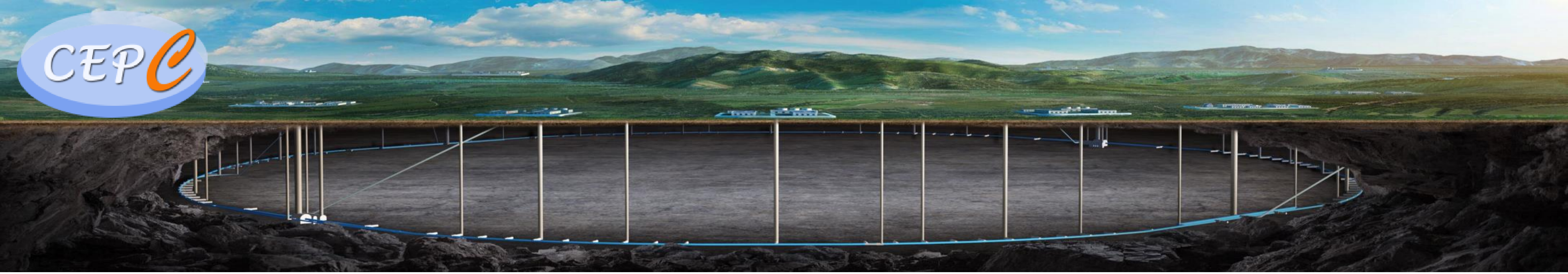


Status of optics tuning simulations in the CEPC

Yiwei Wang, Bin Wang, Yuan Zhang, Sha Bai, Jiyuan Zhai, Yuanyuan Wei
for the CEPC Accelerator Physics Group

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

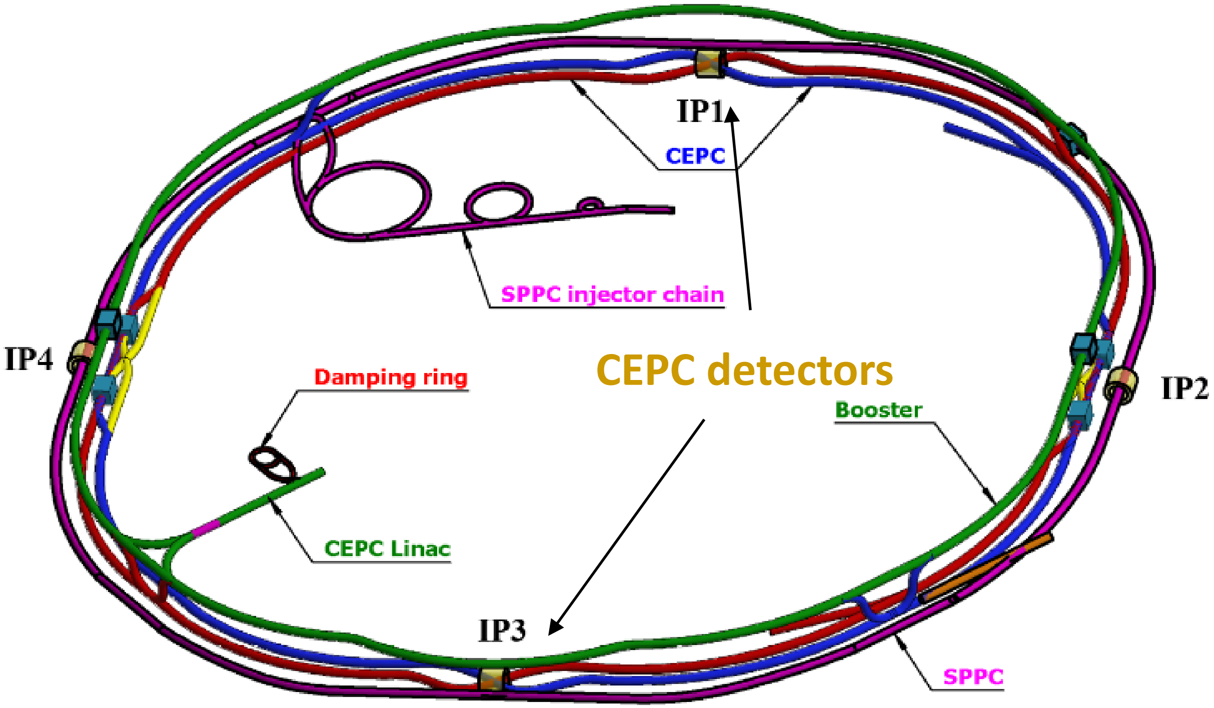
Content

- Introduction
- Lattice design requirement of the CEPC collider ring
  - Interaction region
  - RF region
  - ARC region
- Dynamic aperture w/o errors
- Error correction and dynamic aperture w/ errors
- Conclusions

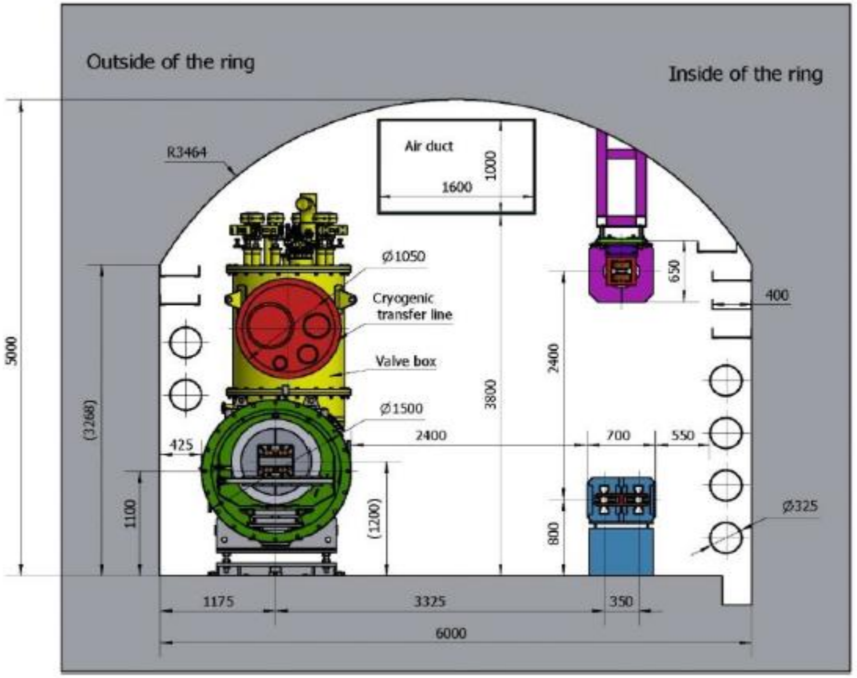
Overall design requirement of the CEPC collider ring

- SR power per beam 30 MW (50 MW upgradable), 100 km, 2 interaction points
- Higgs mode hold the 1st priority and compatible with the ttbar/W/Z modes.
- Compatible with SPPC: 100km, section length, two machines share the most tunnels

