Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

CEPC Collider ring lattice

Yiwei Wang, Bin Wang, Yuanyuan Wei
for the CEPC Accelerator Physics Group
The Institute of High Energy Physics, Chinese Academy of Sciences

eeFACT2022, 13 September 2022
INFN Frascati National Laboratories

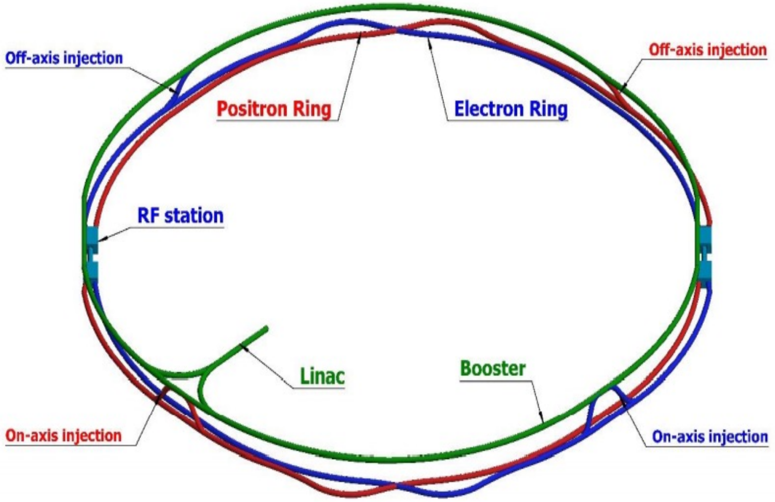
Machine parameters of CEPC

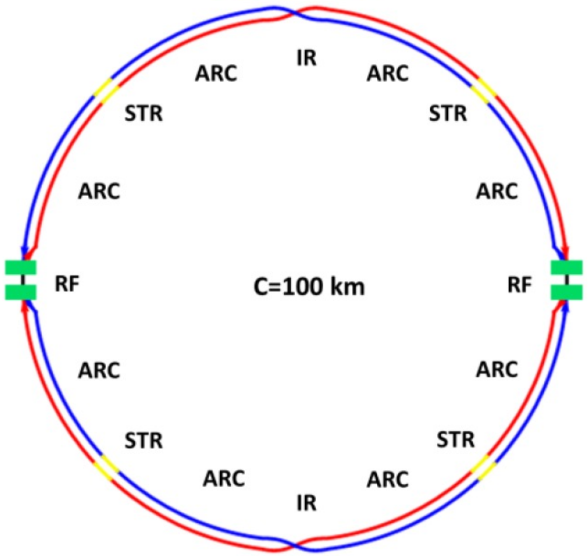
by CEPC AP group, 2 June 2022

	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

Optics design of the CEPC collider ring

- SR power 30MW (50 MW upgradable), 100km, 2 IPs
- Compatible of $t\bar{t}$/H/W/Z modes
- Compatible with SPPC
- Correction of sawtooth orbit
- 2 folded symmetry
- 8 arc sections
  - dual aperture dipole and quadrupole magnets
  - non-interleaved sextupoles
- 4 short straight section
  - injection regions for different modes
- 2 interaction regions
  - crab waist collision
  - local chromaticity correction for the interaction region
  - asymmetric interaction region
- 2 RF acceleration regions
  - shared cavities for two beam @ ttbar, Higgs
  - flexible switching between compatible modes

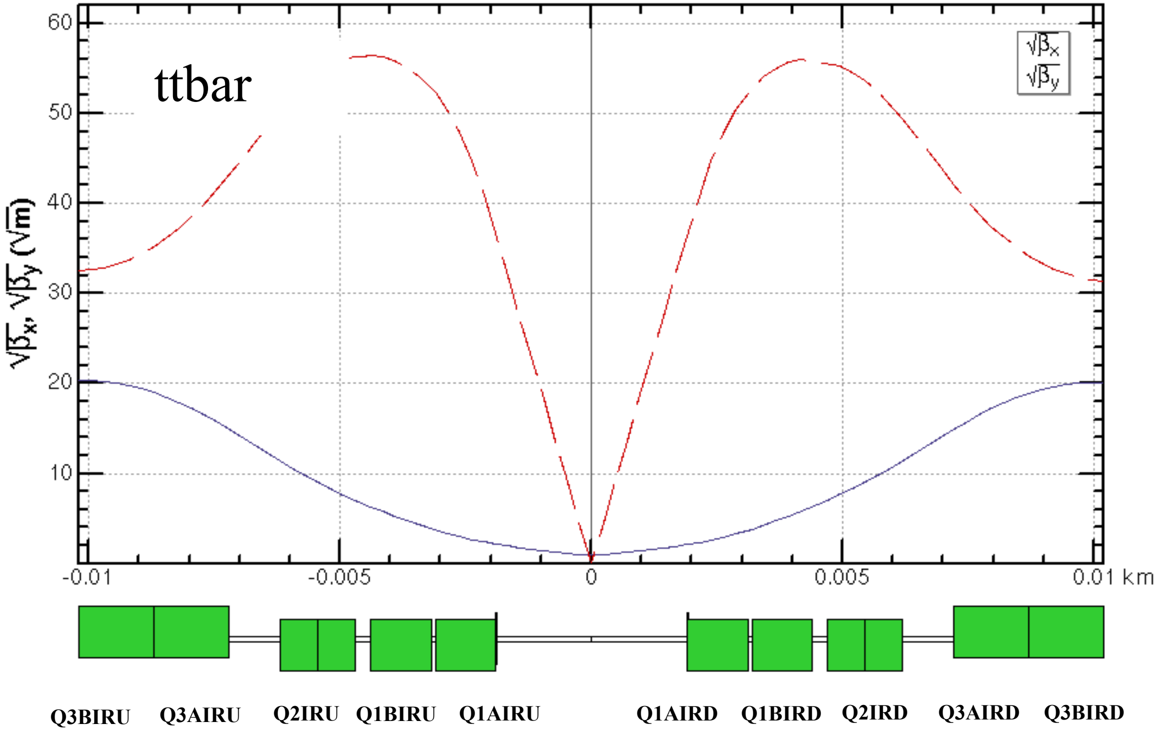




*ref: CEPC-CDR; CEPC pre-CDR; K. Oide, arXiv:1610.07170; M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010); M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010); A. Milanese, PRAB 19, 112401 (2016);

Interaction region for all modes

- Crab waist collision, local chromaticity correction, asymmetric interaction region



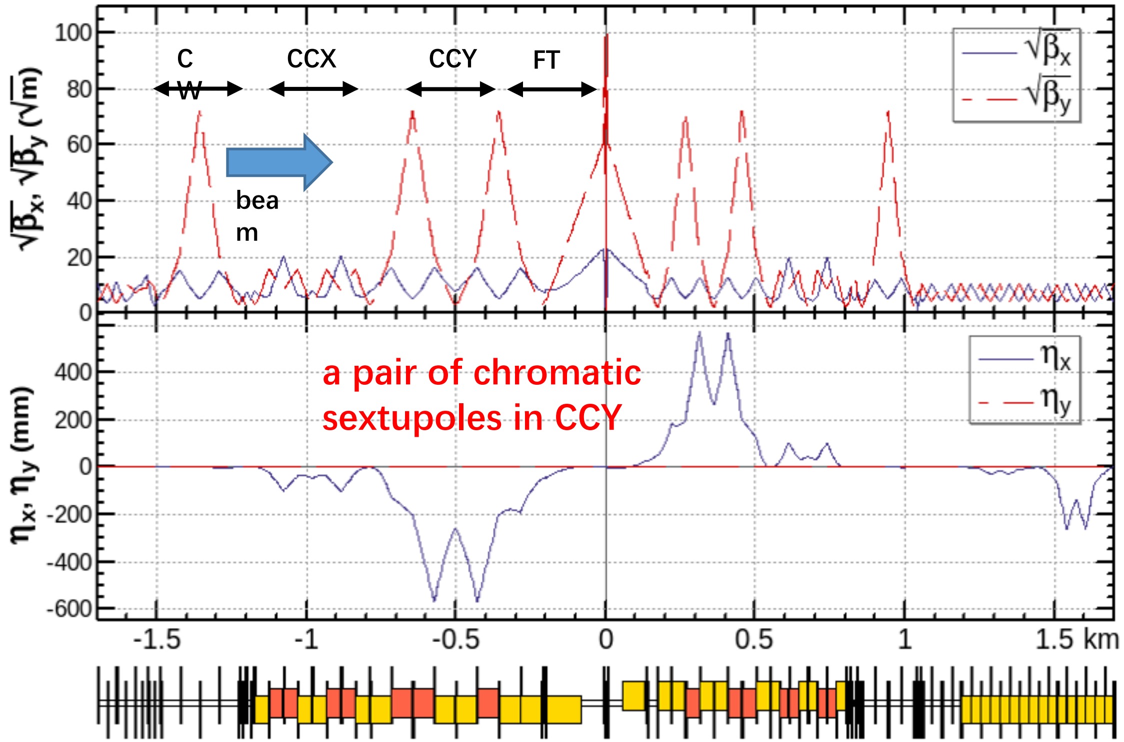
	QD	QF
Z	Q1A	Q1B
W/H	Q1A+Q1B	Q2
ttbar	Q1A+Q1B+Q2	add quad Q3A and Q3B

