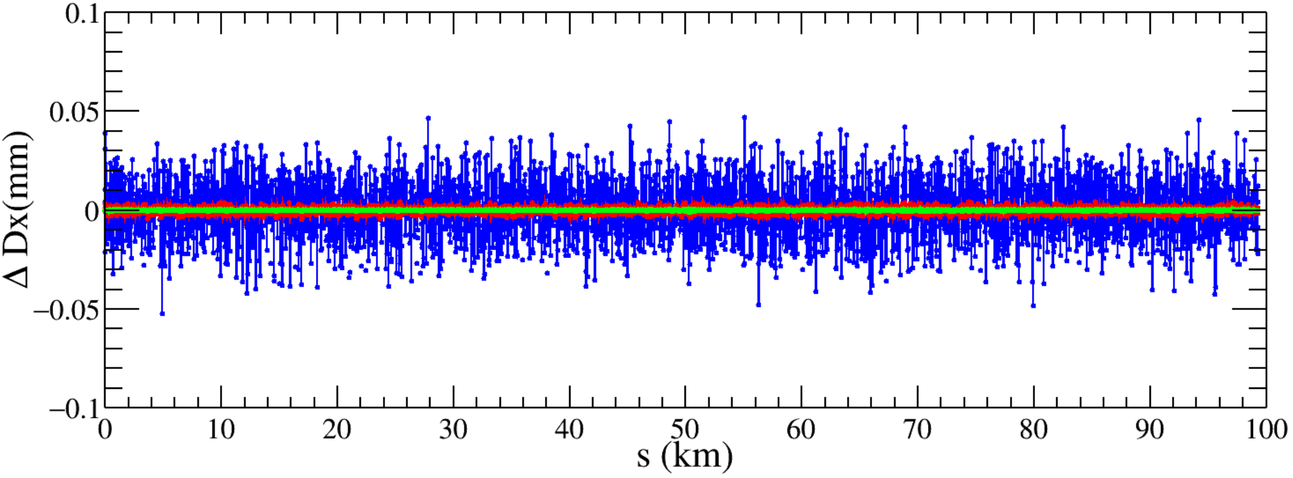
Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.02%
IR Quadrupole	0.10	0.10	0.10	0.02%
Sextupole	0.10*	0.10*	0.10	0.02%

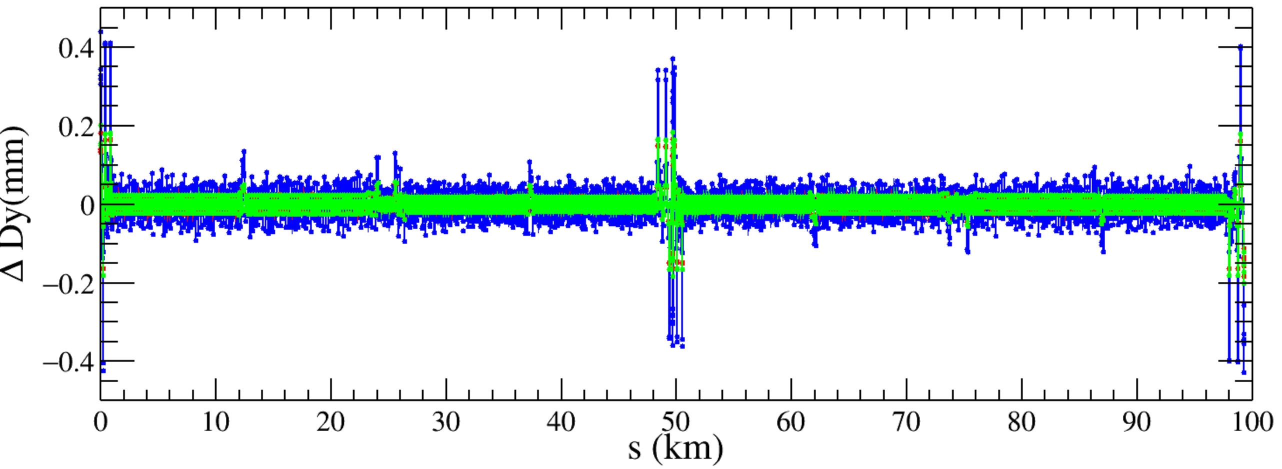
*implement beam-based alignment techniques to reach rms offsets in the order of 10 μm with respect to the beam.