CEPC+SPPC complex

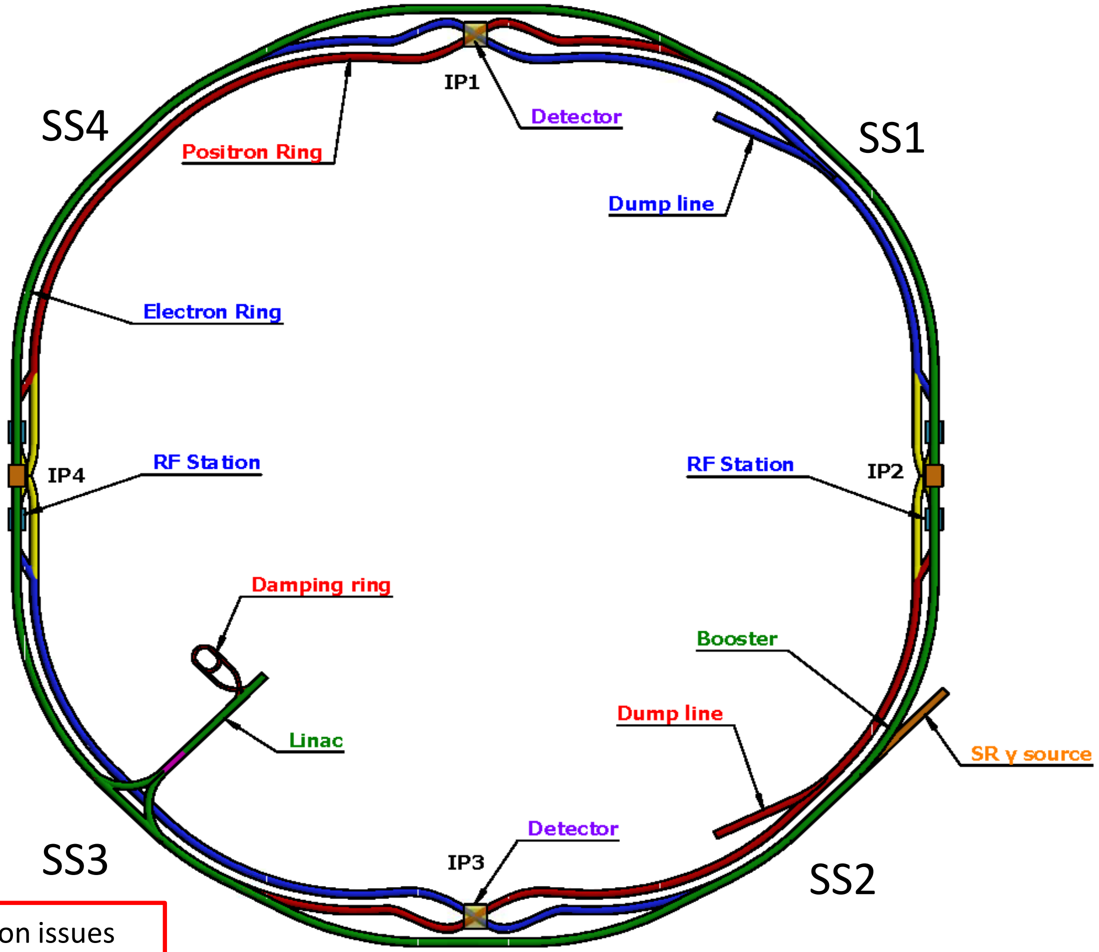


Tunnel in the arc regions



Lattice design requirement of the CEPC collider ring

- Basically 2 folded symmetry
- 2 interaction regions @ IP1 and IP3
  - crab waist collision
  - local chromaticity correction for the interaction region
- 2 RF acceleration regions @ IP2 and IP4
  - shared cavities for two beam @ ttbar, Higgs
  - flexible switching between compatible modes
- 8 arc sections
  - dual aperture dipole and quadrupole magnets
- 4 short straight section
  - on/off axis injection regions for different modes
  - beam dumping, gamma source
- Providing polarized beam*



Ref: CEPC CDR, arXiv:1809.00285, 2018; K. Oide, arXiv:1610.07170; M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010);

*Polarization preservation issues at the CEPC, Zhe DUAN, 16:40, 27 June, this workshop

SS: short straight section

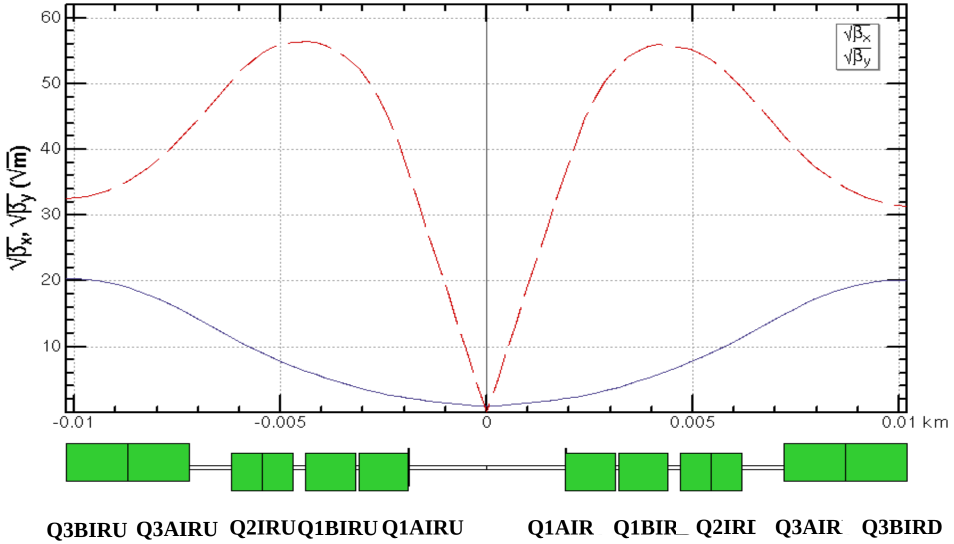
CEPC Design Parameters

	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**

-$\beta y*$ and emittance chosen for luminosity
-adequate Ne for the luminosity and achievable energy acceptance for lattice design

Final quadrupoles for all modes

- Higgs running keep the 1st priority
  - Strength of other modes doesn't exceeded the one of Higgs mode.
- The parameters near the IP are chosen based on a trade-off between the beam dynamics and the machine detector interface.



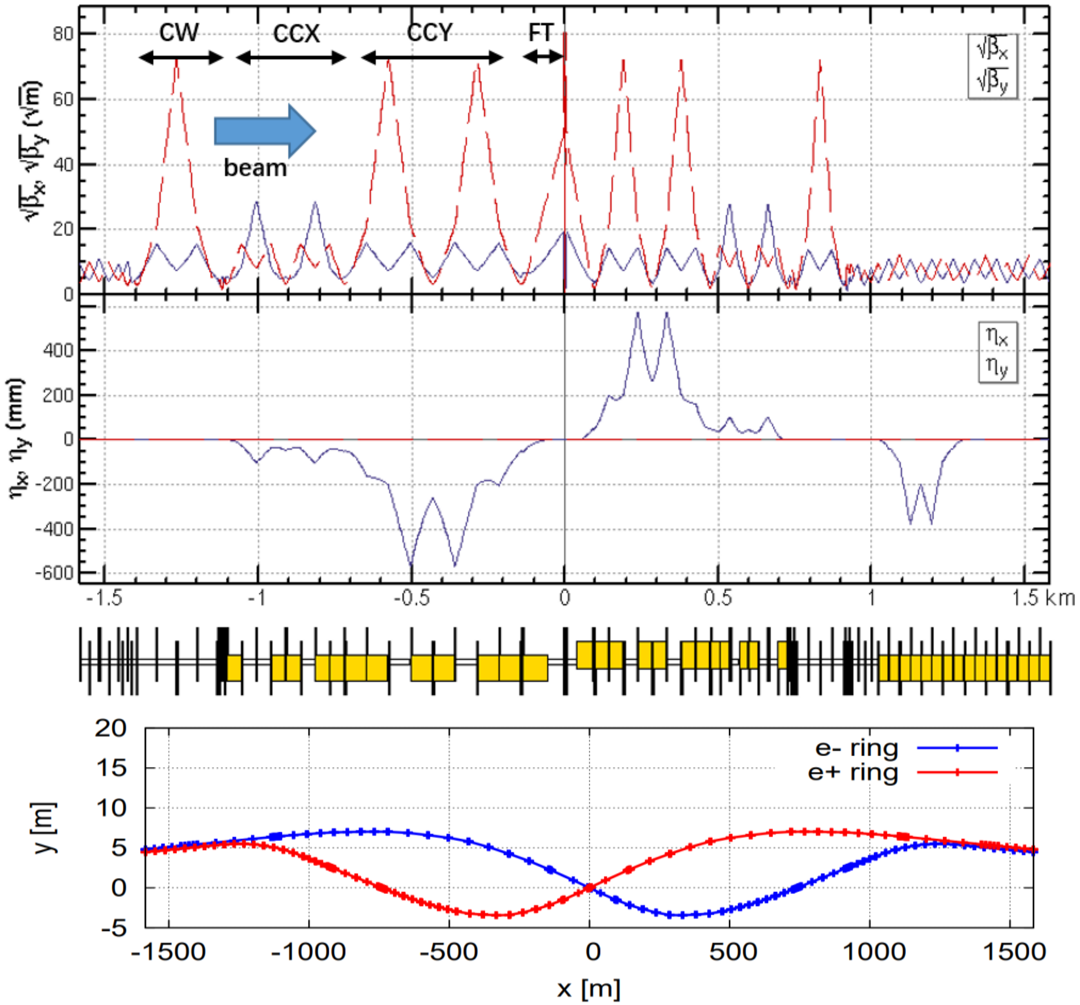
Quadrupole	L [m]	Distance from IP [m]	Strength [T/m]			
			$t\bar{t}$	Higgs	W	Z
Q1AIRU	1.21	1.9	-141	-141	-94	-110
Q1BIRU	1.21	3.19	-59	-85	-56	+65
Q2IRU	1.5	4.7	-51	+95	+63	0
Q3IRU	3	7.2	+40	0	0	+2
Q1AIRD	1.21	-1.9	-142	-142	-95	-110
Q1BIRD	1.21	-3.19	-64	-85	-57	+65
Q2IRD	1.5	-4.7	-47	+96	+64	0
Q3IRD	3	-7.2	+40	0	0	+2

