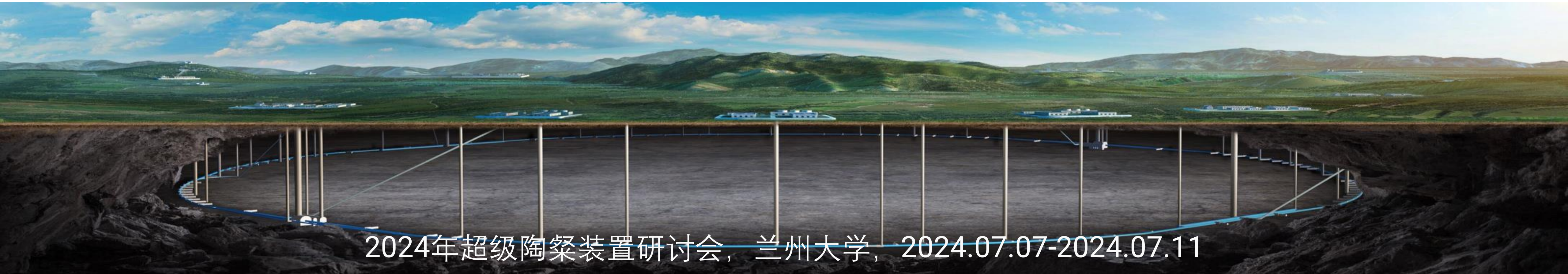
Institute of High Energy Physics
Chinese Academy of Sciences

CEPC误差对亮度的影响和校正研究

王斌

（代表CPEC误差校正团队）

2024.07.09



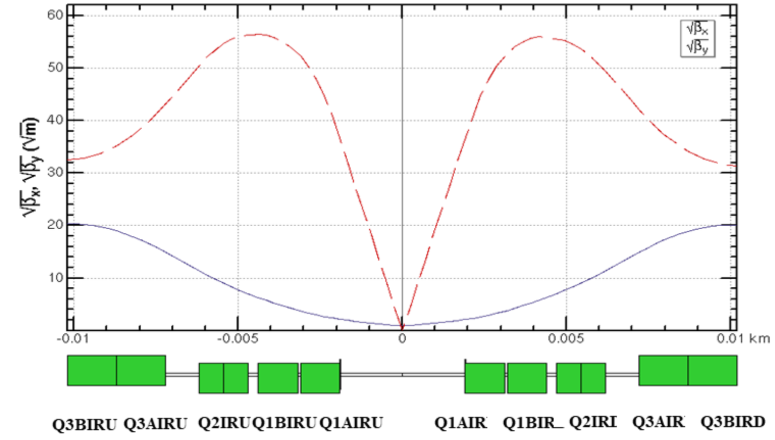
2024年超级陶粲装置研讨会，兰州大学，2024.07.07-2024.07.11

Content

Main parameters in TDR

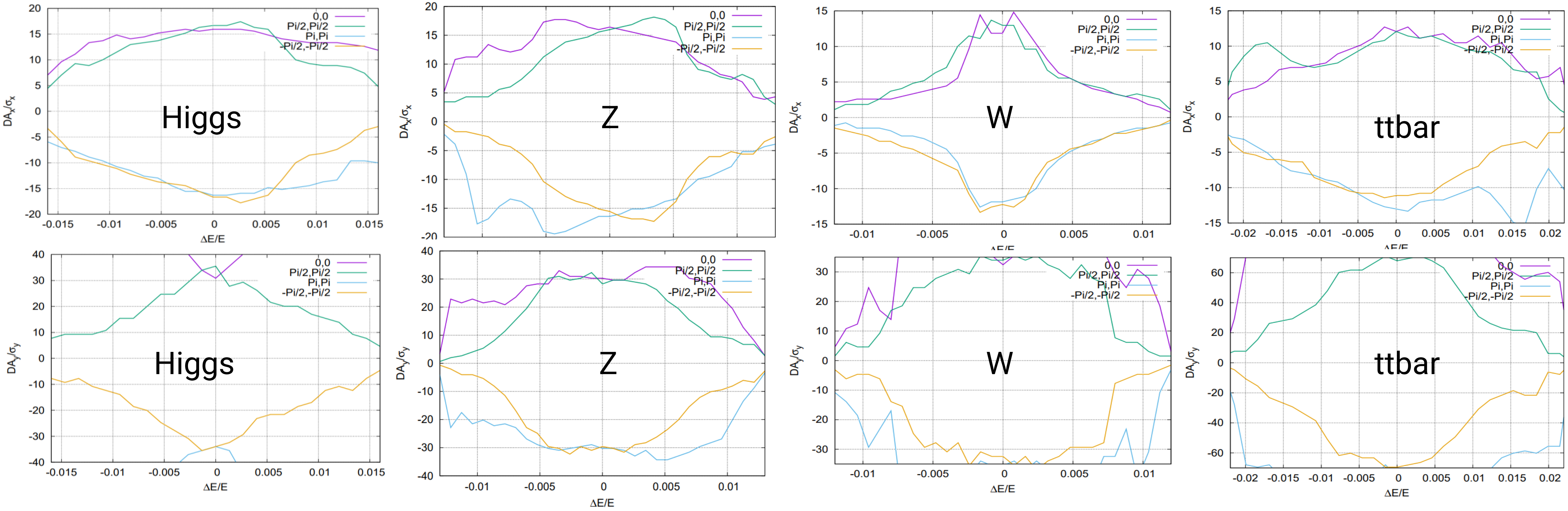
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	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	$13.5\sigma_x \times 20\sigma_y \times 1.6\%$	$11\sigma_x \times 23\sigma_y \times 1.0\%$	$8.5\sigma_x \times 20\sigma_y \times 1.05\%$	$11\sigma_x \times 16\sigma_y \times 2.0\%$