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

- The BPM noise (0.1 μm, 1 μm, and 10 μm) and BPM shift (0.1 μm, 1 μm, 10 μm) are considered during the correction.
- 100 lattice seeds with above error assumptions are generated.
- The whole correction scheme is performed.

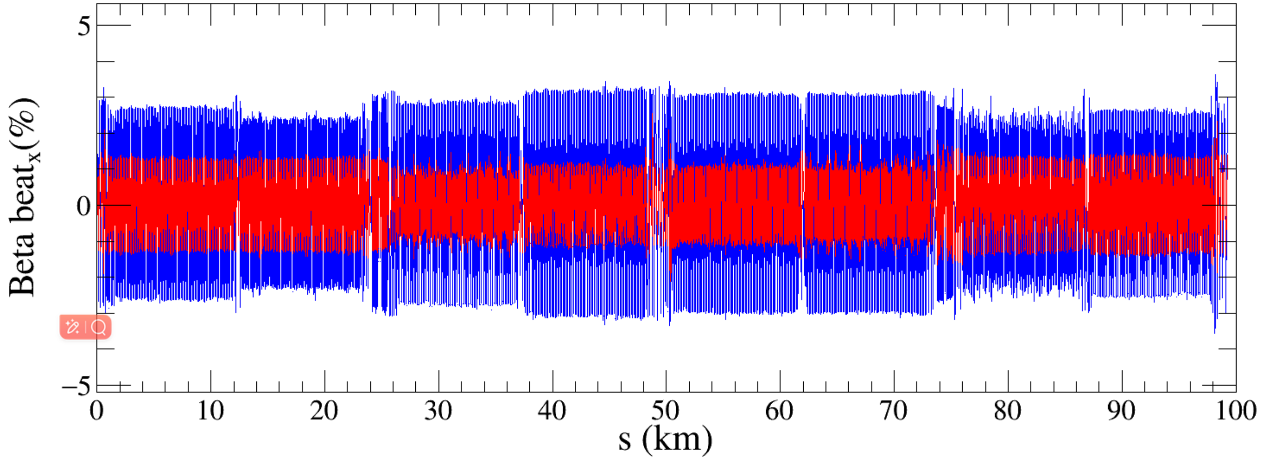
Progress of error correction with BPM error

