Orbit correction and error analysis

Bin Wang (on the behalf of the CEPC error correction team)
Institute of High Energy Physics

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THE 2022 INTERNATIONAL WORKSHOP ON THE HIGH ENERGY CIRCULAR ELECTRON-POSITRON COLLIDER (CEPC)

Content

- Introduction of the high luminosity
- The correction scheme
- The correction results
- Summary and to do list

Beam parameters

CEPC AP group, 2 June 2022; Y. Wang, The 2022 CEPC IARC meeting, June 7-10, 2022, IHEP

	Higgs	Z	W	ttbar
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
Piwinski angle	5.94	24.68	6.08	1.21
Bunch number	268	11934	1297	35
Bunch spacing [ns]	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population [10^10]	13	14	13.5	20
Beam current [mA]	16.7	803.5	84.1	3.3
Momentum compaction [10^-5]	0.71	1.43	1.43	0.71
Beta functions at IP (bx/by) [m/mm]	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance (ex/ey) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP (sigx/sigy) [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	1.3/1.7	1.2/2.5	2.3/2.6
Beam-beam parameters (ksix/ksiy)	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	650	650	650
Longitudinal tune Qs	0.049	0.035	0.062	0.078
Beam lifetime (bhabha/beamstrahlung)[min]	39/40	80/18000	60/700	81/23
Beam lifetime [min]	20	80	55	18
Hour glass Factor	0.9	0.97	0.9	0.89
Luminosity per IP[1e34/cm^2/s]	5.0	115	16	0.5

Lattice and requirements

Y. Wang, The 2022 CEPC IARC meeting, June 7-10, 2022, IHEP

	ttbar	Higgs	W	Z
Horizontal Emittance in collider/booster [nm]	1.4 / 2.83	0.64 / 1.26	0.87 / 0.56	0.27 / 0.19
DA requirement from injection	13.9 $\sigma_x \times 7\ \sigma_y$ off axis	14.4 $\sigma_x \times 7\ \sigma_y$ off axis 7 $\sigma_x \times 7\ \sigma_y$ on axis	10.5 $\sigma_x \times 5\ \sigma_y$ off axis	11.8 $\sigma_x \times 5\ \sigma_y$ off axis
Beam lifetime (mainly bhabha and beamstrahlung) [min]	18	20	55	80
Energy acceptance requirement from beam lifetime [%]	2.3	1.6	1.2	1.3

DA requirement	ttbar	Higgs	W	Z
with on-axis injection	-	$7\sigma_x \times 15\sigma_y$ ×1.6%	-	-
with off-axis injection	$13.9\sigma_x \times 20\sigma_y$ ×2.3%	$14.4\sigma_x \times 15\sigma_y$ ×1.6%	$10.5\sigma_x \times 9\sigma_y$ ×1.2%	$11.8\sigma_x \times 9\sigma_y$ ×1.3%

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Errors definition and challenges

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	

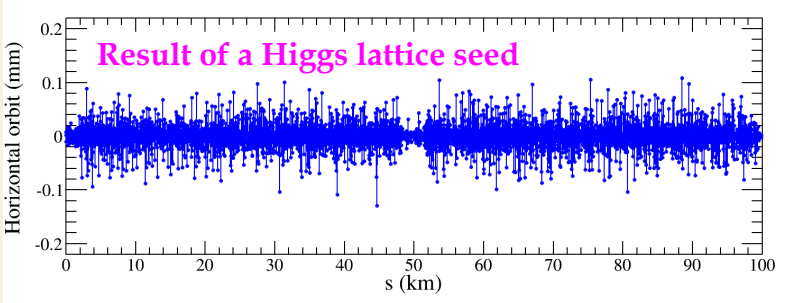
- We include the field error of IR quadrupoles according the IARC 2022 comments.
- 1000 Higgs lattice seeds are generated for optimizing correction programme, 500 Z lattice seeds are generated for a cross check.
- The correction programme are extended to the error correction of 100 W lattice seeds and 100 ttbar lattice seeds.