	L [m]	Strength [T/m]			
		ttbar	Higgs	W	Z
Q1AIRU	1.21	-141	-141	-94	-110
Q1BIRU	1.21	-59	-85	-56	+65
Q2IRU	1.5	-51	+95	+63	0
Q3AIRU	1.5	+40	0	0	+2
Q3BIRU	1.5	+40	0	0	+2
Q1AIRD	1.21	-142	-142	-95	-110
Q1BIRD	1.21	-64	-85	-57	+65
Q2IRD	1.5	-47	+96	+64	0
Q3AIRD	1.5	+40	0	0	+2
Q3BIRD	1.5	+40	0	0	+2

Strength of other modes doesn’t exceeded the one of Higgs mode.

Interaction region for all modes (cont.)

- Crab waist collision, local chromaticity correction, asymmetric interaction region



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	QD	QF
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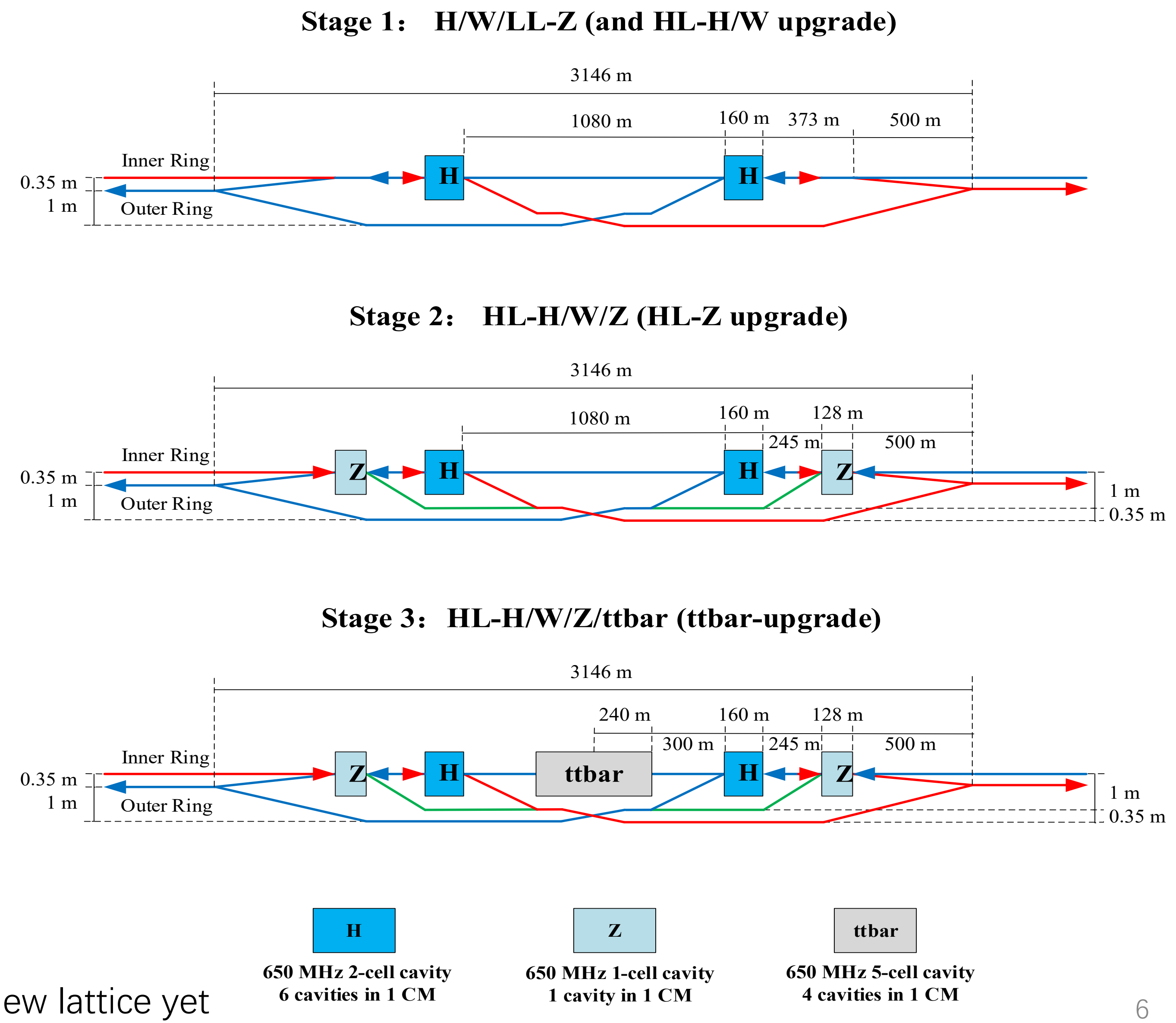
*ref: Y. Cai, IAS2016, HKUST; K. Oide, arXiv:1610.07170;
P. Raimondi, Proc. of the 2nd SuperB Workshop, Frascati, March 2006；
M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010);

New RF Scheme*

*more details in Jiyuan ZHAI, Cavity and cryomodules developments for CEPC 10:20 - 10:40, 14 Sep 2022, eeFACT22

- All-mode seamless switching in whole lifecycle (CEPC, ep …)
- 1st priority of the Higgs running
- Highest luminosity in each energy
- Maximize the performance and flexibility of future circular electron positron collider

Operation Mode	Collider Ring 650 MHz Cavities / Cryomodules
Higgs	240 2-cell / 40 CMs
HL-Z	100 1-cell / 100 CMs
W	240 2-cell / 40 CMs
ttbar	+240 5-cell / +60 CMs



*quire recent scheme, not implemented in the new lattice yet

ARC region for all modes

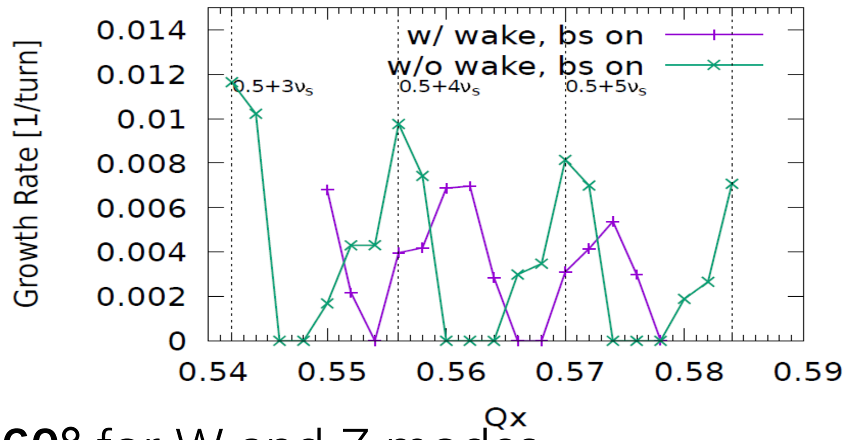
- Z and W modes need larger momentum compaction factor αp and thus larger emittance εx, Qs
  - To suppress the impedance induced instability at Z mode
  - To increase stable tune area if considering beam-beam effect and impedance consistently at W and Z modes

Microwave instability

$$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e}\sigma_{e0}^2\sigma_l}{R\left|\frac{Z_{\parallel}}{n}\right|_{eff}}$$