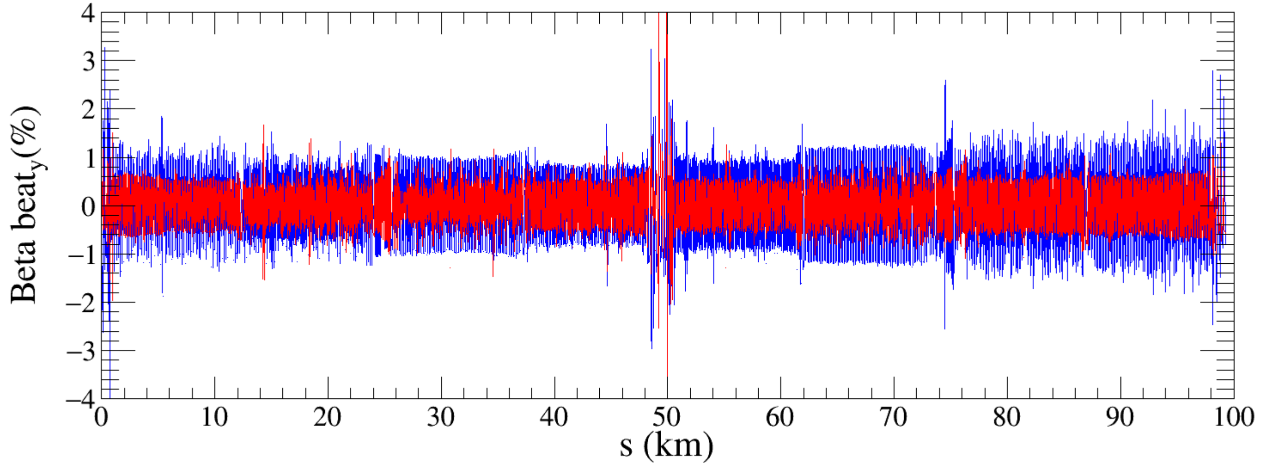




- The closed orbit difference after correction with three BPM error assumptions (0.1 μm, 1 μm, and 10 μm) are compared.
- For the 0.1 μm and 1 μm cases, the horizontal closed orbit shows no significant change (<5μm), whereas the vertical closed orbit exhibits changes on the order of tens of micrometers.
- For the 10 μm case, the horizontal closed orbit exhibits changes on the order of tens of micrometers, while the vertical closed orbit shows changes on the order of hundreds of micrometers.

Progress of error correction with BPM error





- The Beta beating correction is performed with BPM errors, while only case with 0.1 μm is converged.
- After considering the BPM errors, the beta beating has significantly increased.
- Continuing our attempts to find a convergent solution for optics correction with 1 μm, and 10 μm BPM errors.

Content

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Progress of the first turn correction