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

	L* [m]	LQ1 [m]	LQ2 [m]	GQ1 [T/m]	GQ2 [T/m]	d [m]
CDR	2.2	2.0	1.5	-136	111	0.3
TDR	1.9	1.22/1.22	1.5	-141/-85	+95	0.3

Lattice design of the interaction region

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



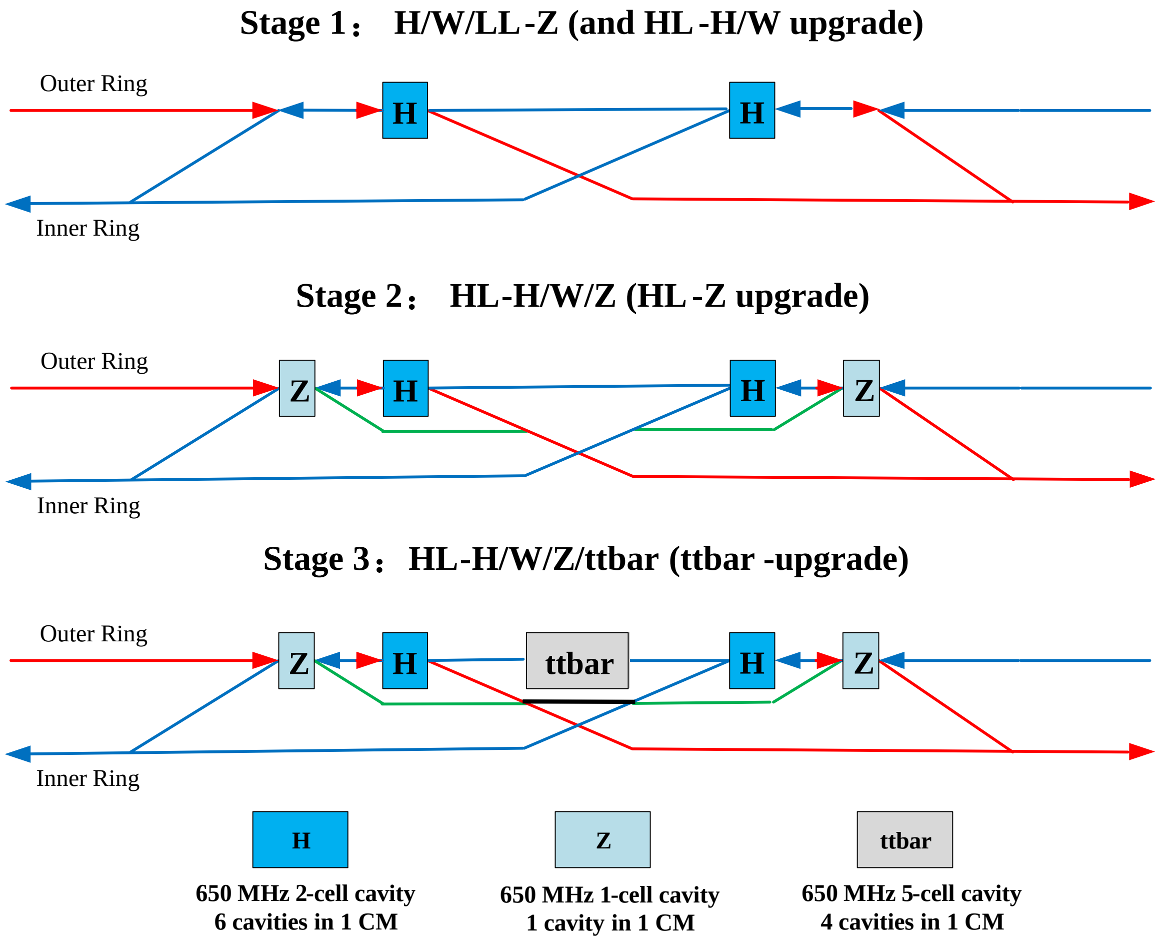
- Up to 3rd order chromaticity is corrected with pairs of main sextupoles, phase tuning and additional sextupoles respectively.
- Main resonance driving terms (RDT) due to sextupoles in 3^{rd} and 4^{th} order Lie operators are cancelled.
- The tune shift due to the finite length of the main sextupoles is corrected with additional weak sextupoles.

RF region Layout

- 1st priority of the Higgs running and switching between different modes
- Shared cavities for two beam @ Higgs, ttbar; Bunches filled in each half rings
- Independent cavities; bunches filled in each whole rings for the W and Z
- Maximize the performance and flexibility of future circular electron positron collider

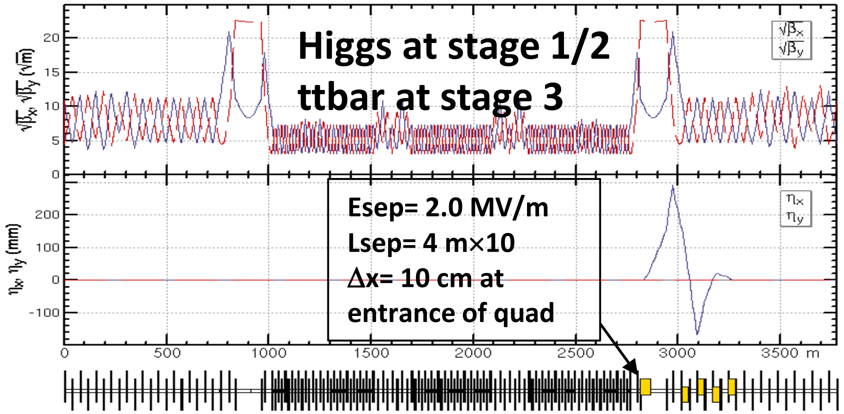
Peak luminosity at different stages with SR power for **30/50MW per beam**