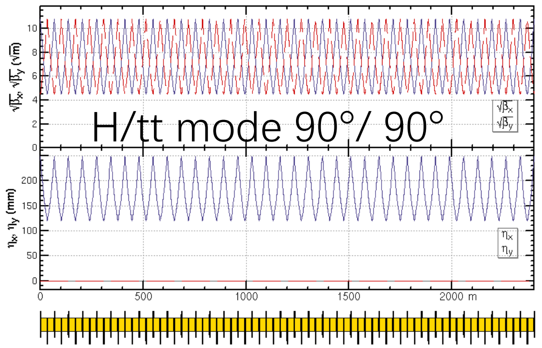
Na Wang,
CEPC Day, March 2020

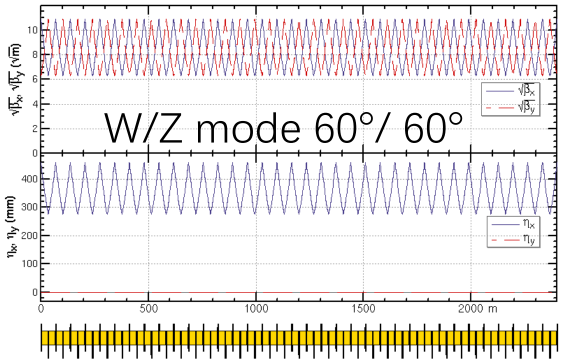
stable tune area with both beam-beam and impedance (Z mode 90/90)



Yuan Zhang

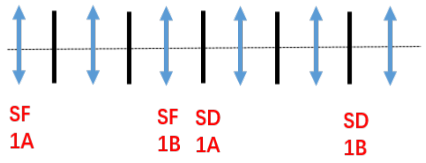
- **Phase advance reduced from 90° to 60°** for W and Z modes



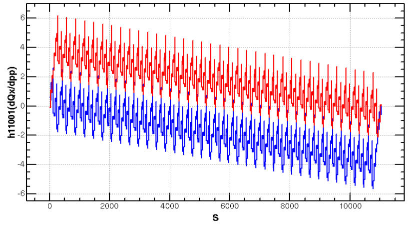


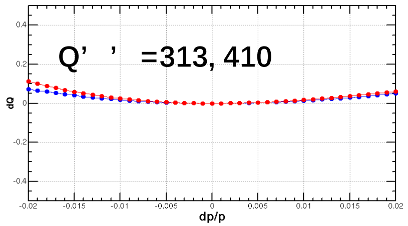
ARC region for compatible modes

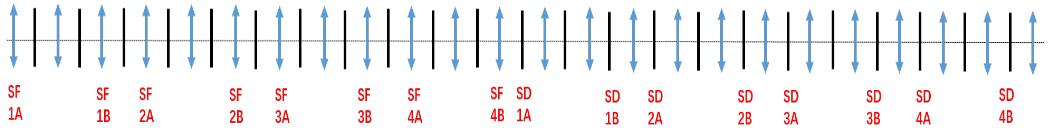
- 2^{nd} order chromaticity is a main aberration for the optimization of momentum acceptance with 2-repeated sextupole scheme.
  - In previous versions, 2^{nd} order chromaticity generated in the ARC region are corrected with IR knobs (phase advance or K1).
  - However, the IR knobs will generate distortions at IP (beta, alfa and dispersion) especially for the horizontal plane.
- A lattice with **four –I sextupole pairs scheme** for Higgs & ttbar modes
  - much less 2^{nd} order chromaticity for the horizontal plane
  - The distribution of sextupoles for Higgs & ttbar modes (90 deg cell) allowed to select –I sextupole pairs for W &Z modes (60 deg cell) .



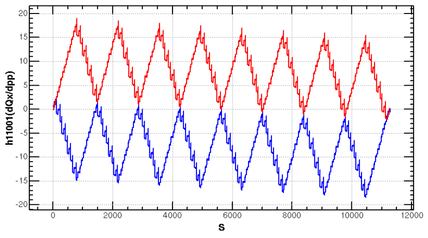
Scheme with **one –I sextupole pair**
Proposed by K. Oide

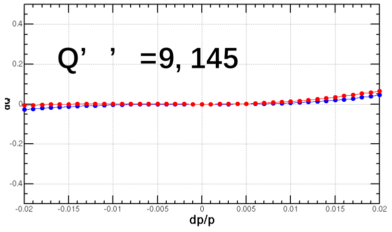






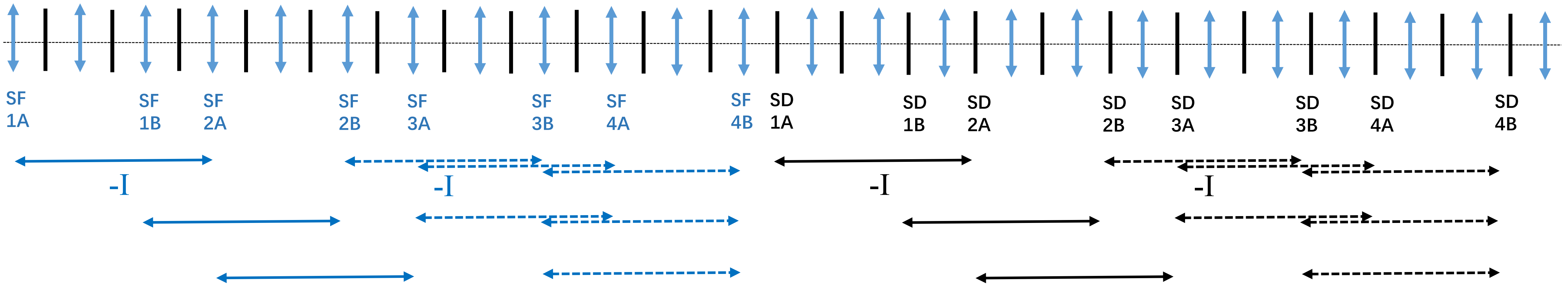
Scheme with **four –I sextupole pairs**
Proposed by Tianjian Bian





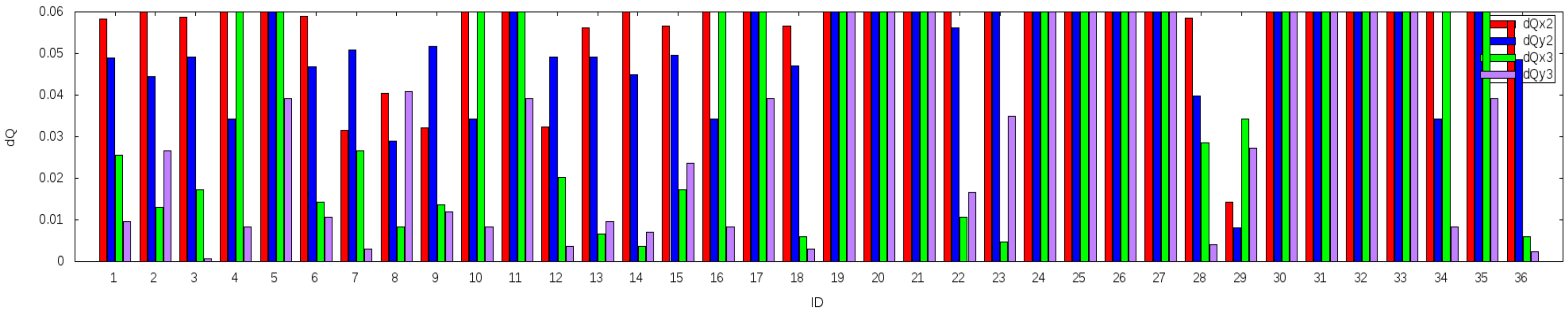
Optimization of the ARC aberration at W and Z modes

- The distribution of sextupoles for Higgs & ttbar mode allowed to select –I sextupole pairs for W &Z mode.
  - 6*6=36 cases for 23 cells
  - There are much more combinations if choose different cases in each arc section (184 cells)