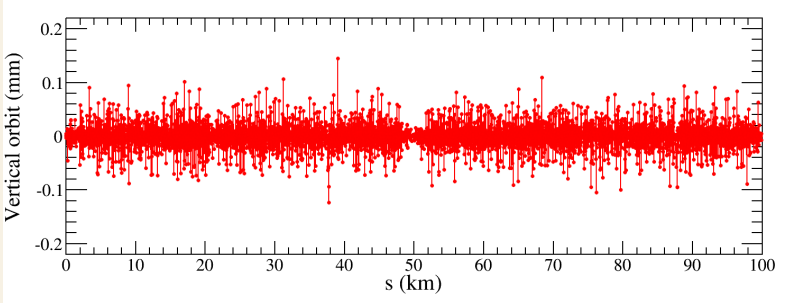
The correction scheme

- Software: SAD and AT
- COD correction with **sextupoles off**
- **Turn on the sextupoles** and perform COD correction again.
- Dispersion correction (DFS)
- Beta beating correction (LOCO)
- Coupling and vertical dispersion correction (Local coupling parameter correction）

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





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

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

Dispersion correction

Dispersion free steering principle (DFS): θ_c

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

$\vec{u}$: Orbit vector

$\vec{D}_u$: Dispersion vector

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

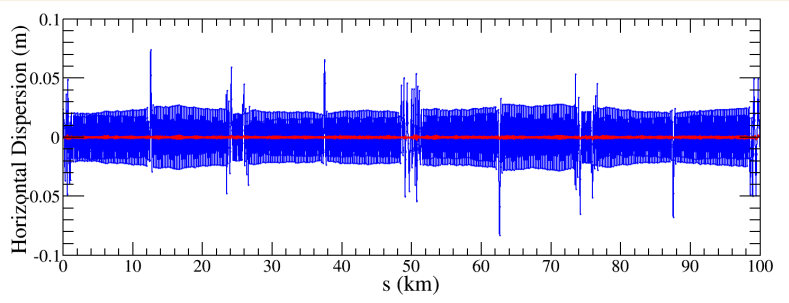
α: Weight factor

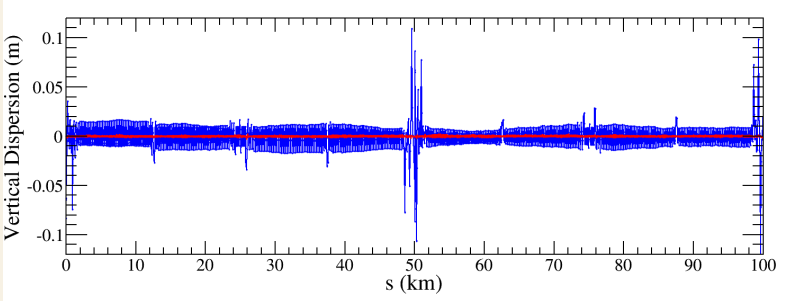
A: Orbit response matrix

B: Dispersion response matrix

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

Result of a Higgs lattice seed





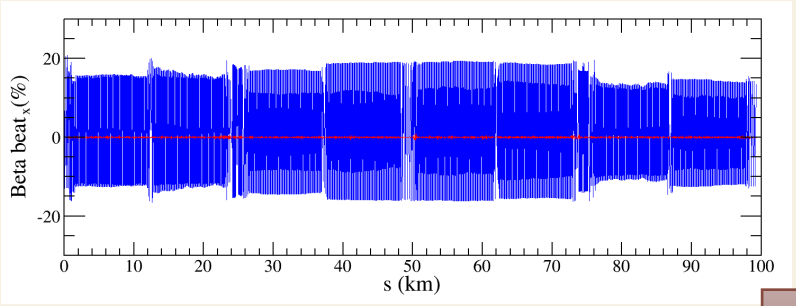
Before DISP correction

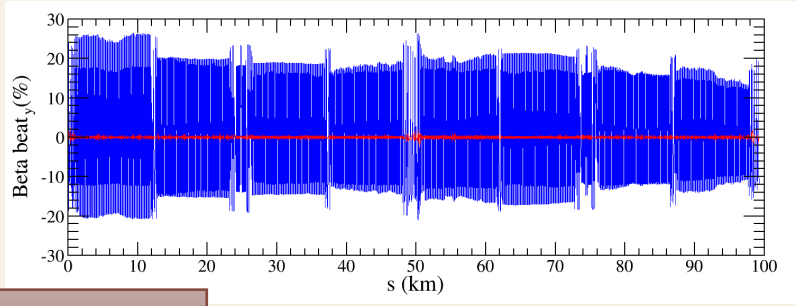
After DISP correction

Beta-beating correction

- Correct the beta functions with sextupoles on.
- Based on AT LOCO: model based correction
  - Establish lattice model M_{mod}, multi-parameter fit to the orbit response matrix 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.