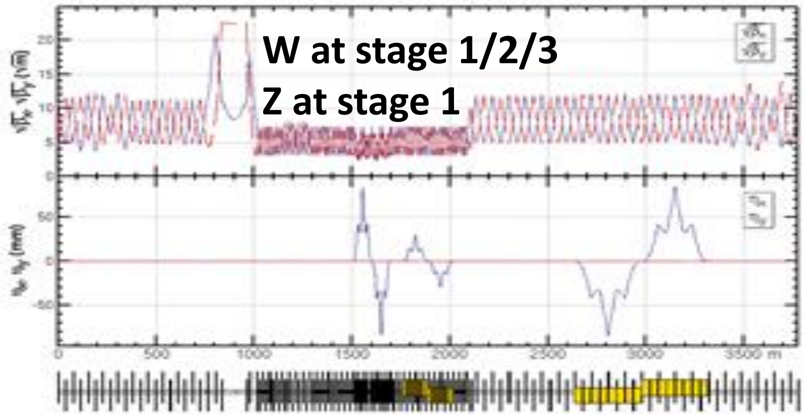
Luminosity/IP [10^34/cm^2/s]	Higgs	Z	W	ttbar
Stage 1	5/8.3	38 (10MW limit)	16/26.7	-
Stage 2	5/8.3	115/192	16/26.7	-
Stage 3	5/8.3	115/192	16/26.7	0.5/0.83

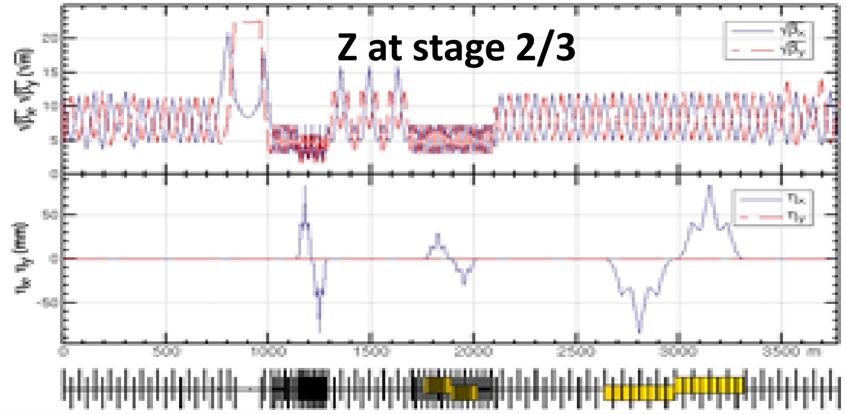


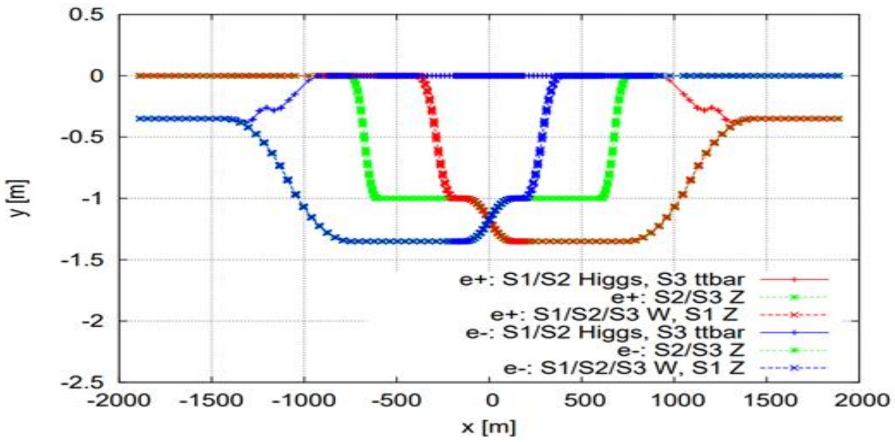
Lattice design of the RF region

- The lattice was designed to satisfy the RF system design for different energies.
  - bypass and section length for different RF stages, small average beta functions to reduce the multi-bunch instability



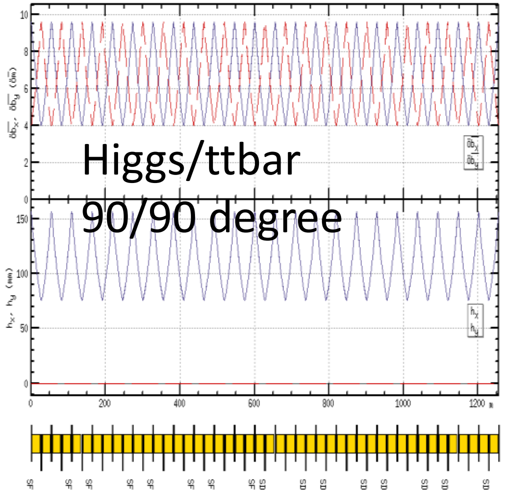


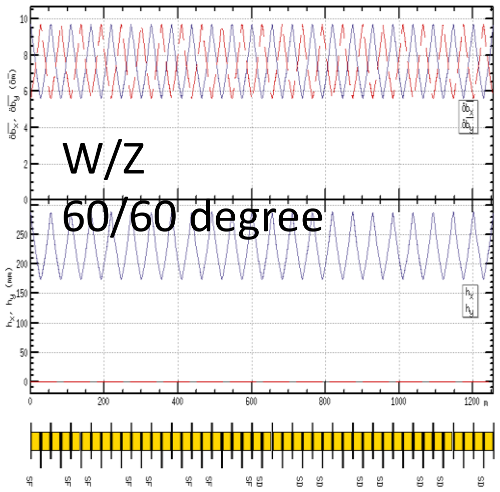


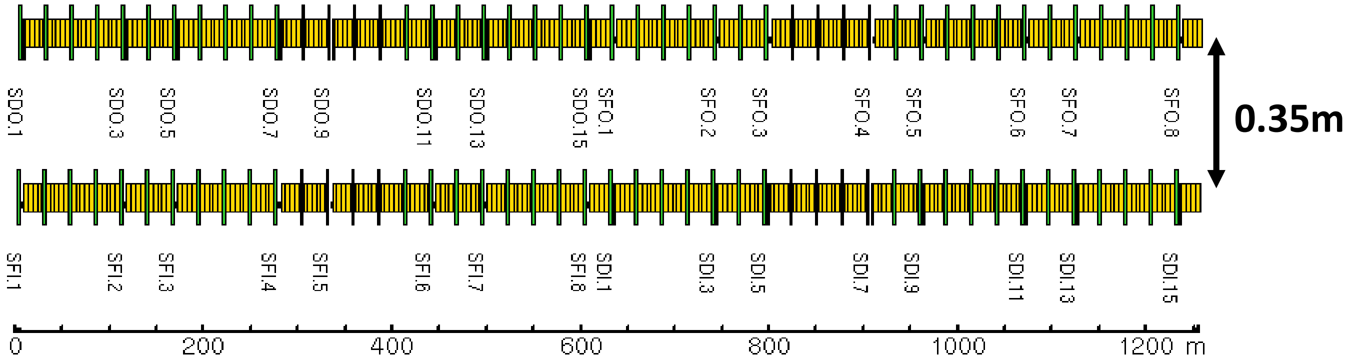


Lattice design of the ARC region

- FODO cell to provide a large filling factor.
- 90/90 degrees' phase advances for the Higgs and ttbar modes due to the emittance and nonlinearity cancelation.
- 60/60 degrees' phase advances for the W and Z modes to fulfil the collective instability requirement.
  - suppress the impedance induced instability at Z mode
  - increase stable tune area if considering beam-beam effect and impedance consistently at W and Z modes
- The distance 0.35m and opposite polarity between two beams fulfill the requirement technical design of the twin-aperture of dipoles and quadrupoles.