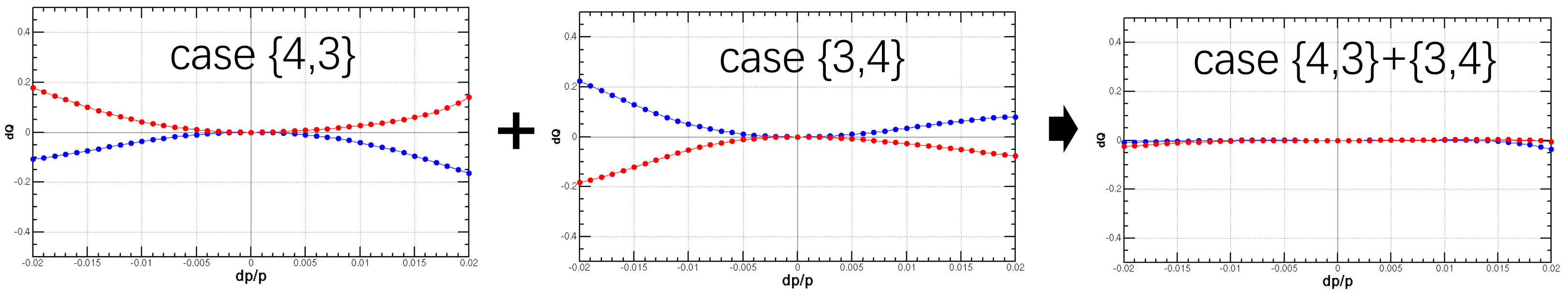
1st pair	2nd pair		
(1A, 2A)	(2B,3B)	(3A,4A)	(3B,4B)
(1B, 2B)	-	(3A,4A)	(3B,4B)
(2A, 3A)	-	-	(3B,4B)

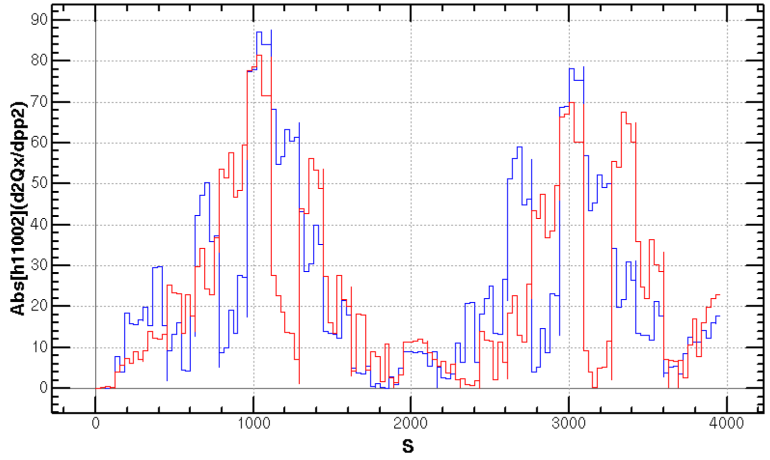
2nd and 3rd order dQ@dp/p=1% in x, y

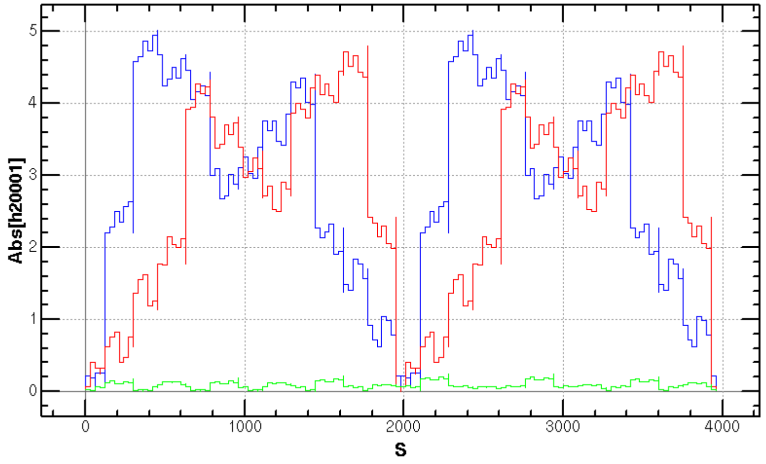


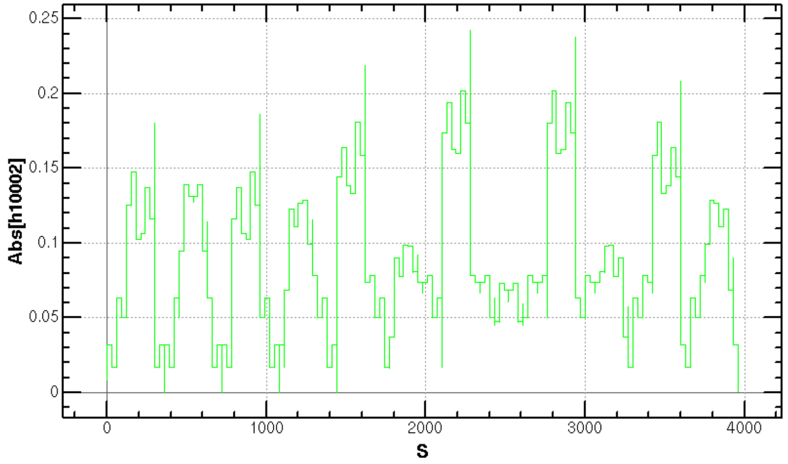
Optimization of the ARC aberration at W and Z modes (cont.)

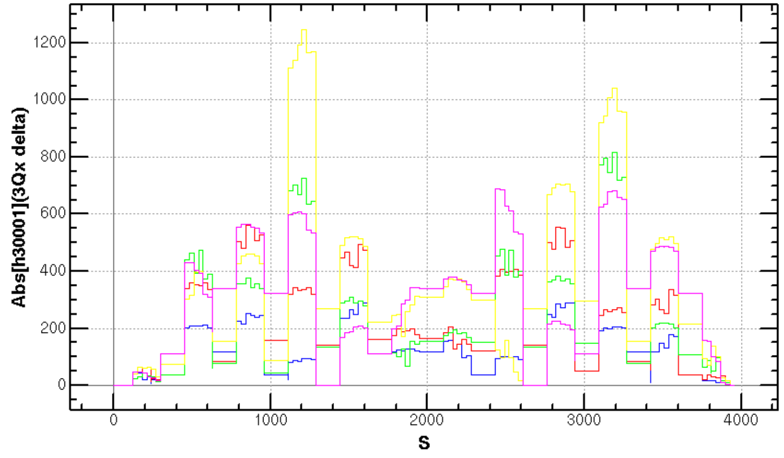
- Cancellation of main aberration has period of 23*3 cells.