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





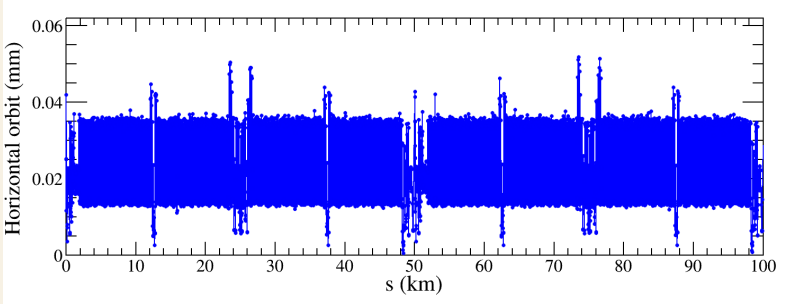
$\Delta\beta/\beta_{rms} < 3\%$

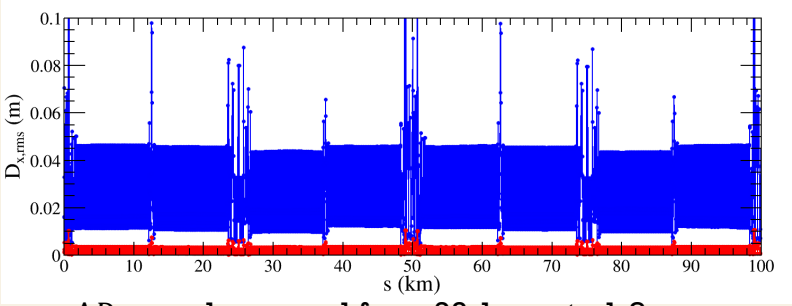
Especially many thanks to committee and computing center group for supplying a significant amount of computing resources.

The correction results

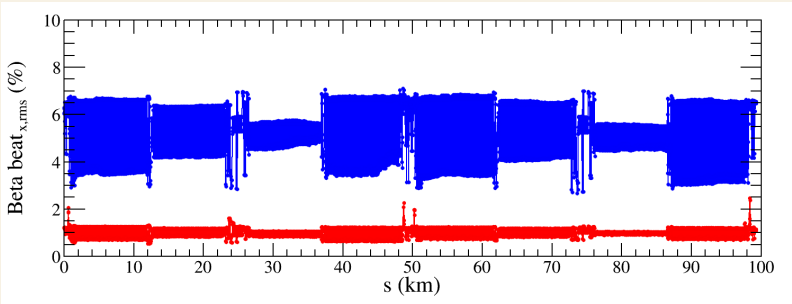
- Introduction of the high luminosity
- The correction scheme
- The correction results -- Higgs lattice
- Summary and to do list