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 μm with respect to the beam.

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

- 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

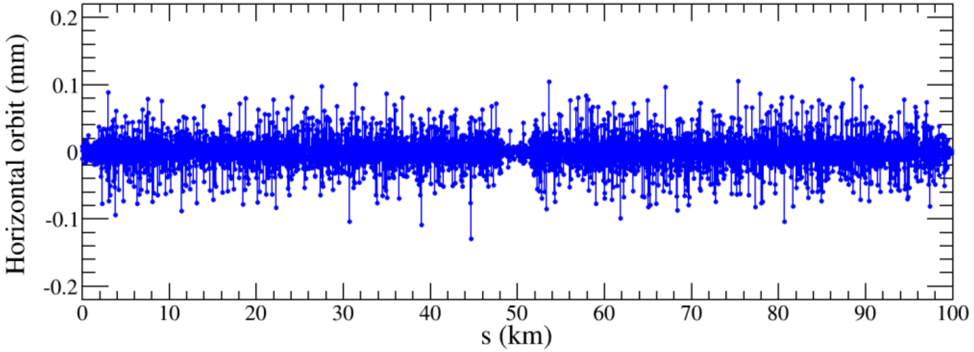
- Software: SAD and Matlab-based accelerator toolbox (AT)

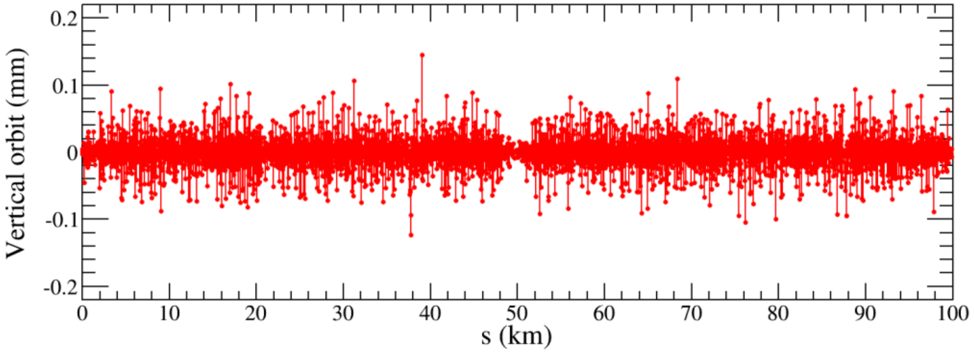
1. Closed-orbit distortion (COD) correction was performed with sextupoles off, then the sextupoles were turned on and the COD correction repeated.
2. The dispersion correction and beta-beating correction are also used for optics correction.
3. The coupling and vertical dispersion correction are used 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

- ~1850 BPMs placed at quadrupoles
- ~1850 Horizontal correctors placed beside focusing quadrupoles
- ~1850 Vertical correctors placed beside defocusing quadrupoles
- There are some minor adjustments for different modes
- Orbit correction is applied using orbit response matrix and SVD method

Result of a Higgs lattice seed





Both horizontal and vertical orbit are mostly lower than 50 μm.