Bin Wang and Daheng Ji

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%
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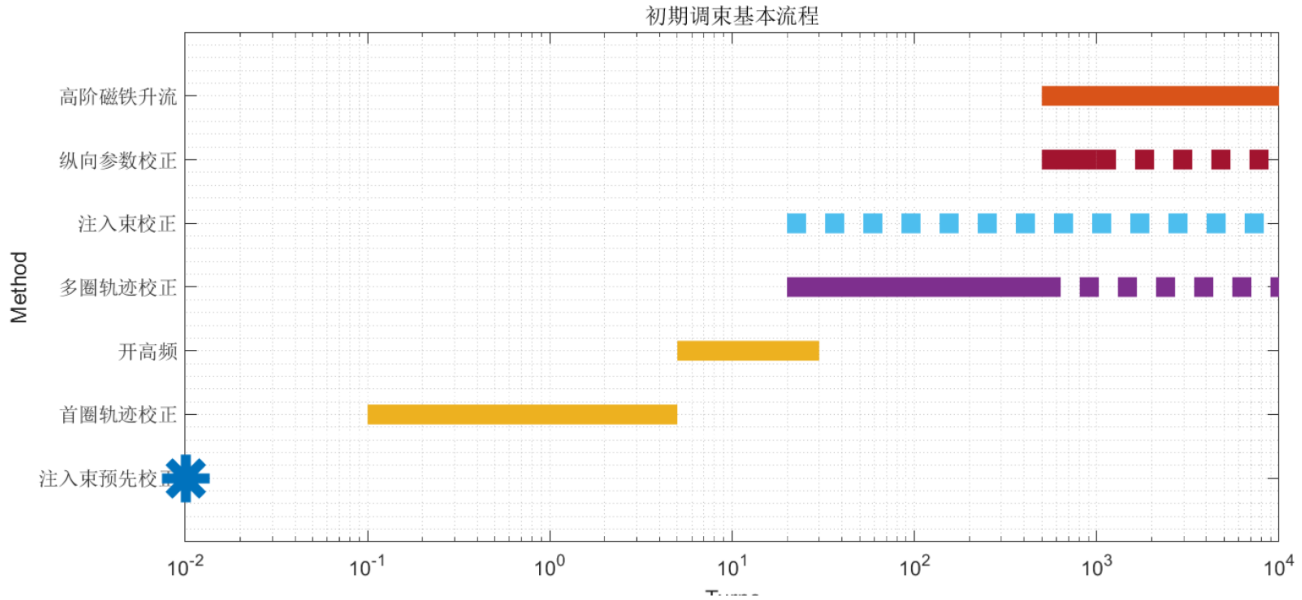
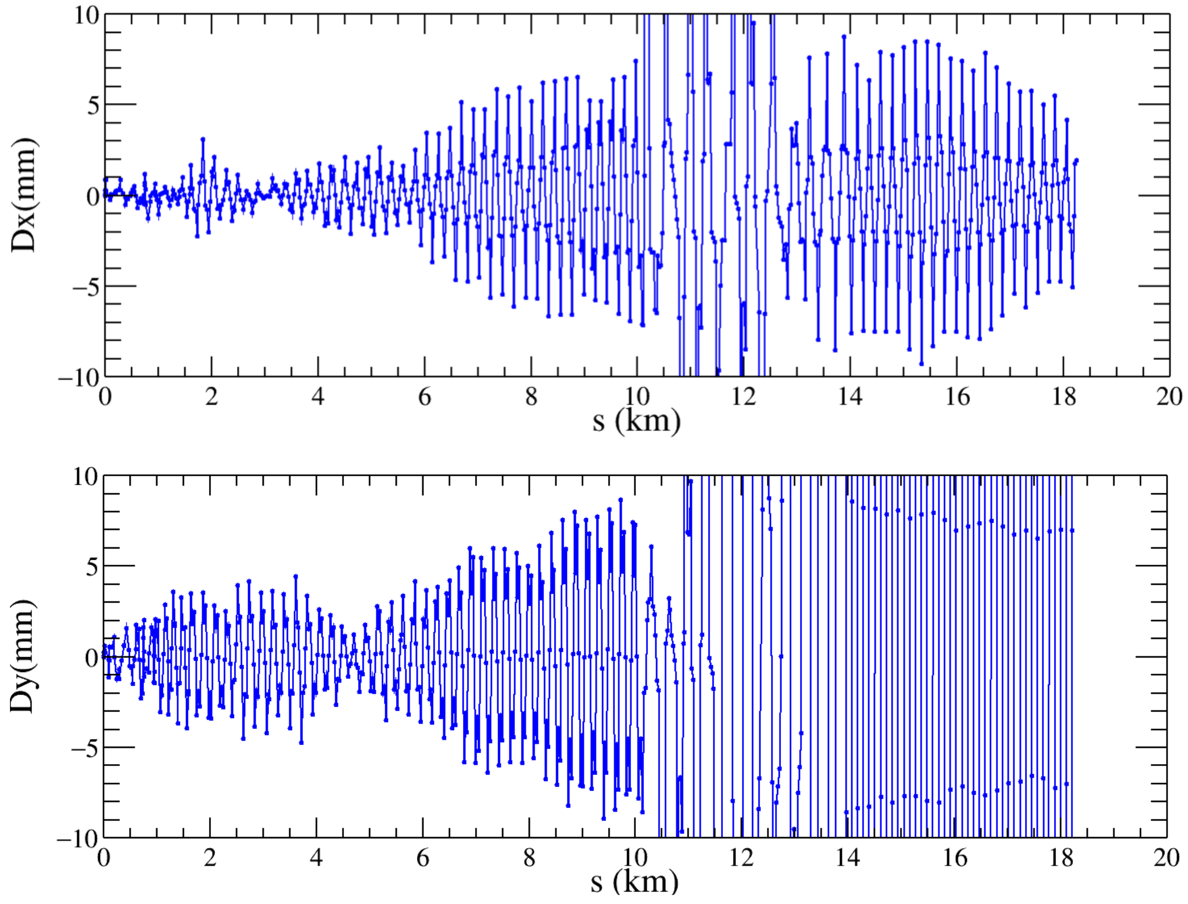


- The whole first turn commission program has been developed for HEPS, part of the program has already been modified according to the CEPC lattice.
- First turn commission test is undergoing.

季大恒，崔小昊，王斌，储存环初期调束模拟研究，HEPS-AC-AP-TN-2023-008-V0

Progress of the first turn correction

Bin Wang and Daheng Ji



- Based on the lattice in the CEPC TDR, the beam can only be transmitted for around 10 km.
- A commission Lattice or lattice with large beta function is necessary, Yiwei is currently designing.