Results -- Higgs lattice

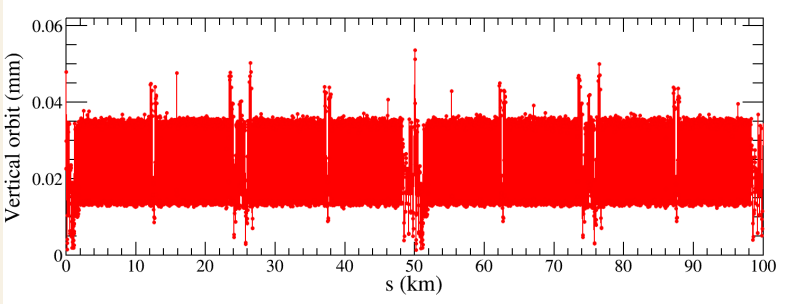


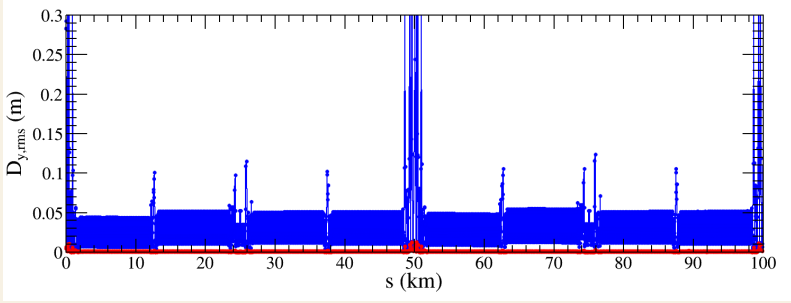


$\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm

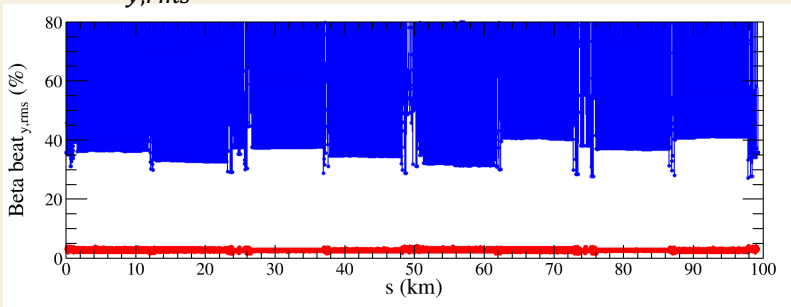


$\Delta\beta/\beta_{x,rms}$ decreased from 5.2% to 1.0%



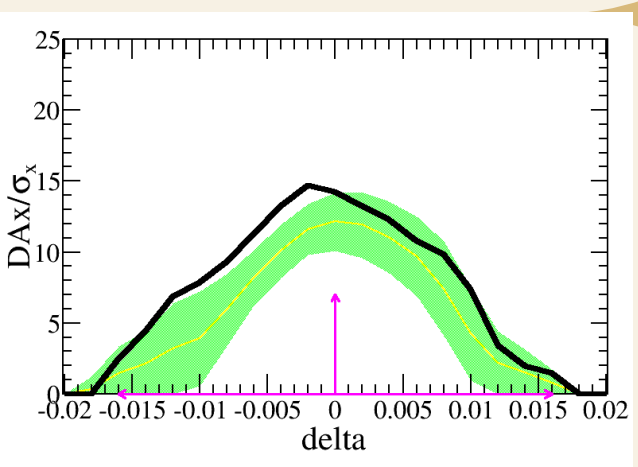


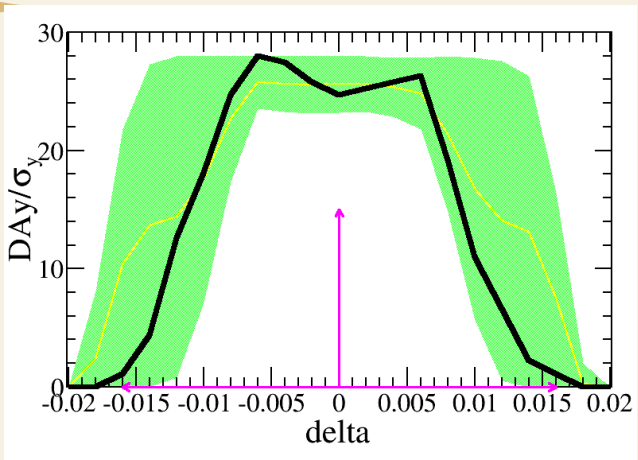
$\Delta D_{y,rms}$ decreased from 31.9 mm to 0.9 mm



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

Results -- Higgs lattice





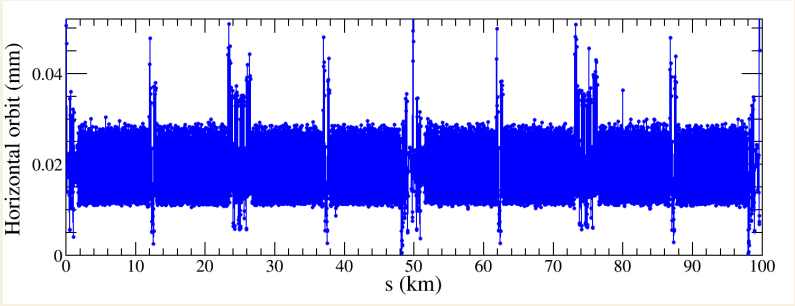
The yellow lines and green bands are the mean value and its corresponding statistics errors, the black line is the DA of bare lattice. The pink arrows are the DA requirement.