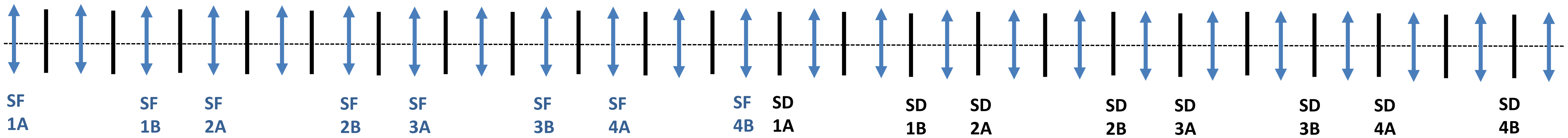




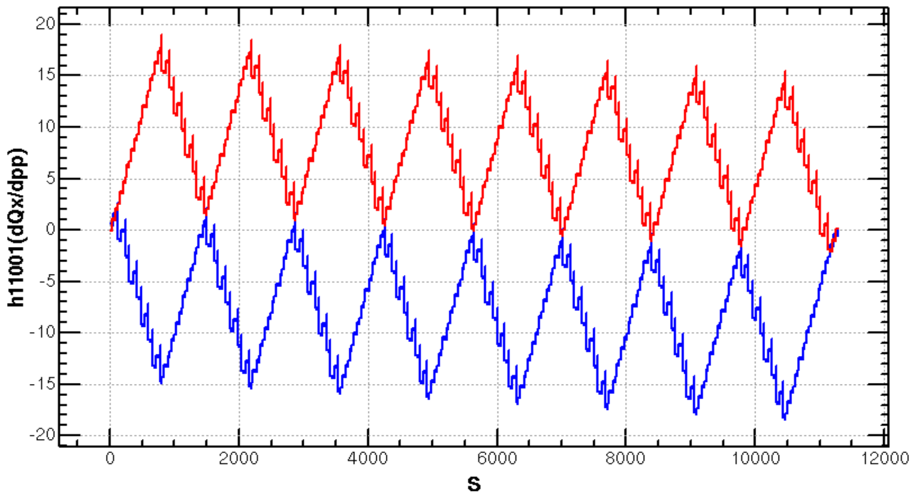
Dual aperture quadrupole and bend with opposite polarity in two ring

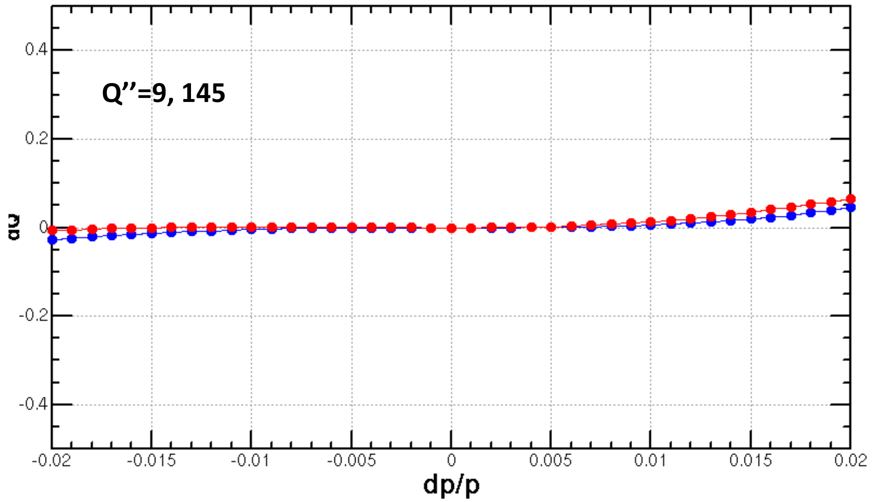
Optimization of ARC aberration for Higgs/ttbar modes

- Four –I sextupole pairs scheme for Higgs & ttbar modes
  - With small 2nd order chromaticity esp. for the horizontal plane
  - 2nd order chromaticity for the vertical plane generated in the ARC region are further corrected with IR knobs.



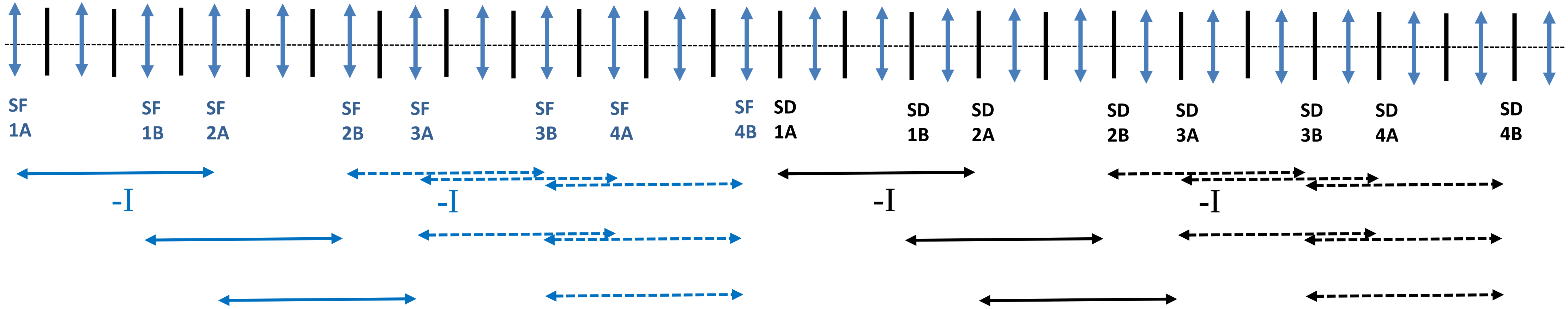
Scheme with **four –I sextupole pairs,** T. Bian, PhD thesis 2018, IHEP

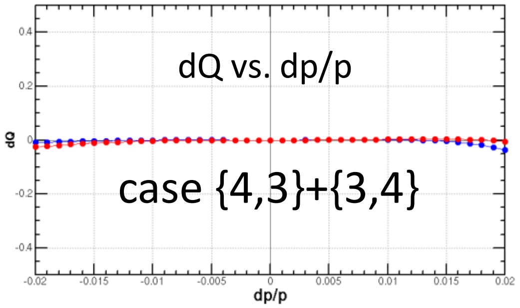


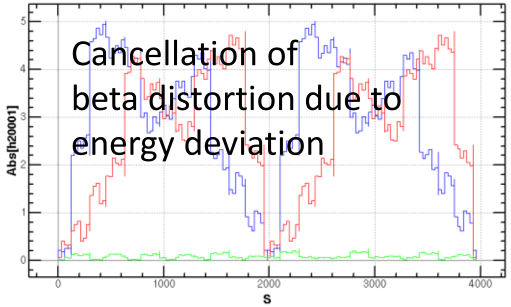


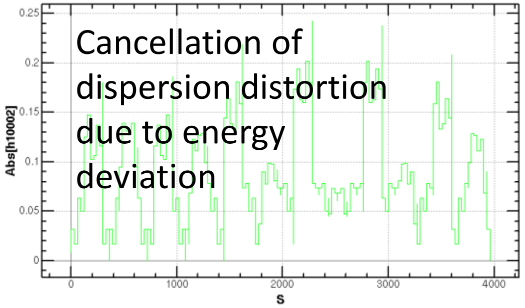
Optimization of ARC aberration for W/Z

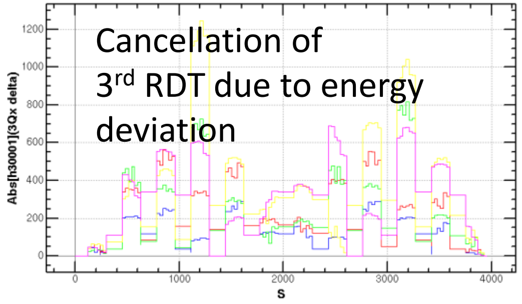
- The distribution of sextupoles for Higgs & ttbar mode allowed to select –I sextupole pairs for W &Z modes.
- Cancellation of main aberration has period of 23*3 cells. Give a good start point for the dynamic aperture optimization.