Summary and To do list

- Manpower:
  - Bin Wang: Main contribution, the least further correction experience within the current team
  - Yiwei Wang: Lattice design
  - Daheng Ji and Yuanyuan Wei: first turn correction, IP tuning, …
  - More manpower is necessary, especially colleagues with experience in error correction tasks.
- Commission Lattice (lattice with large beta function) is necessary for first turn correction.
- Other correction works are ongoing.

Thanks for your attention!

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%
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- 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.

Correction performance

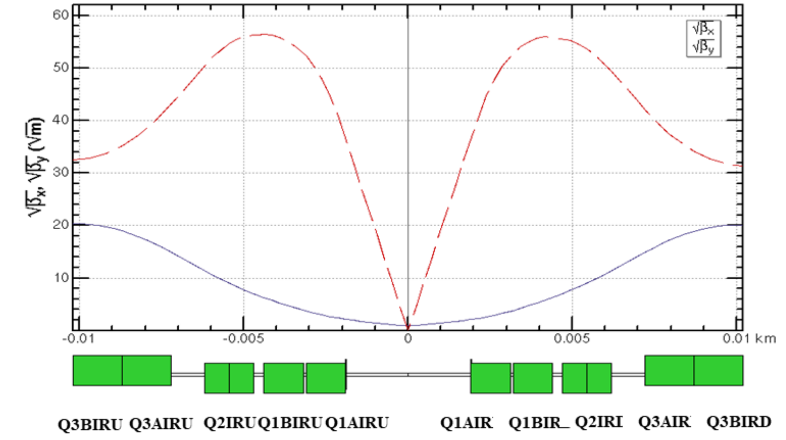
- To reduce the statistical fluctuation, 100 random lattices seeds with errors are generated for correction, all error sources follow a Gaussian distribution truncated at $\pm3\sigma$.
- The above correction scheme is adjusted (such as the iteration times, the step size, the size of response matrix, 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

Main parameters in TDR

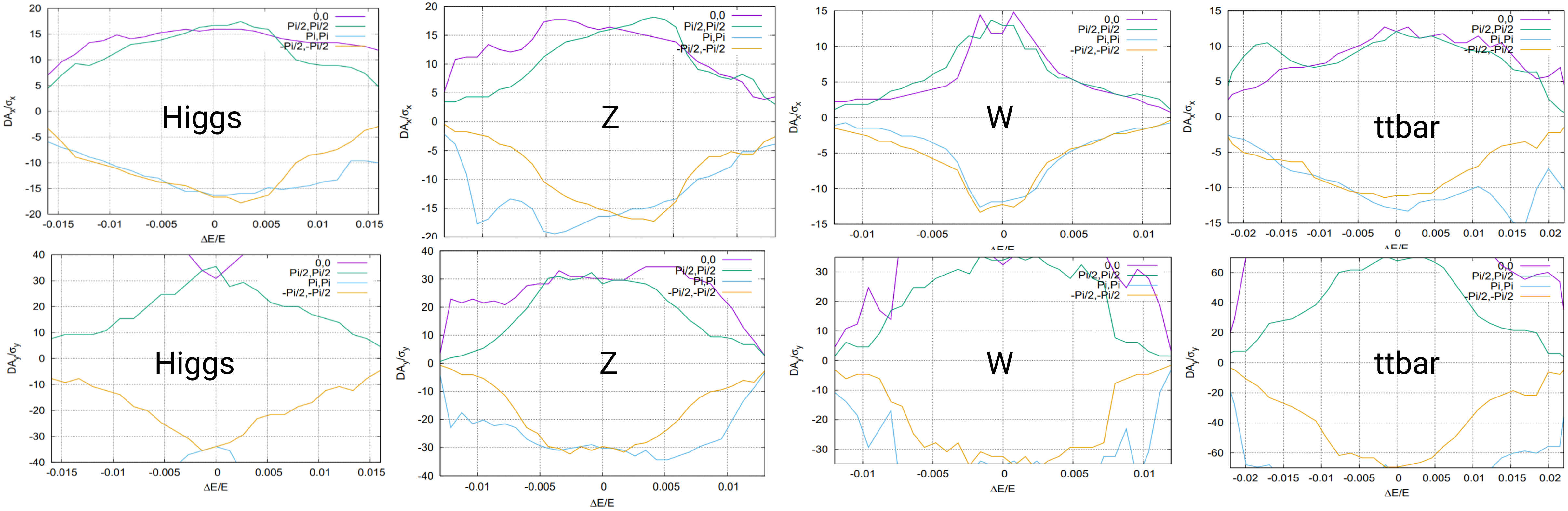
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	**100.0**			
SR power per beam (MW)	**30**			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	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