$\boldsymbol{RMS_{COD} < 0.03\ mm}$

Dispersion correction

Dispersion free steering principle (DFS): θ_c

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

$\vec{u}$: Orbit vector

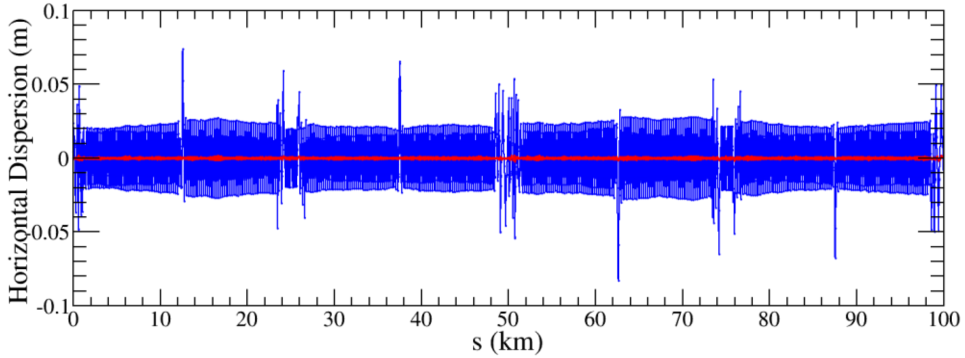
$\vec{D}_u$: Dispersion vector

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

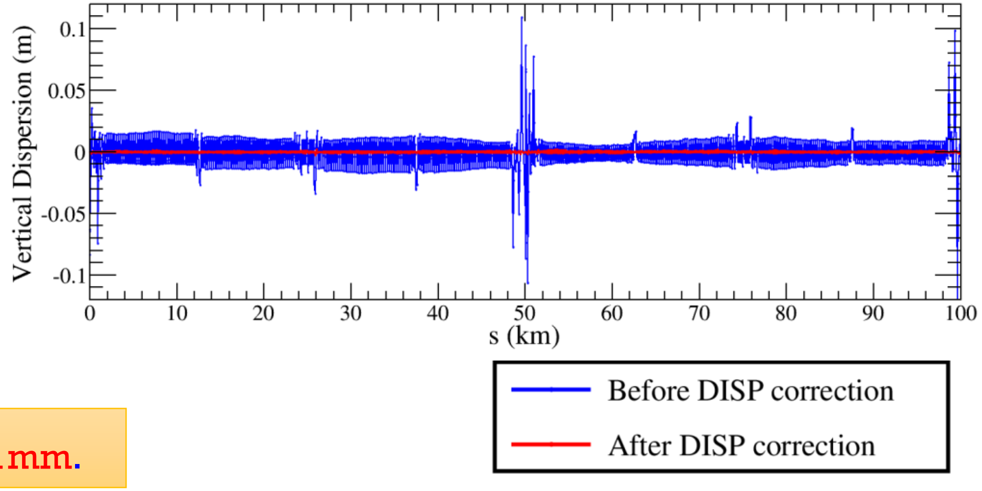
α: Weight factor

A: Orbit response matrix

B: Dispersion response matrix



Result of a Higgs lattice seed

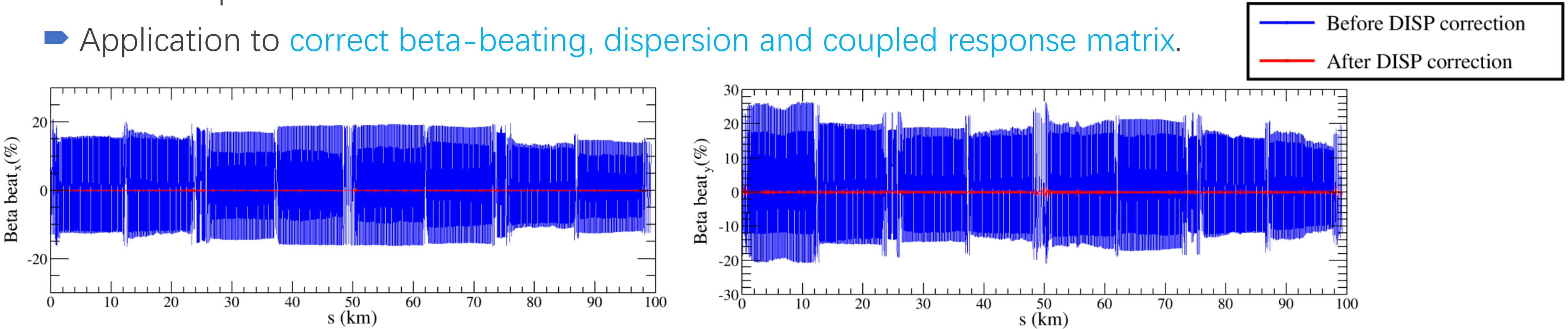


The dispersion is corrected well, the RMS dispersion is about 1mm.

Beta-beating correction