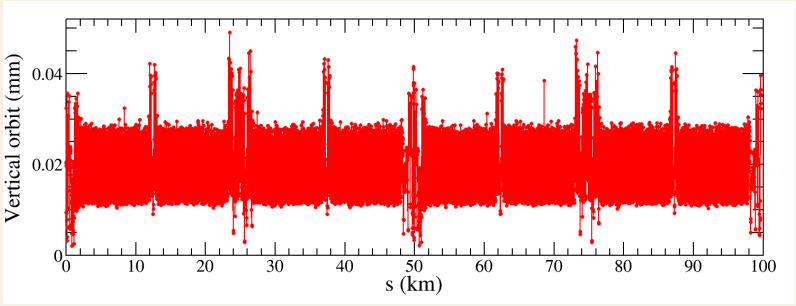
- 1000 Higgs lattice seeds with errors are fully corrected.
- The DA with error correction are tracked and satisfy the on-axis injection requirement, $7\sigma_x \times 15\sigma_y$ & 0.016.

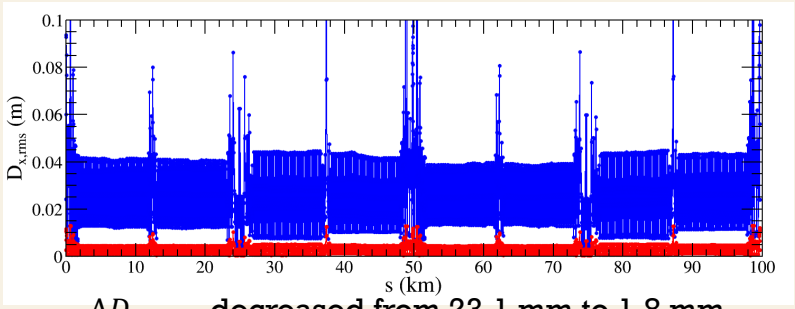
The correction results

- Introduction of the high luminosity
- The correction scheme
- The correction results -- Z lattice
- Summary and to do list

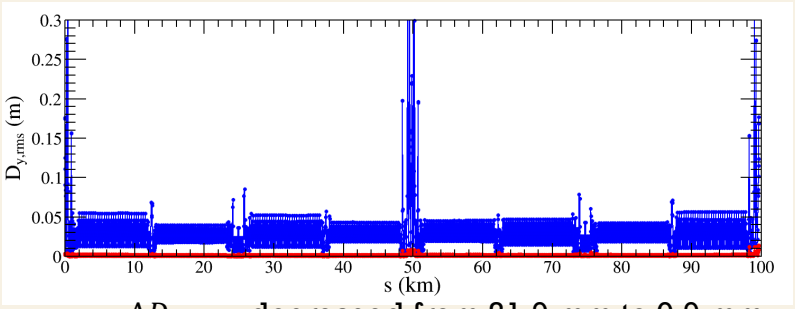
Results -- Z lattice



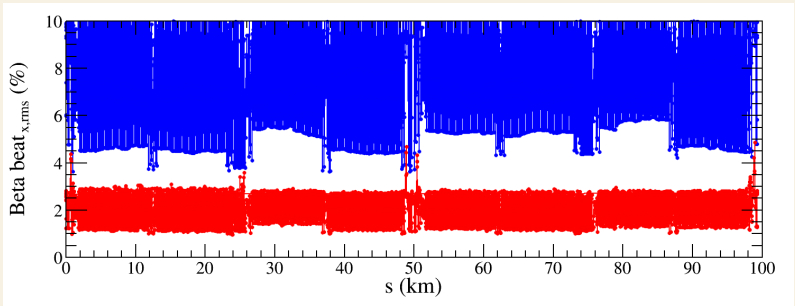




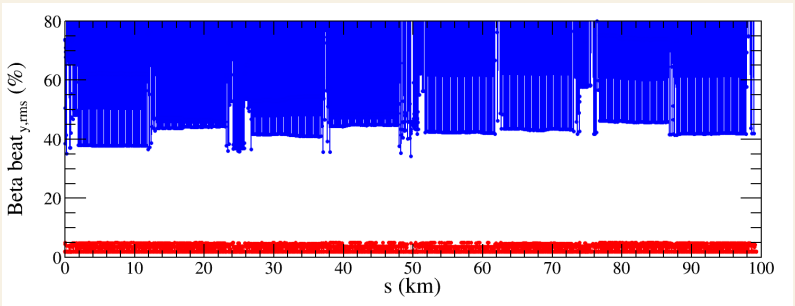
$\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm