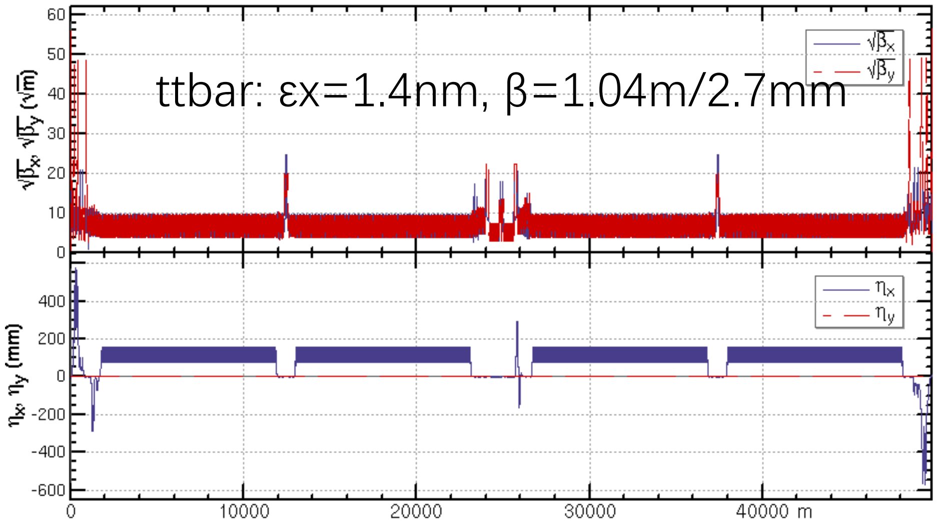


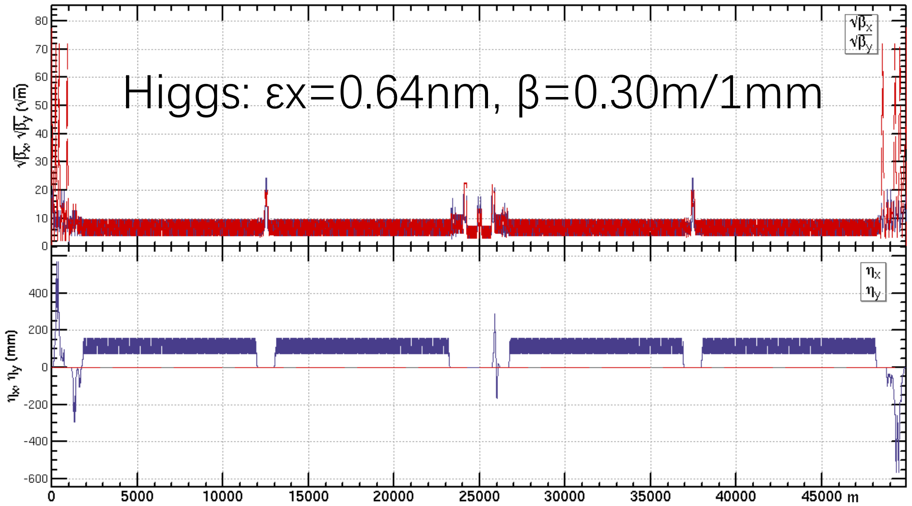


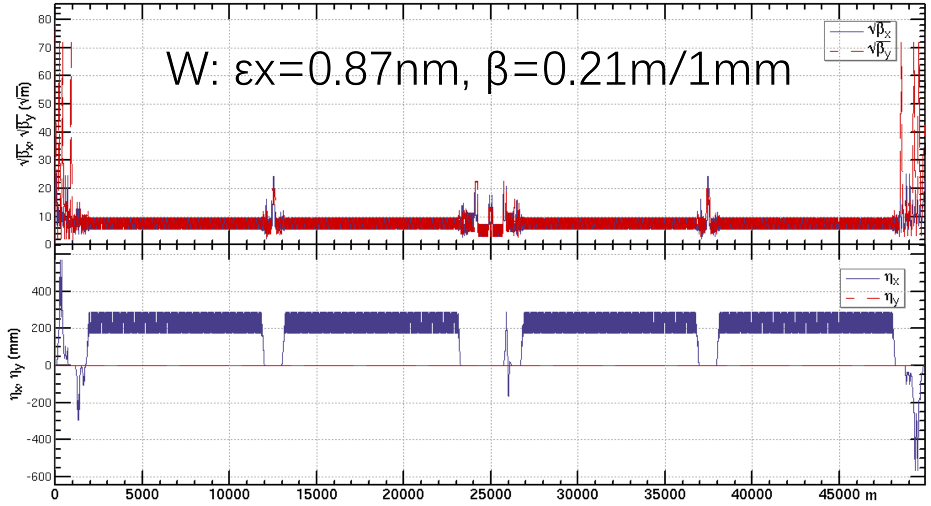


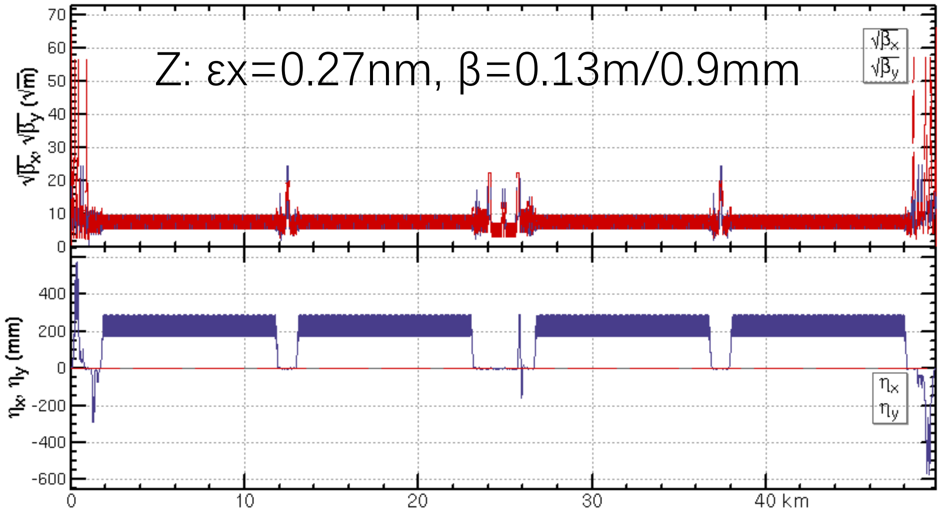


Lattice of half ring









Dynamic aperture requirement

X. H. Cui, Y. Zhang, Y. W. Wang

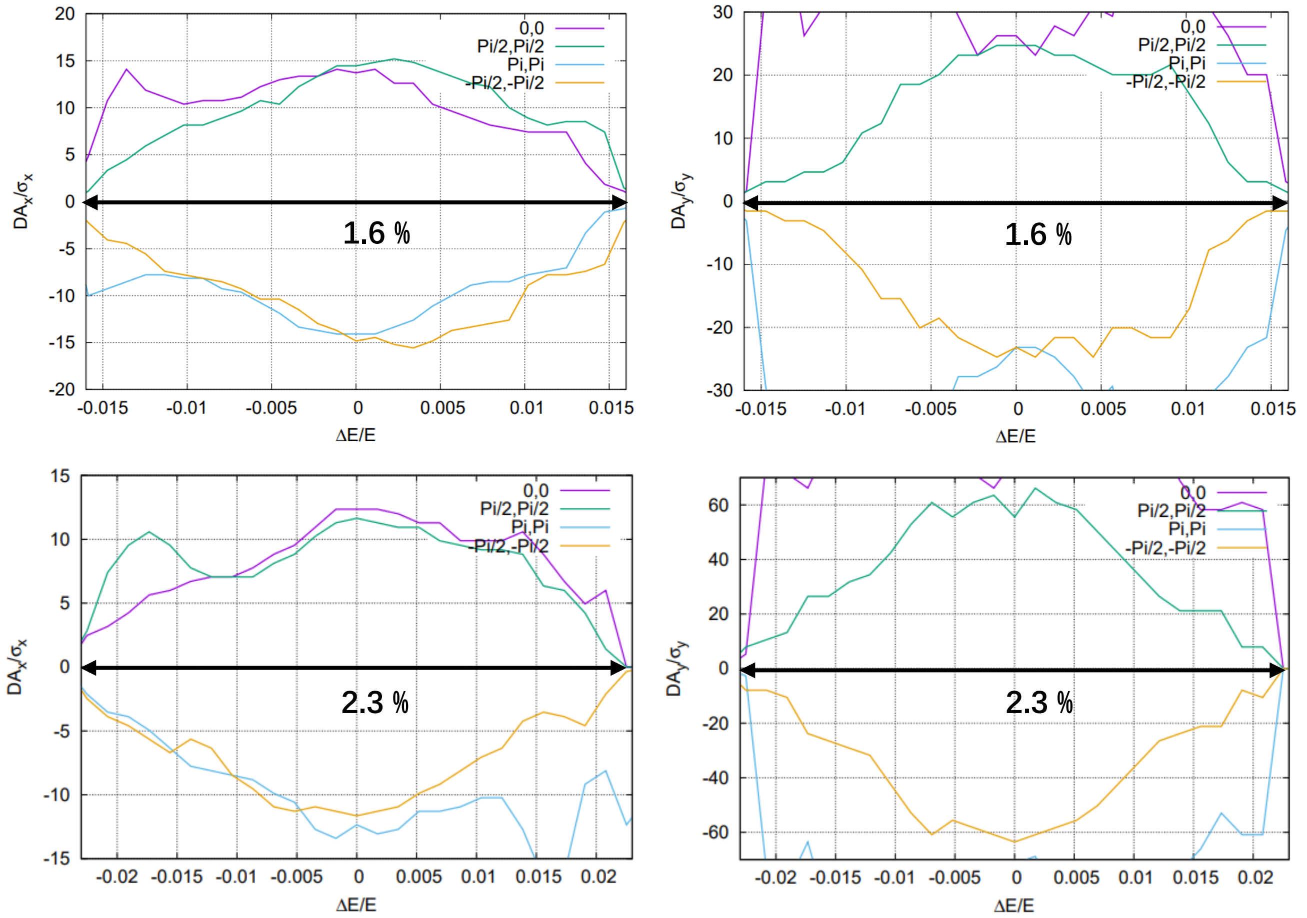
	ttbar	Higgs	W	Z
Horizontal Emittance in collider/booster [nm]	1.4 / 2.83	0.64 / 1.26	0.87 / 0.56	0.27 / 0.19
DA requirement from injection	13.9 $\sigma_x \times 7\ \sigma_y$ off axis	14.4 $\sigma_x \times 7\ \sigma_y$ off axis 7 $\sigma_x \times 7\ \sigma_y$ on axis	10.5 $\sigma_x \times 5\ \sigma_y$ 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