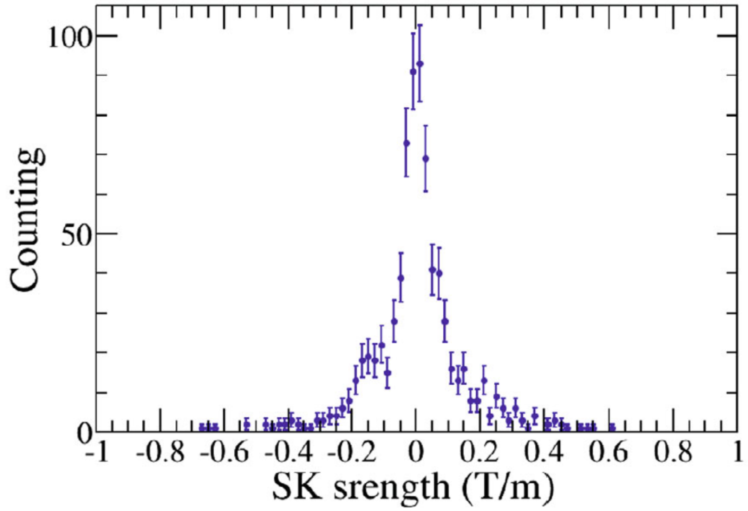
- Correct the beta functions with sextupoles on.
- Based on AT LOCO: model based correction
    - Establish lattice model Mmod, multi-parameter fit to the orbit response matrix Mmeas to obtain calibrated model:
    - Parameters fitted: K, KS …
    - Use calibrated model to perform correction and apply to machine.
    - Fit the dispersion at the same time.
    - Application to correct beta-beating, dispersion and coupled response matrix.

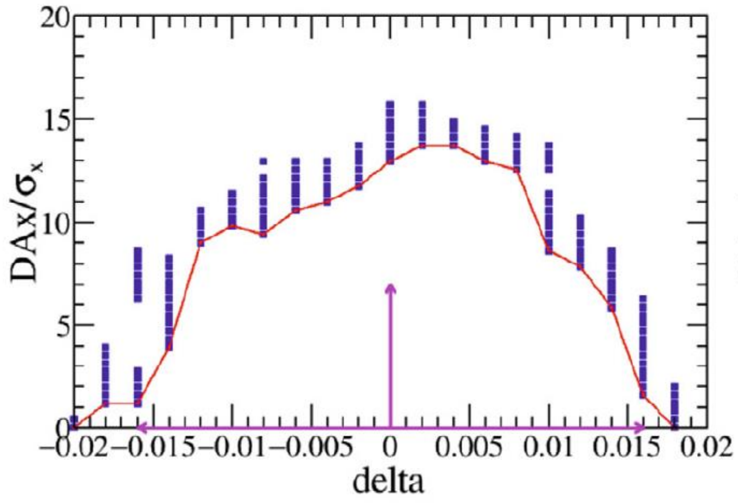
$$\chi^2 = \sum_{i,j} \frac{(M_{\mathrm{mod},ij} - M_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2$$