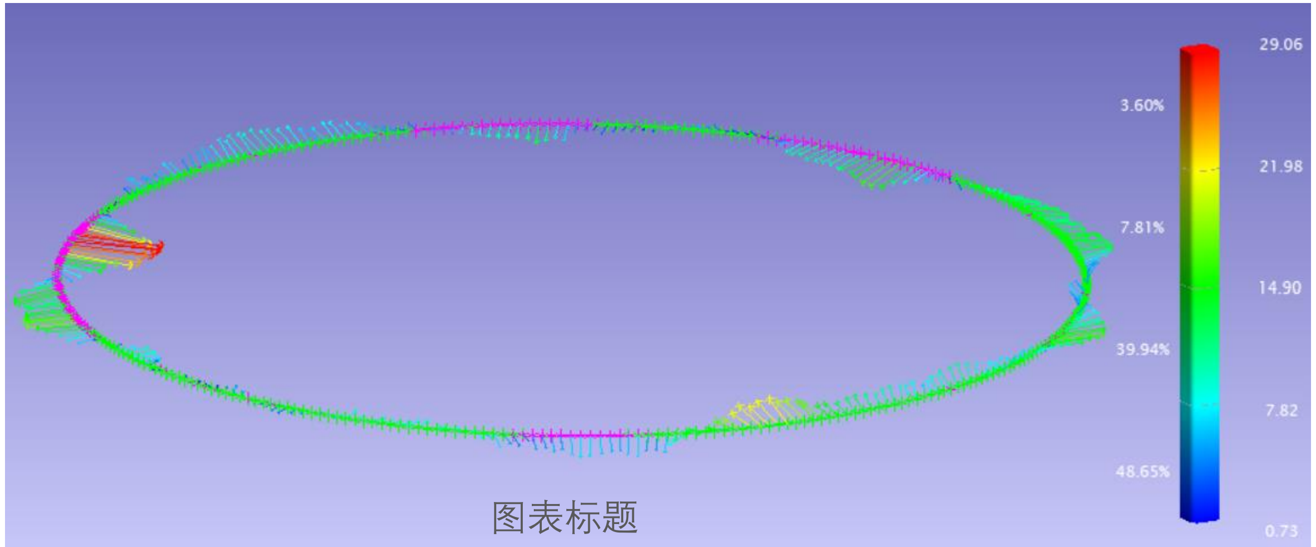
- The error correction in the CEPC TDR uses this version of parameters and corresponding lattices.
- Currently, we still use the same lattice and parameters to do more error study for the CEPC EDR.