* need beam-beam simulation to check for y

Dynamic aperture @ Higgs and ttbar

- Tracking to get DA **without errors**, with turns for one transvers damping time, with 4 initial phases
- DA optimized with 84 variables (64 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advance)

Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole



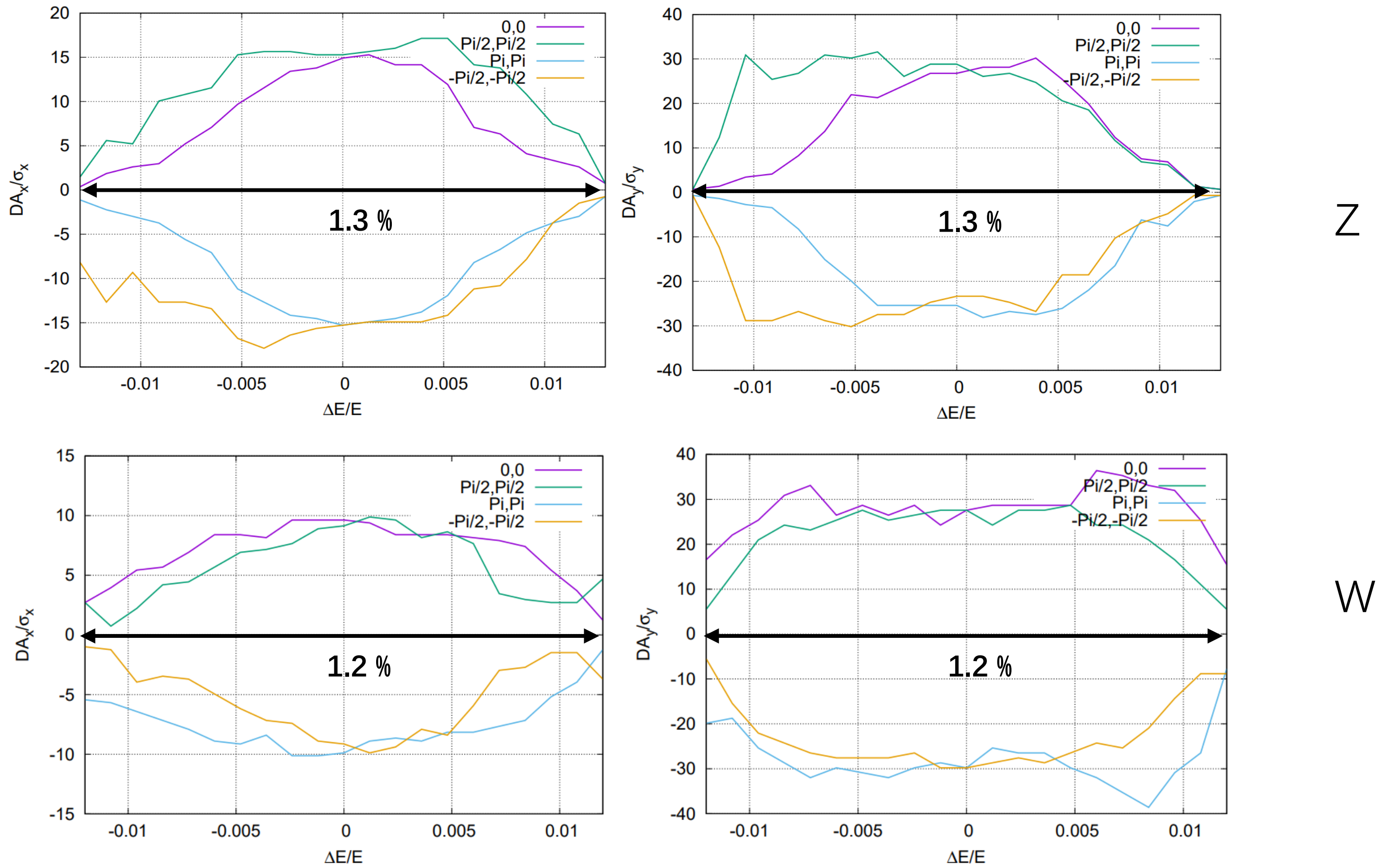
Higgs

ttbar

Dynamic aperture @ Z and W

- Tracking to get DA **without errors**, with turns for one transvers damping time, with 4 initial phases
- DA optimized with 116 variables (96 arc sextupole families + 8 IR sextupoles + 4 multipoles + 8 phase advance)

Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole



Correction scheme for magnets errors

by Bin WANG, Yuanyuan WEI, Yiwei WANG

- Correction procedures
  - The closed orbit distortion (COD) correction with sextupoles off
  - Turn on the sextupoles and perform COD correction again.
  - Dispersion correction
  - Beta beating correction
  - Coupling and vertical dispersion correction (Local coupling parameter correction)
- Uniform settings (corrector settings, BPM selection, iteration times, steps and so on) of the batched correction are optimized for all the lattice seeds.
- Individual further correction (additional iteration and adjustment of the corrector settings according to correction result) are performed for those un-converged seeds.

Correction of the closed orbit distortion

- Correction of the closed orbit distortion (COD) with sextupoles off is made firstly.
- Turn on the sextupoles and perform COD correction again.
- Mover used to get fine alignment of sextupole
- Orbit correction is applied using orbit **response matrix and SVD method.**

Dispersion correction

- **With dispersion free steering (DFS):** orbit manipulation by knob correctors.

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

$$\vec{d} + M\vec{\theta} = 0$$

$\vec{u}$ orbit vector
$\vec{D}_u$ dispersion vector
$\vec{\theta}$ Corrector strengths vector
α Weight factor
A Orbit response matrix
B Dispersion response matrix

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:

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

  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
  - Application to correct beta-beating, dispersion and coupled response matrix.

Coupling correction

- Neglecting beam-beam effects

$$\varepsilon_y \simeq \varepsilon_{y0} + \kappa\varepsilon_x + rE^2(D_y^{\mathrm{rms}})^2$$

- Both coupling and vertical dispersion are controlled.
- Using the trim coils of the sextupoles, 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

$\bar{c}_{b,22}, \bar{c}_{b,12}, \bar{c}_{c,11}, \bar{c}_{c,12}$: local coupling parameters

$$\bar{c}_{b,12} = M_c\overrightarrow{ks}$$

M_c: $\bar{c}_{b,12}$ response matrix

$\overrightarrow{ks}$: skew-quadrupole vector

Correction for the compatible lattices

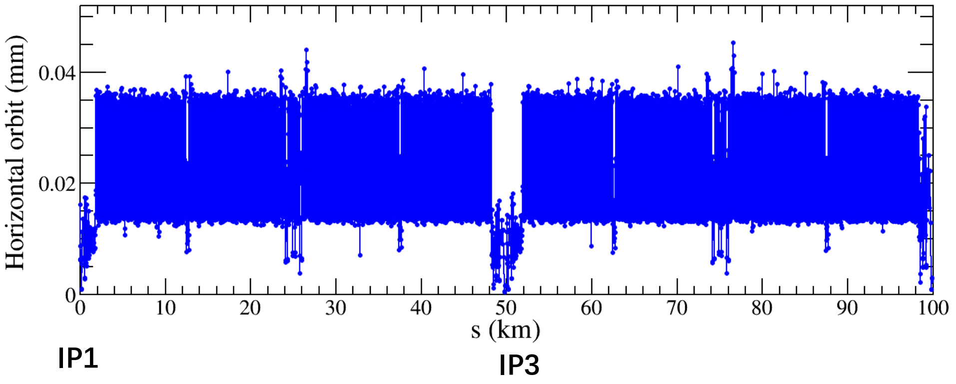
- With assumption of 100 um transverse misalignments
- The Higgs and ttbar lattices are similar, the Z and W lattices are similar.
  - The error corrections have been performed for the Higgs and Z lattices.
  - 1000 seeds used for the Higgs, 500 lattice seeds used for the Z