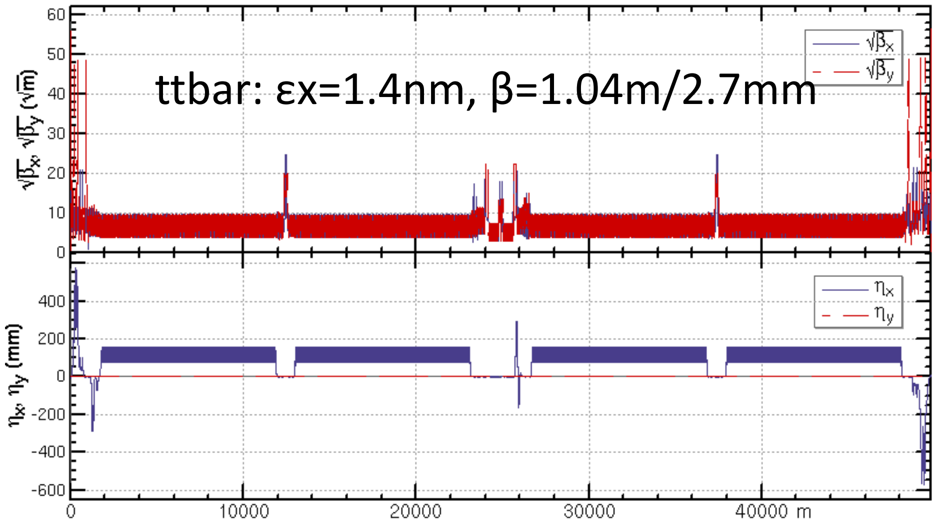


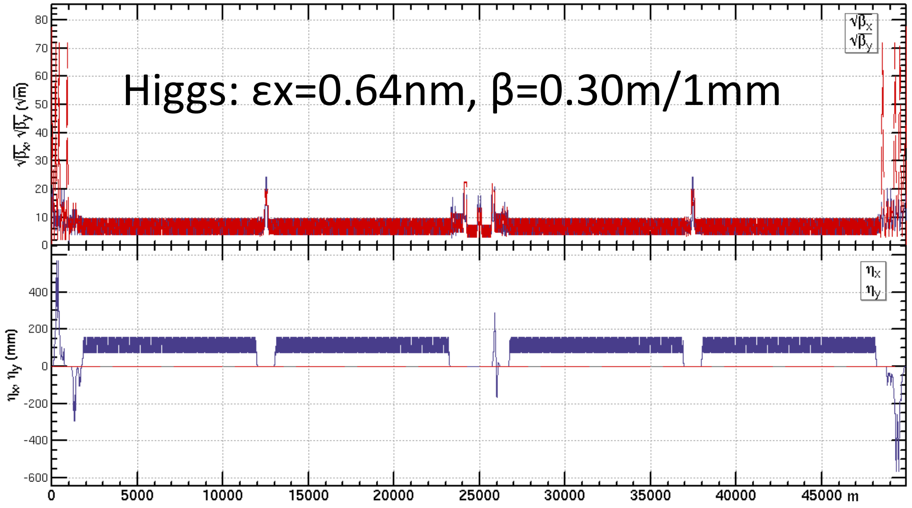


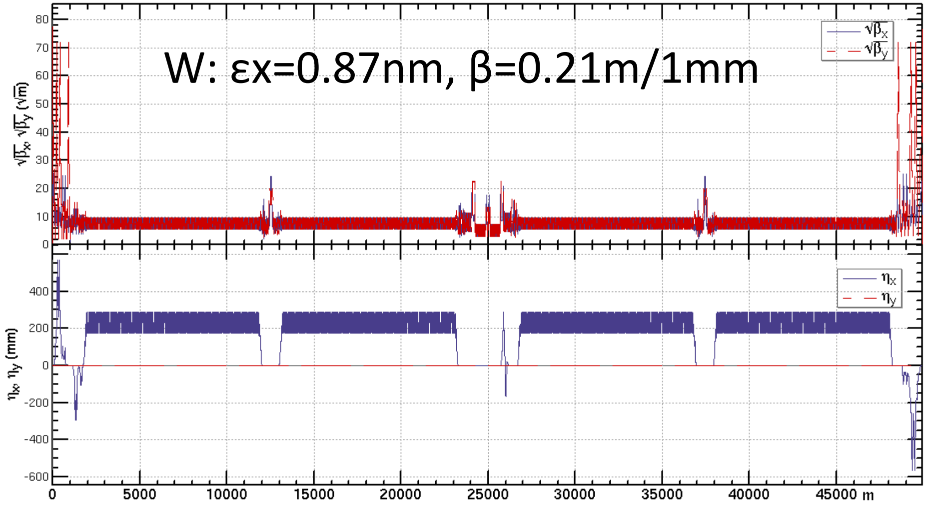


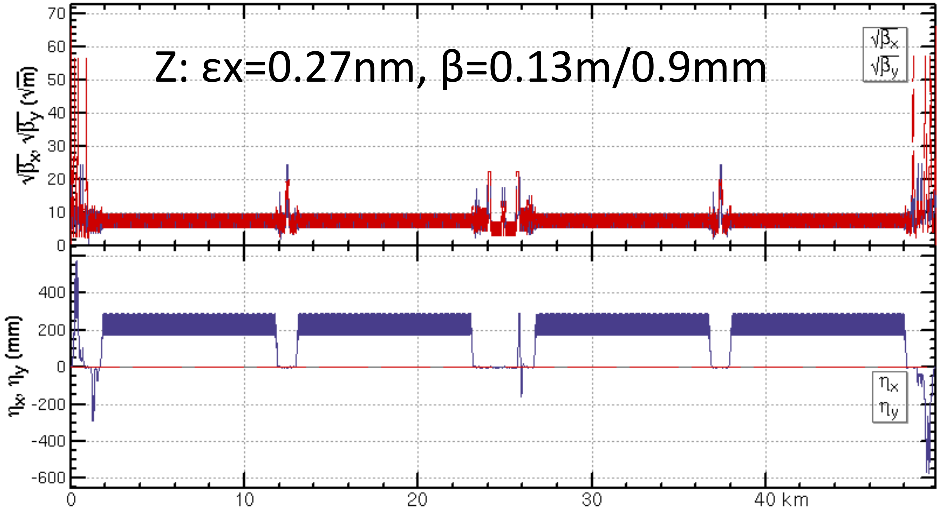


Lattice design of the CEPC half ring









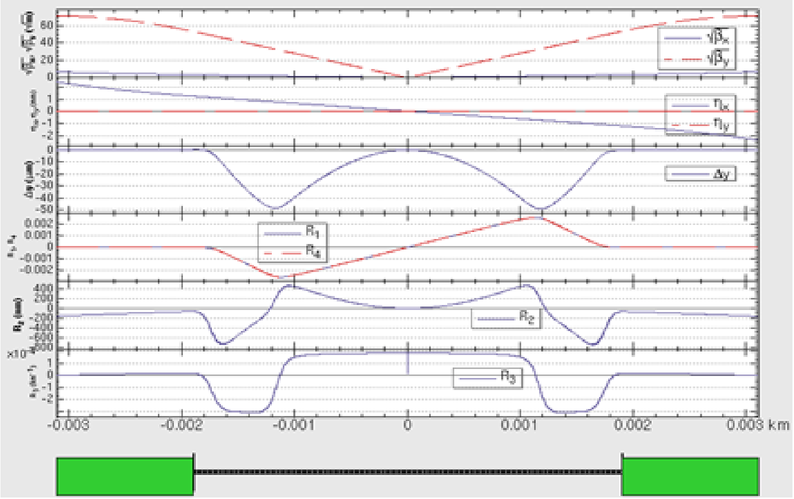
Vertical emittance generated by solenoid field

- The detector solenoid are compensated locally with anti-solenoids
  - 3T for $t\bar{t}$/Higgs/W, 2T for the Z
  - cancel the ∫Bzdz between the IP and the faces of the final quadrupole
  - exists a transverse fringe field esp. at the fringe of anti-solenoid
  - The vertical emittance increases due to the fringe field of the anti-solenoid combined with the horizontal crossing angle.
- The solenoid field induced vertical emittance fulfill the parameter list.