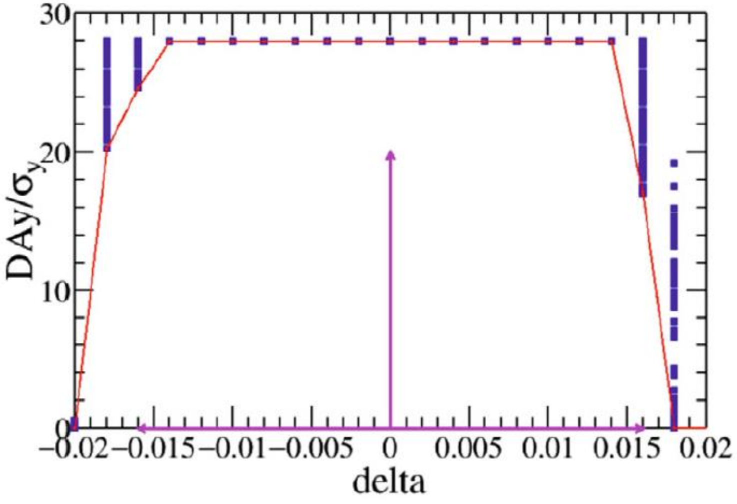


$\Delta\beta/\beta_{rms} < 3\%$

Dynamic aperture with error @ Higgs







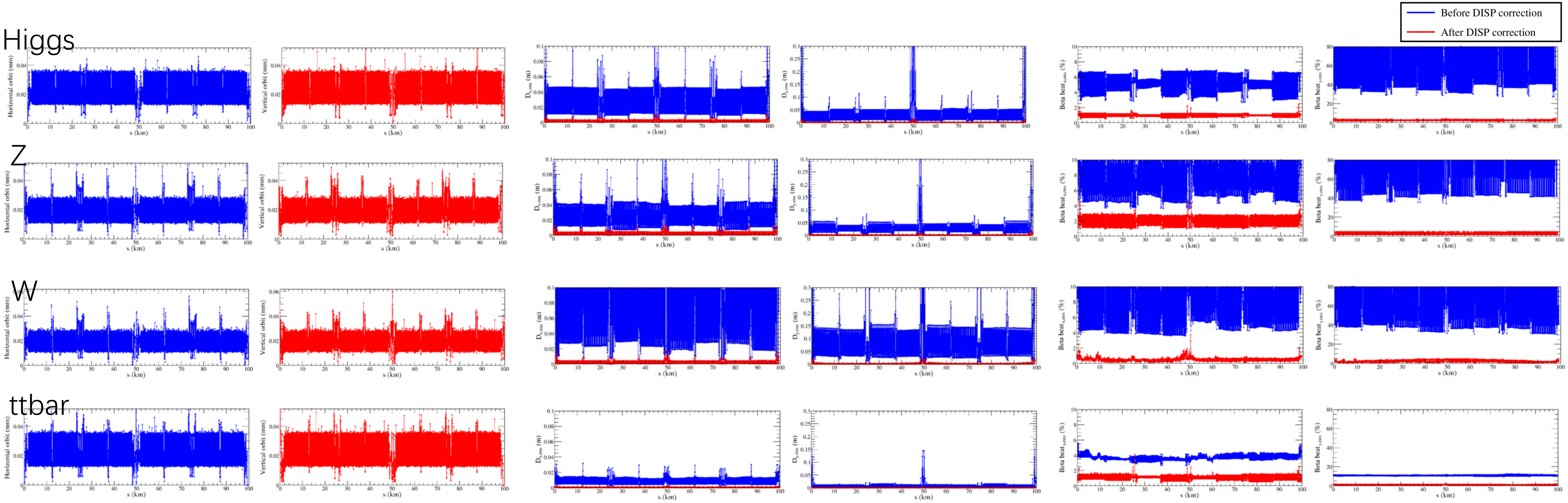
- The emittance after correction is evaluated to be $\epsilon_x = 0.666$ nm and $\epsilon_y = 0.209$ pm, the emittance ratio ($^{\epsilon_y}/_{\epsilon_x}$) is 0.03%, which satisfies the design requirement.
- The dynamic aperture in Higgs mode is tracked over 145 turns, about one damping time.
- The tracking dynamic aperture after error correction satisfies the requirements of on-axis injection, which is $8\sigma_x \times 20\sigma_y$ ×1.6%. .