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

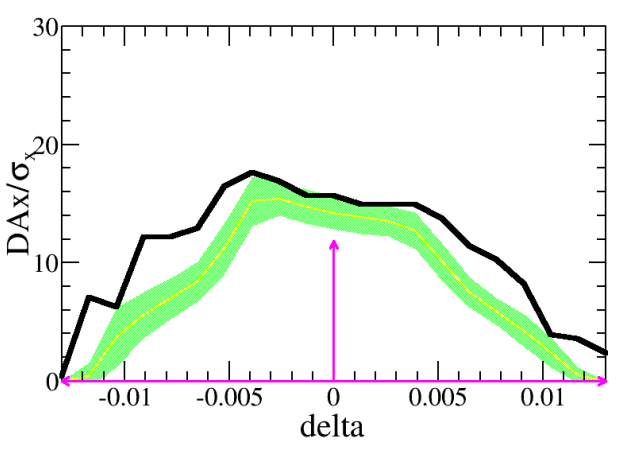


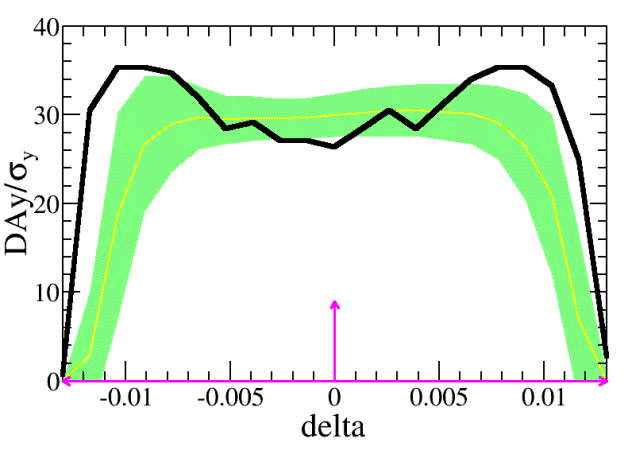
$\Delta\beta/\beta_{x,rms}$ decreased from 7.5% to 2.0%



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

Results -- Z lattice





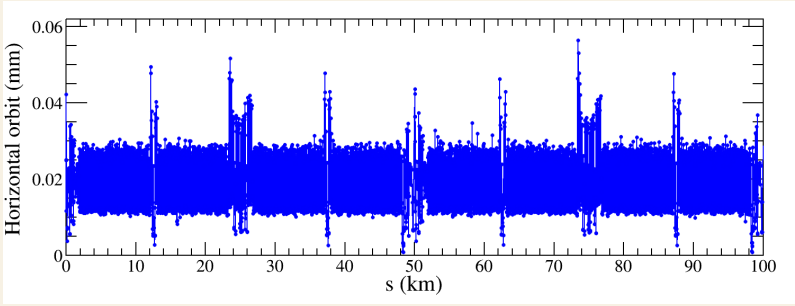
The yellow lines and green bands are the mean value and its corresponding statistics errors, the black line is the DA of bare lattice. The pink arrows are the DA requirement.

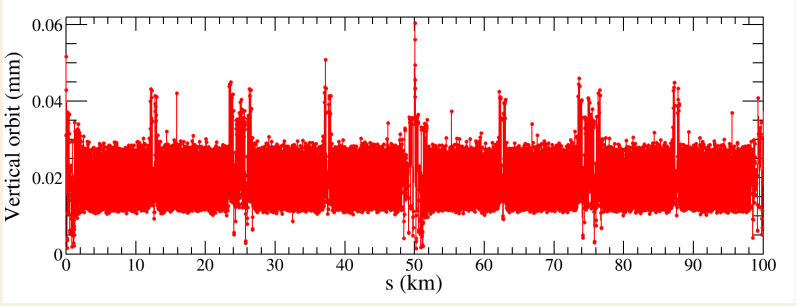
- 500 Z lattice seeds with errors are fully corrected.
- The DA with error correction are tracked and satisfy the on-axis injection requirement, $11.8\sigma_x \times 9\sigma_y$ & 0.013.