Vertical emittance due to the solenoid field

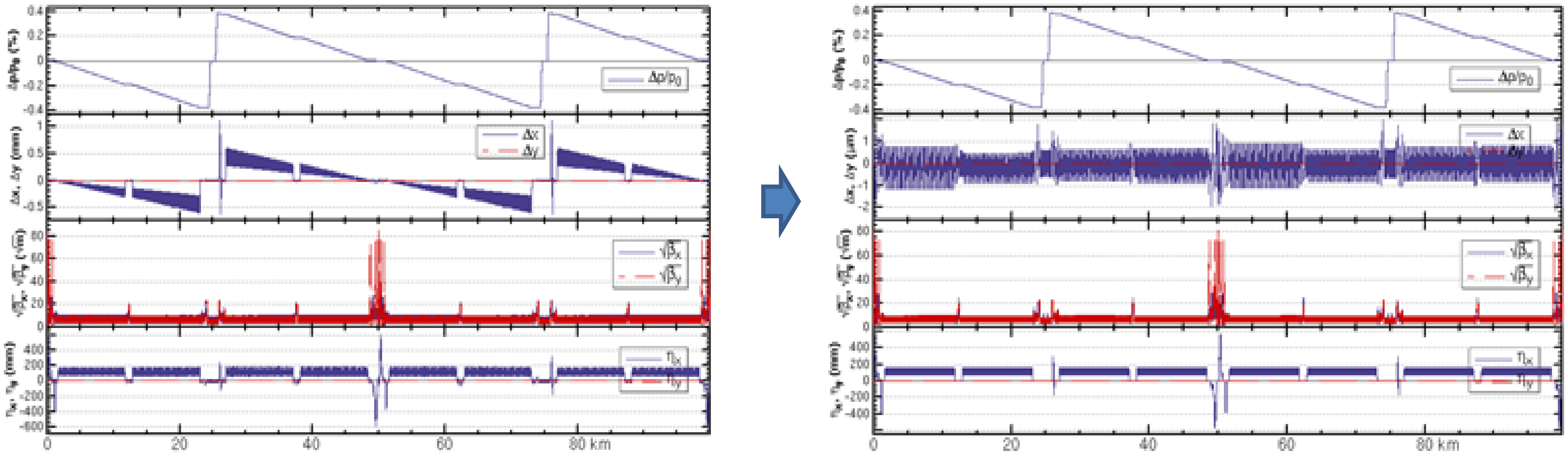
	ttbar 3T	Higgs 3T	W 3T	Z 2T
EmitY nominal (pm)	4.7	1.3	1.7	1.4
EmitY (pm)	0.04	0.41	1.35	1.07

IR optics with solenoid for Higgs energy



Energy sawtooth effects and correction

- With only two RF stations, the energy sawtooth is around ±0.4 % @ H and 1.3 % @ ttbar
- The closed orbit distortion in CEPC collider ring is around 1 mm and becomes 1um after tapering* the magnet strength with beam energy.
  - require adjusting range of magnets strength ±2.5% with the trim coil



*Ref: CEPC CDR, arXiv:1809.00285, 2018

Dynamic aperture requirement

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

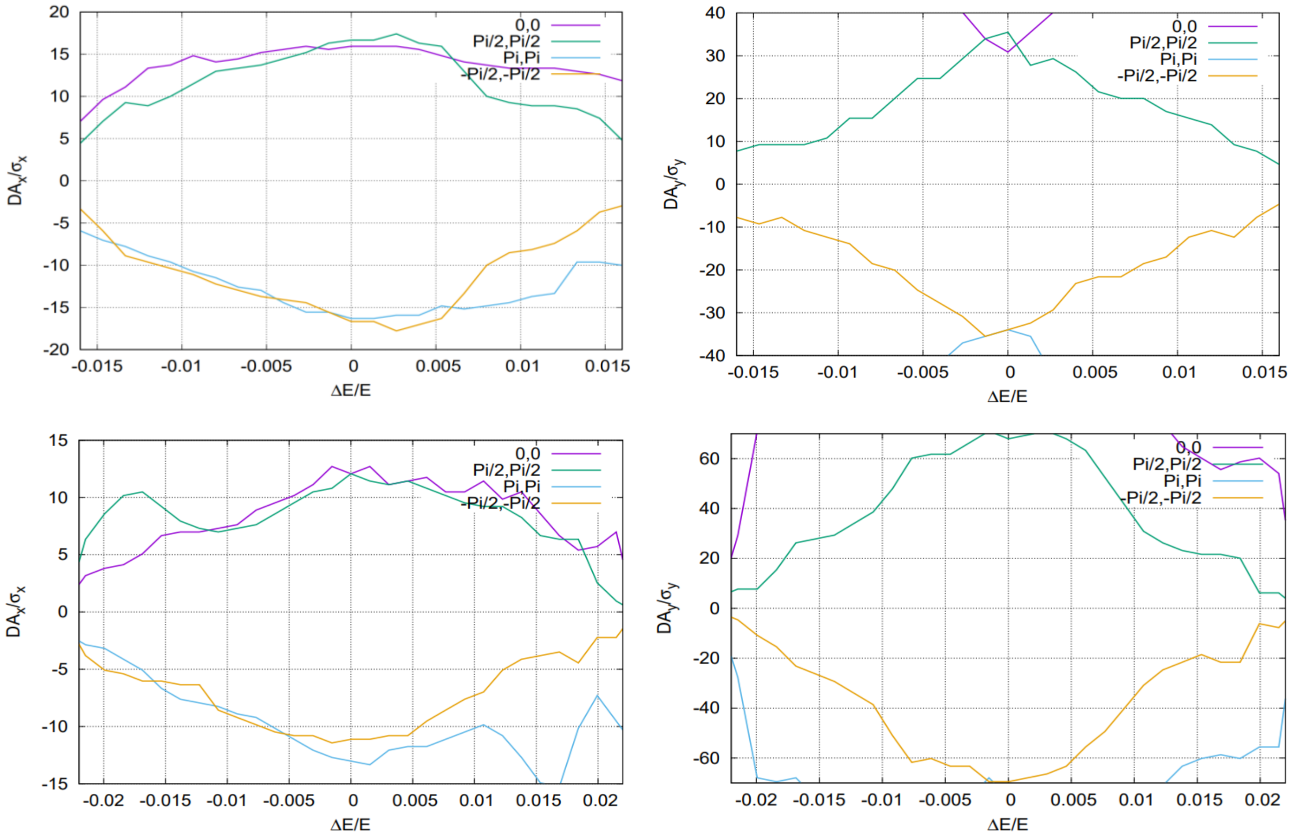
- The dynamic aperture requirement comes from the horizontal injection parameters, beam lifetime for the top-up injection.