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



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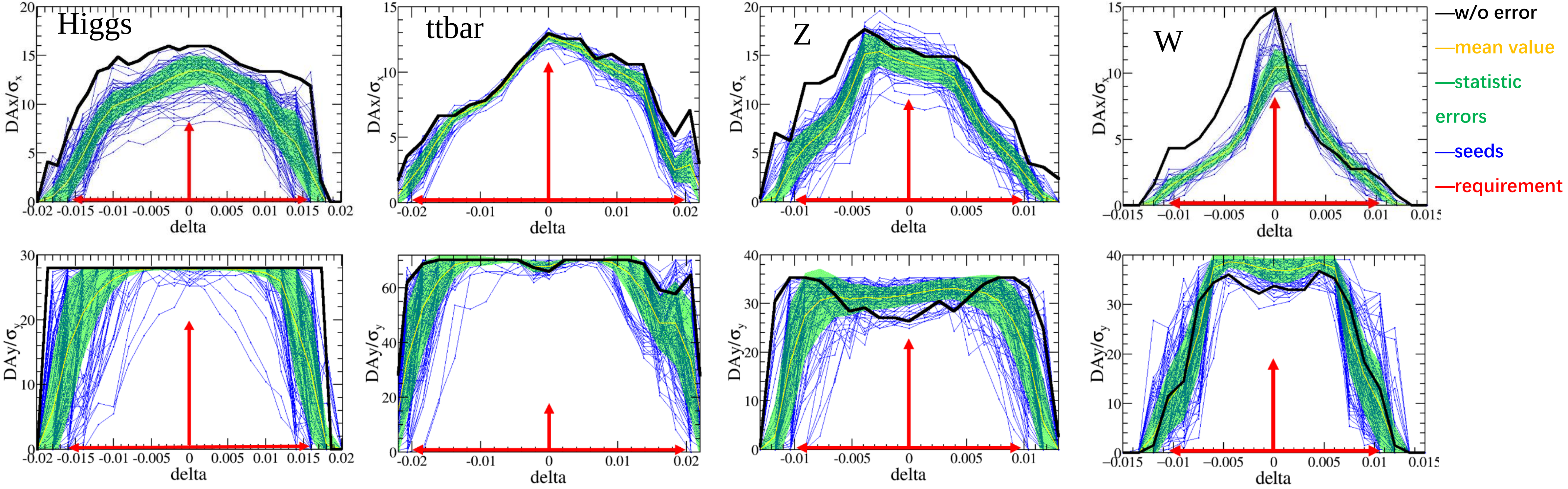
- The error correction to lattice with all four modes (Higgs, Z, W, and ttbar) are achieved in the CEPC TDR.

Correction performance



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- The error correction to lattice with all four modes (Higgs, Z, W, and ttbar) are achieved in the CEPC TDR.
- The dynamic apertures after correction are tracked and meet the injection requirement with a success rate of >90%.

Summary and To do list

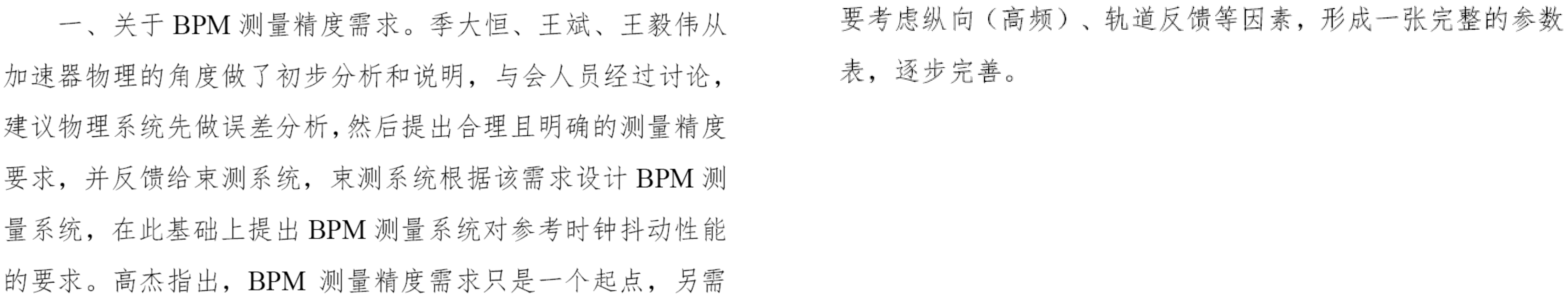
- The imperfection correction to lattices with 4 modes (Higgs, Z, W, and ttbar) are performed.
- The dynamic apertures after correction are tracked and meet the injection requirement with a success rate of >90%.
- All above correction results are included in the CEPC TDR.

Gao, J. CEPC Technical Design Report: Accelerator. *Radiat Detect Technol Methods* 8, 1–1105 (2024). https://doi.org/10.1007/s41605-024-00463-y

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

Thanks for your attention!