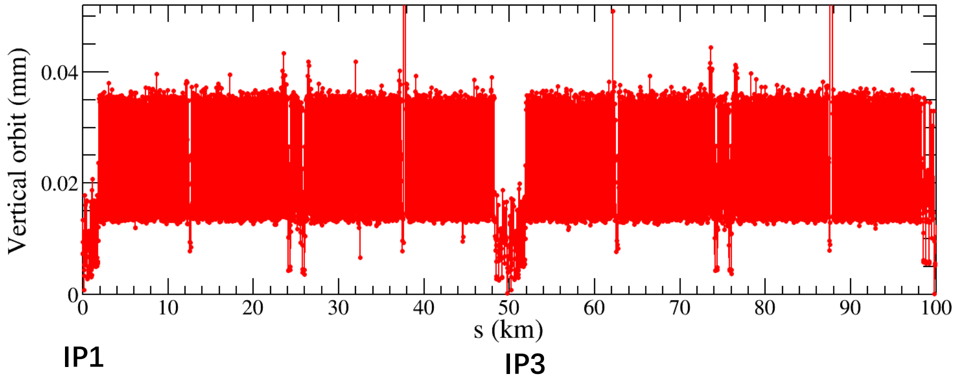
Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.02%
IR Quadrupole	0.10	0.10	0.10	
Sextupole	0.10*	0.10*	0.10	

* reduced to 0.01 mm with movers

Correction of the closed orbit distortion @ Higgs

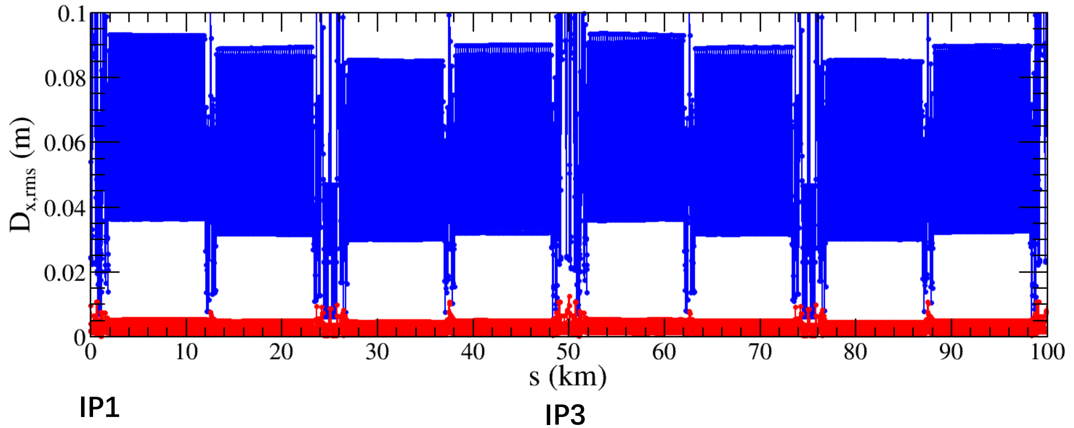
- BPMs placed at each quadrupoles
- H/V correctors placed beside focusing/defocusing quadrupoles
- The converged seeds is increased from 678 to **799** after additional iteration and manual optimization.
  - The rest 201 seeds are not manual optimized yet due to time being.



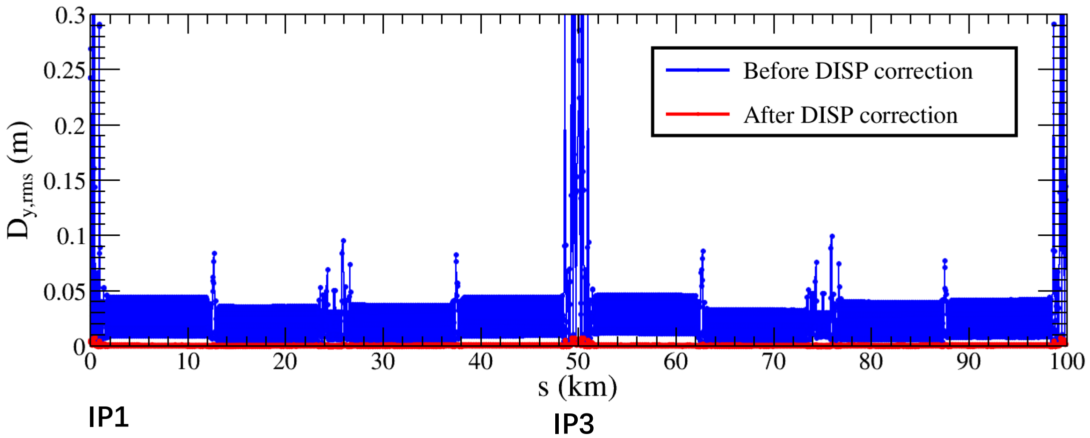


$RMS_{COD} < 0.05\ mm$

Dispersion correction @ Higgs



$\Delta D_{x,rms}$ decreased from 55.0mm to 2.7mm

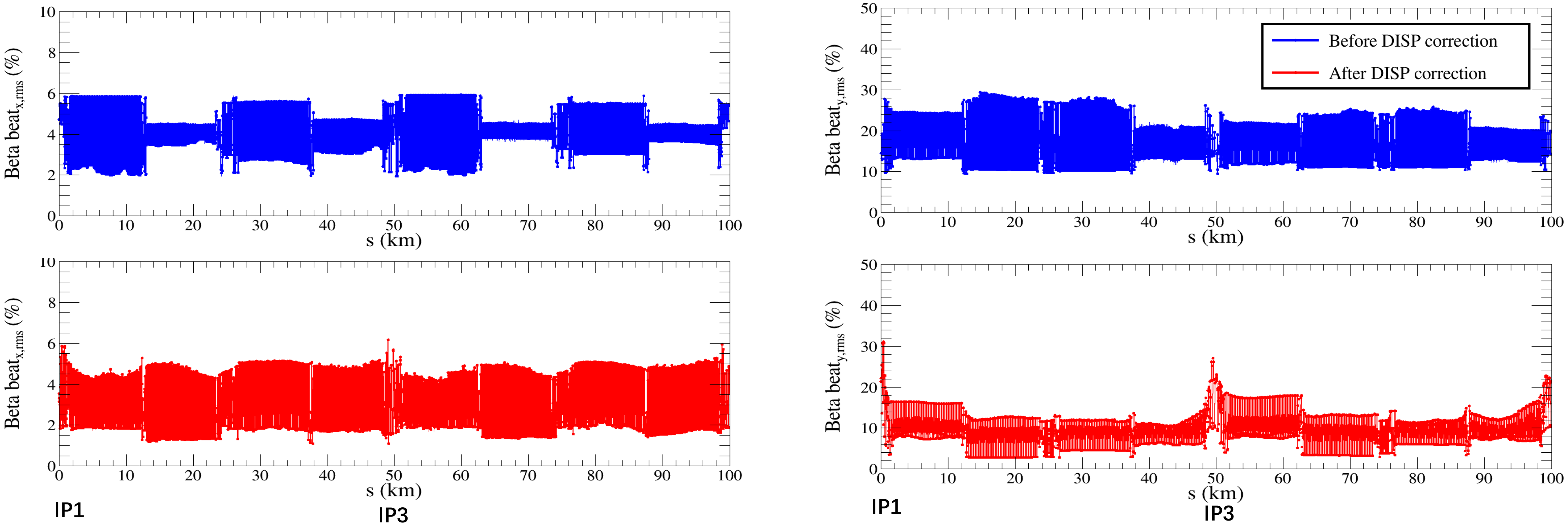


$\Delta D_{y,rms}$ decreased from 27.9mm to 0.7mm

- The dispersion correction is performed for the 799 lattice seeds.
- 541 seed converged after batched dispersion correction
- The converged seeds is increased from 541 to **649** with manual optimization.