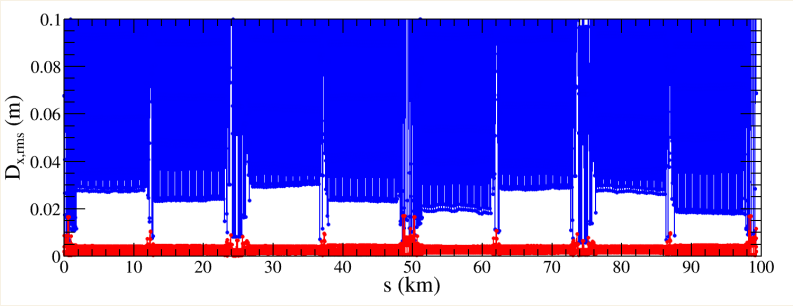
The correction results

- Introduction of the high luminosity
- The correction scheme
- The correction results -- W/ttbar lattice
- Summary and to do list

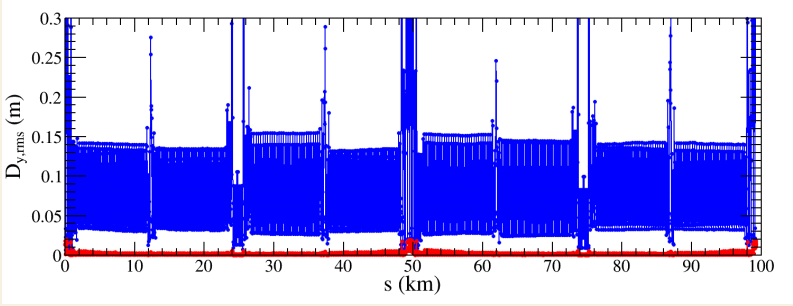
Results -- W lattice



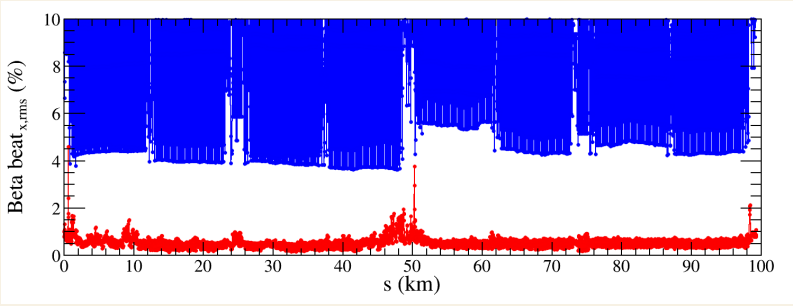




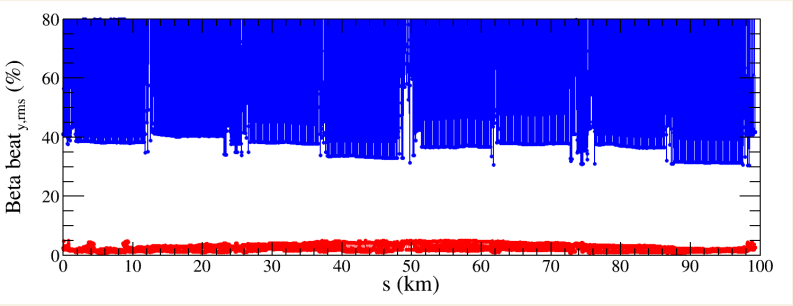
$\Delta D_{x,rms}$ decreased from 85.0 mm to 2.7 mm



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

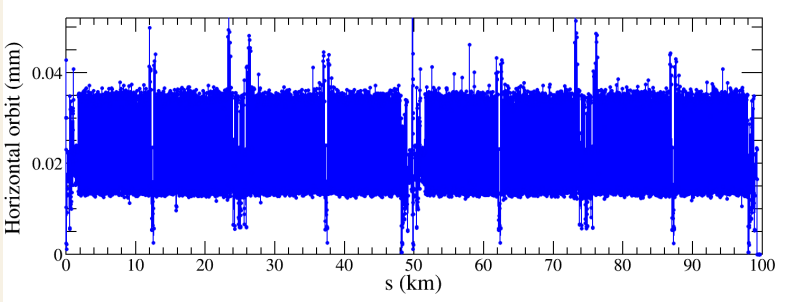


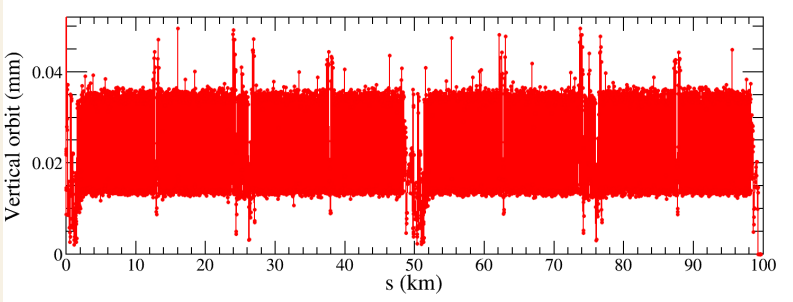
$\Delta\beta/\beta_{x,rms}$ decreased from 8.1% to 0.5%