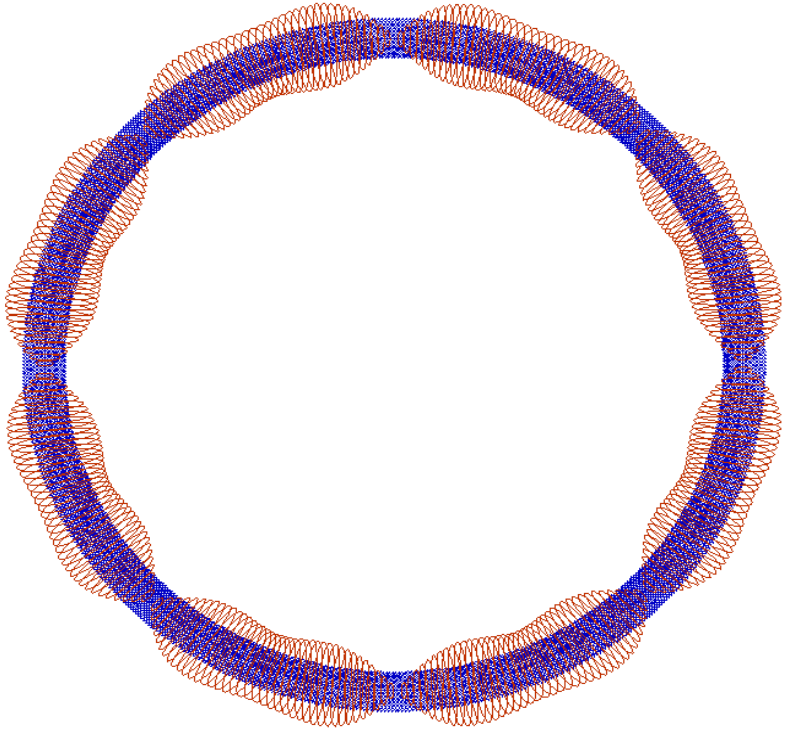
Dynamic aperture and requirement

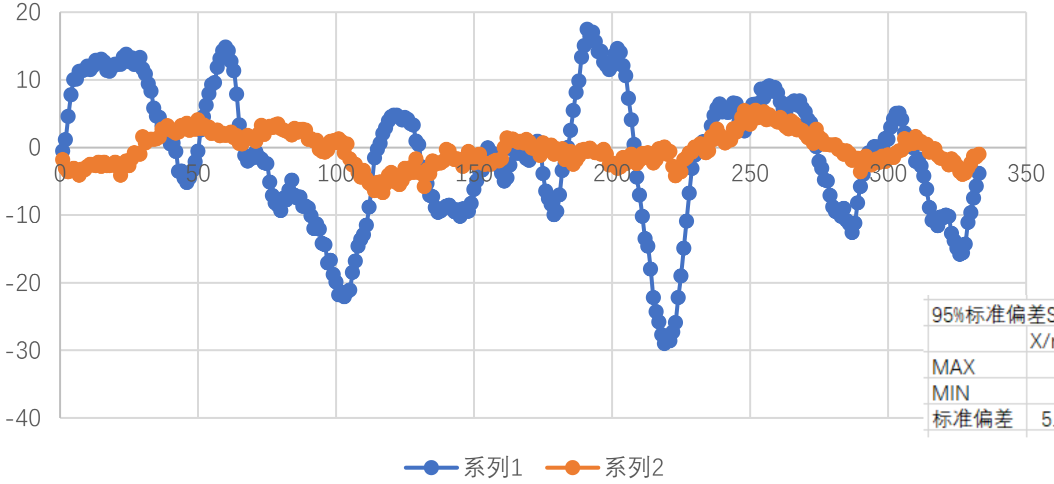


DA requirement	Higgs	Z	W	ttbar
with on-axis injection	$8\sigma_x \times 20\sigma_y \times 1.6\%$	-	-	-
with off-axis injection	$13.5\sigma_x \times 20\sigma_y \times 1.6\%$	$11\sigma_x \times 23\sigma_y \times 1.0\%$	$8.5\sigma_x \times 20\sigma_y \times 1.05\%$	$11\sigma_x \times 16\sigma_y \times 2.0\%$

the long range alignment errors







95%标准偏差Standard Deviations	X/mm	Y/mm	Z/mm
MAX	8.687	8.664	19.103
MIN	0	0	0
标准偏差	5.182894	5.166892	15.64744

95%误差椭圆Error Ellipses	Semi-Majc	Semi-Minc	Elev
MAX	21.404	5.469	37.442
MIN	0	0	0
标准偏差	17.55649	3.559261	30.66861

95%Relative Error Ellipses	Semi-Majc	Semi-Minc	Elev
MAX	7.673	1.498	17.291
MIN	3.468	1.279	13.396
标准偏差	5.4913	1.392215	15.39154