Beta-beating correction @ Higgs

misalignment of sextupoles reduced to 10 um with movers
w/o main field errors of the sextupole and IR quadruple

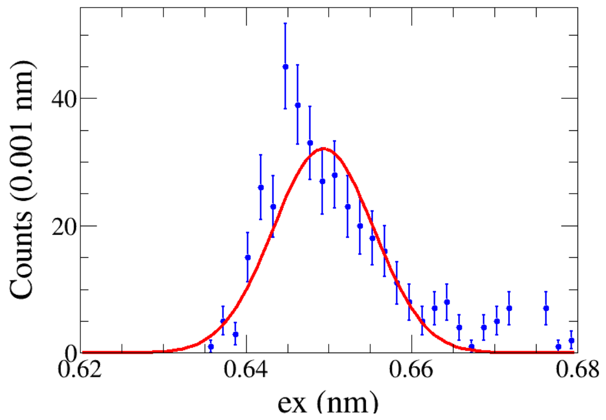


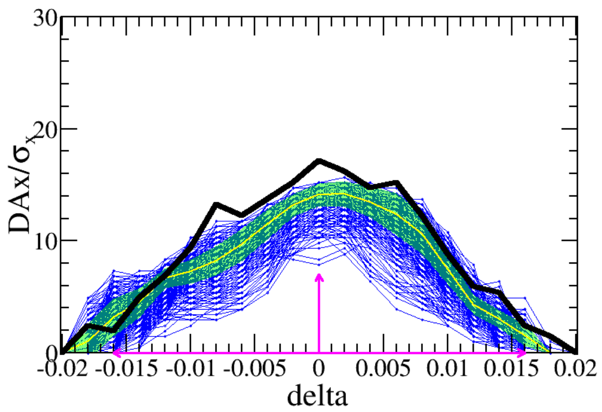
$\Delta\beta/\beta_{x,rms}$ decreased from 4.1% to 2.9%

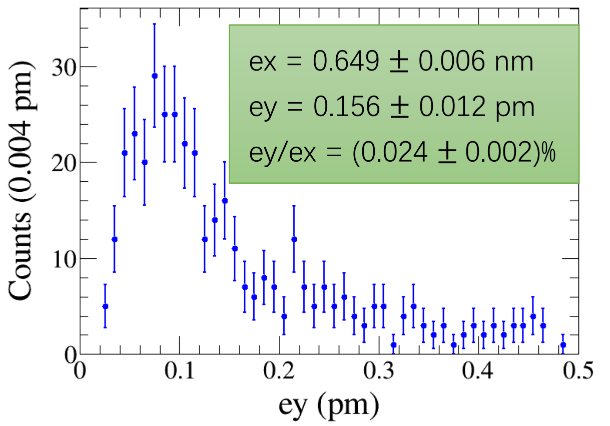
$\Delta\beta/\beta_{y,rms}$ decreased from 17.0% to 9.8%

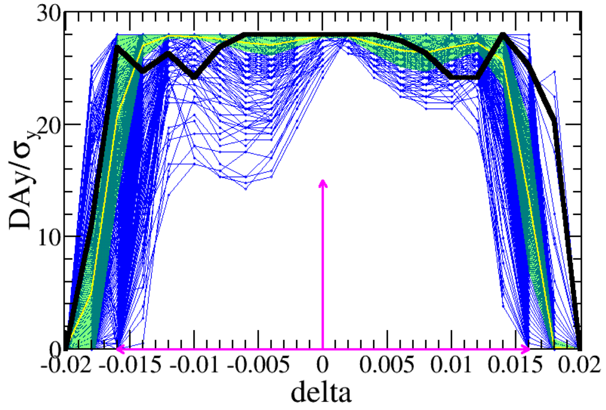
- For the beta beating correction, the manual adjustment is necessary for almost all lattice seeds
- only **541** lattice seeds are performed for beta beating correction

Emittance and dynamic aperture with error @ Higgs









Lattice cepc.lat.diff.8713.346.2p used

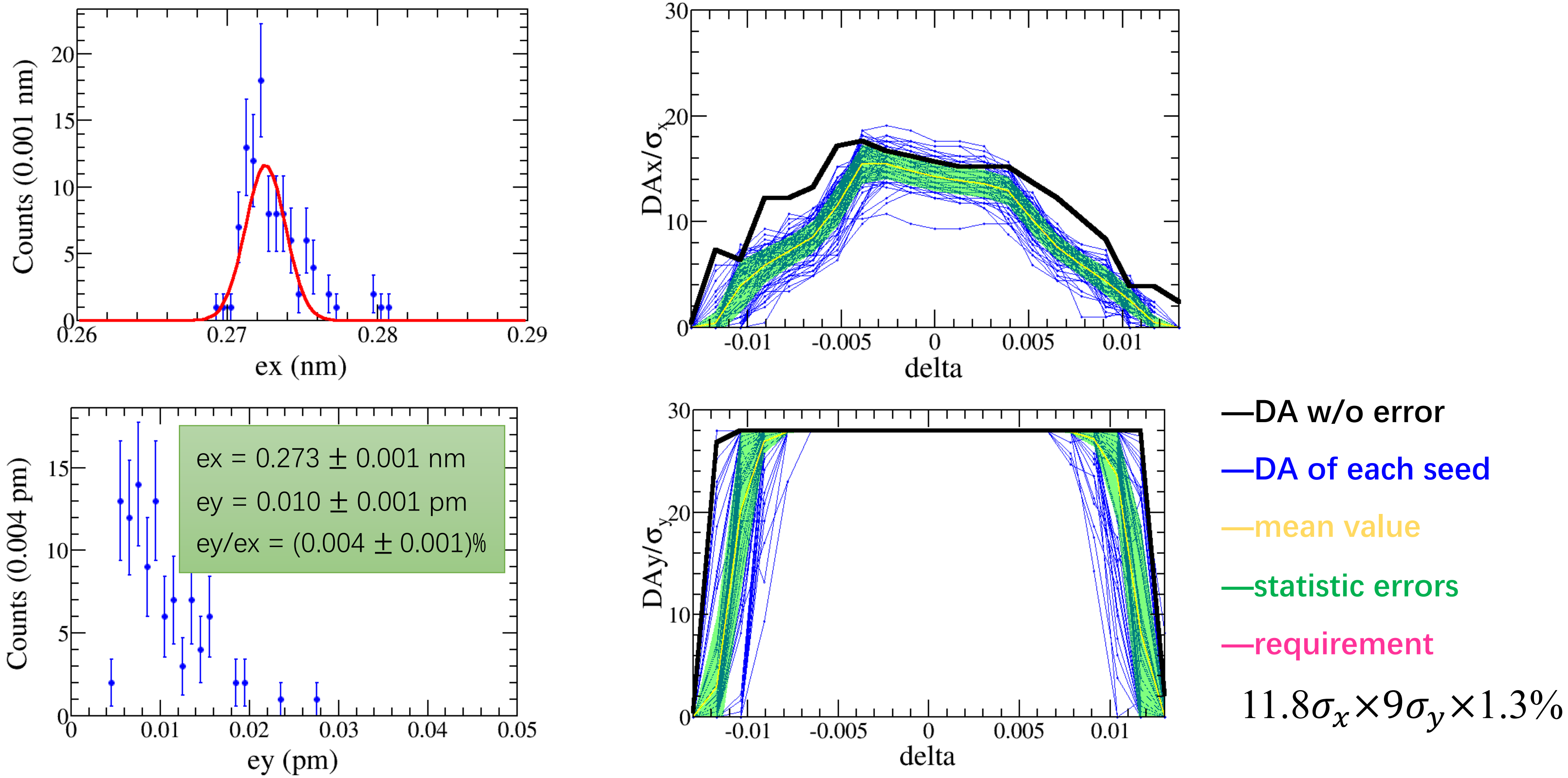
—DA w/o error
—DA of each seed
—mean value
—statistic errors
—requirement

$7\sigma_x \times 15\sigma_y \times 1.6\%$

Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole

- The emittance coupling fulfill the requirement (<0.2%)
- With batched correction for Higgs mode, 404 out of 1000 seeds satisfy the DA.
- For the remaining 596 error seeds, 97 seeds out of randomly-selected 108 seeds satisfy the DA requirements after individual further correction. In the near future we will finish the study of all the 1000 seeds.

Emittance and dynamic aperture with error @ Z



- The dedicated correction code for Z mode is still under development. 96 seeds out of randomly-selected 102 seeds satisfy the DA requirements after individual further correction.
- In the near future we will finish the study of all the 500 seeds by both batched and individual further correction.
- The emittance coupling fulfill the requirement (<0.5%)

Summary

- The optics of CEPC collider ring was designed with luminosity goal 5e34/cm^2/s/IP @ Higgs with 30 MW/beam.
  - RF region: 1st priority of the Higgs running and flexible switching
  - ARC: The distribution of sextupoles for Higgs & ttbar modes (90 deg cell) allowed to select –I sextupole pairs for W &Z modes (60 deg cell) .
  - IR: Crab waist collision, local chromaticity correction, asymmetric interaction region
- Dynamic aperture w/o error for four modes achieve the requirement of energy acceptance.
- The lattice w/ error for Higgs and Z modes are corrected
  - The emittance coupling fulfill the requirement
  - For both Higgs and Z lattice, the pass rate of random seeds is high enough to fully satisfy the DA requirements with both batched correction and individual further correction .
  - Further correction study with girder misalignment, main field errors of the sextupole and IR quadruple are under going.