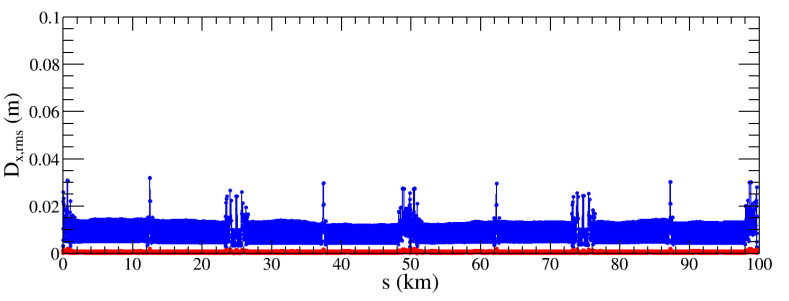


$\Delta\beta/\beta_{y,rms}$ decreased from 106.8% to 2.5%

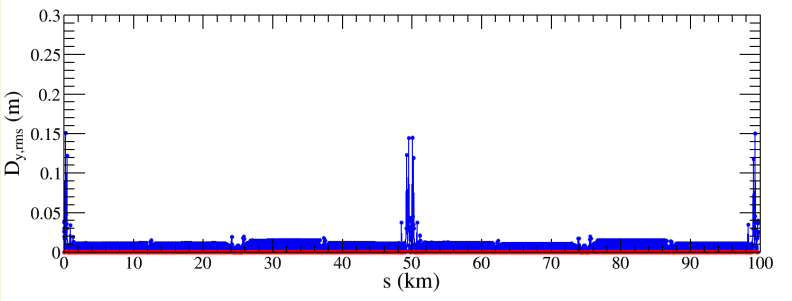
Results -- ttbar lattice



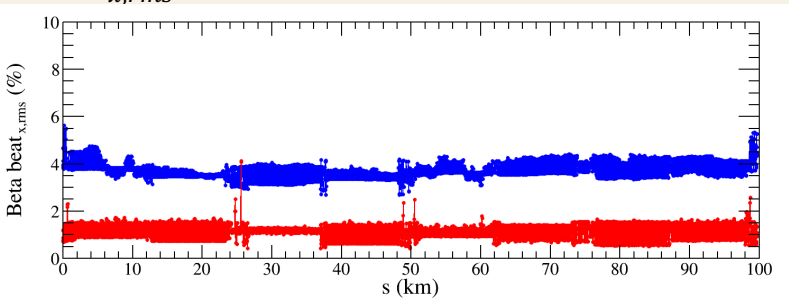




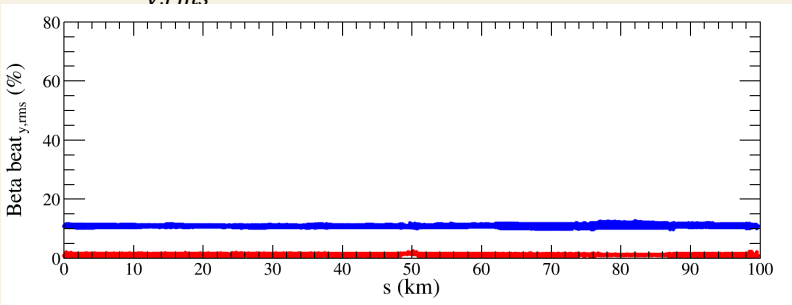
$\Delta D_{x,rms}$ decreased from 8.8 mm to 0.6 mm



$\Delta D_{y,rms}$ 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%

Summary and to do list

- The imperfection correction to lattices with 4 modes (Higgs, Z, W, and ttbar) are performed.
- 1000 Higgs lattice seeds, 500 Z lattice seeds, 100 W lattice seeds and 100 ttbar lattice seeds with errors are corrected, where the closed orbit, dispersion and beta beating are corrected well.
- The DA of Higgs lattice and Z lattice after error correction are tracked and satisfy the on-axis injection requirement.

- The DA of W lattice and ttbar lattice after error correction are coming soon.
- Include more types of imperfections.

E-mail:
wangbin@ihep.ac.cn