	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	$11\ \sigma_x \times 7\ \sigma_y$ off axis	$13.5\ \sigma_x \times 7\ \sigma_y$ off axis $7\ \sigma_x \times 7\ \sigma_y$ on axis	$8.5\ \sigma_x \times 5\ \sigma_y$ off axis	$11\ \sigma_x \times 5\ \sigma_y$ off axis
Energy acceptance requirement [%]	2.0	1.6	1.2	1.0
Beam lifetime (mainly bhabha and beamstrahlung) [min]	18	18	21	72

Dynamic aperture @ Higgs and ttbar

- Tracking to get DA **without errors**, with turns for one transvers damping time, with 4 initial phases
- Higgs case optimized with 256 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances
- ttbar case optimized with 64 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances

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



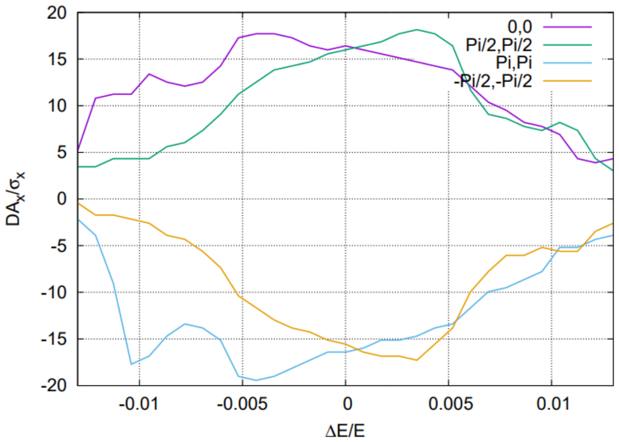
Higgs

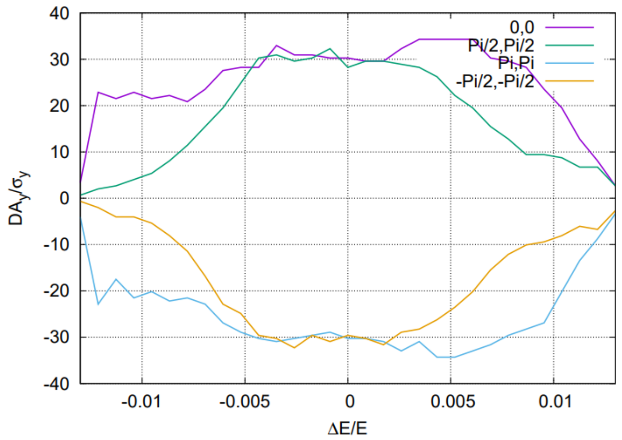
ttbar

Dynamic aperture @ Z and W

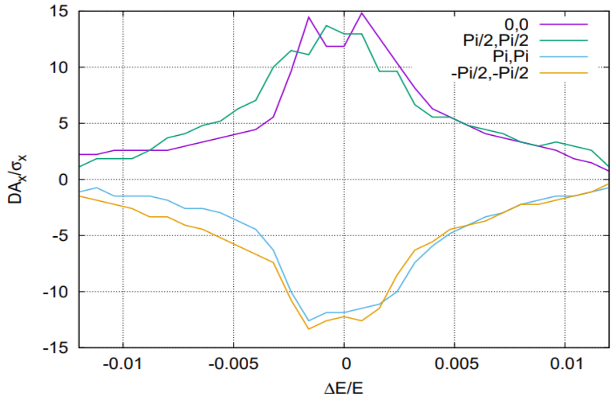
- Tracking to get DA **without errors**, with turns for one transvers damping time, with 4 initial phases
- Higgs case optimized with 128 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances
- ttbar case optimized with 128 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances

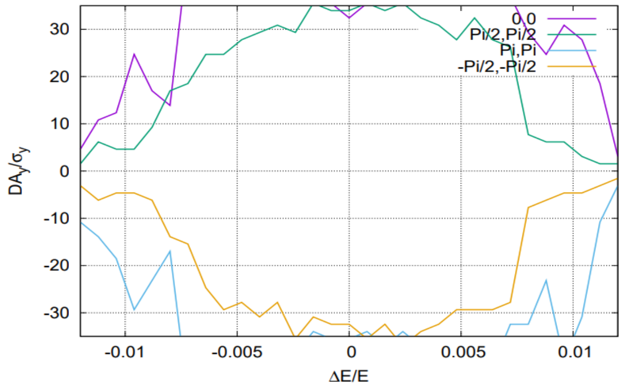
Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole





Z





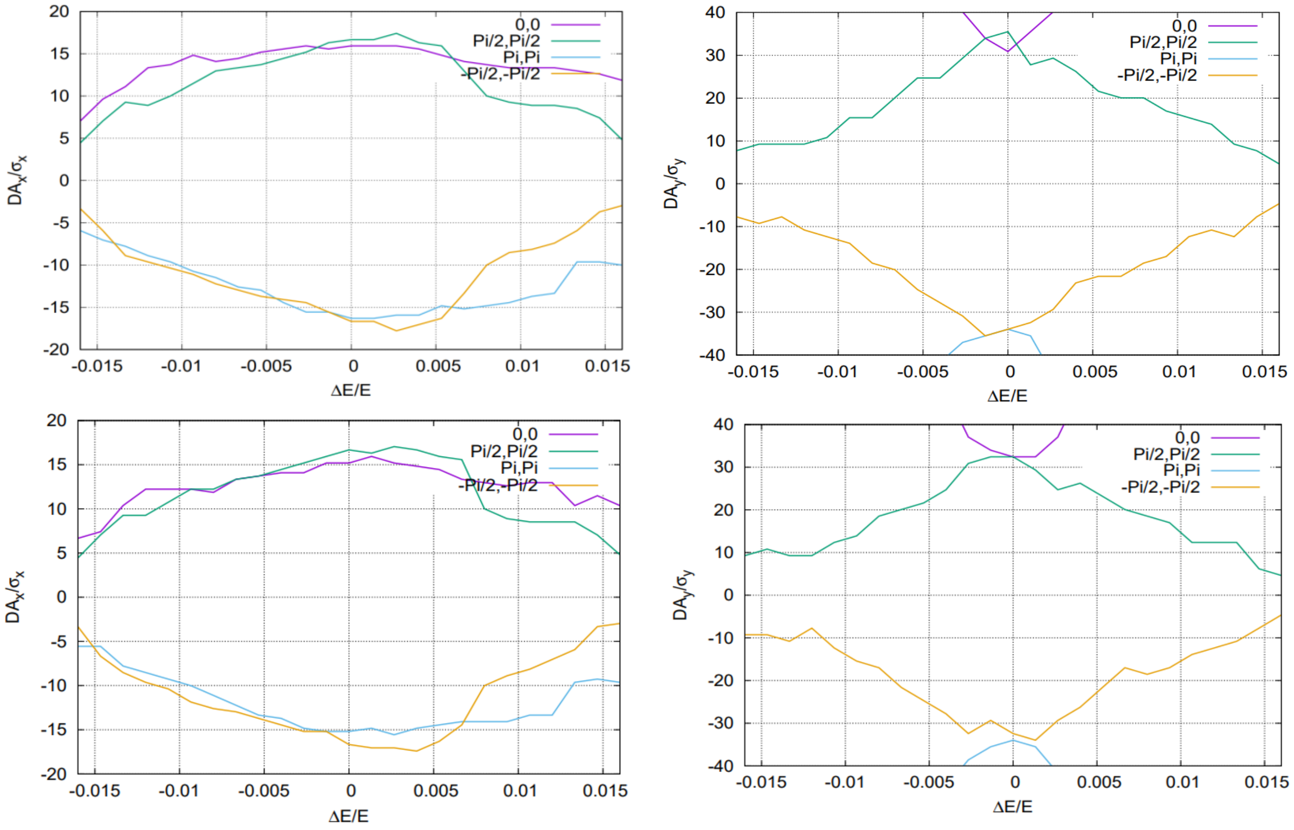
W

Solenoid effect on Dynamic aperture

Ander Ma, Yingshun Zhu et al

- The anti-solenoid cancel the ∫Bzdz between the IP and the faces of the final quadrupole.
- The Twiss function distortion due to solenoid field was corrected with final quadrupoles.
- **The solenoid effect on the dynamic aperture is small.**

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



Higgs without solenoid

Higgs with solenoid

Correction scheme for magnets errors

- 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.
  - Orbit correction is applied using orbit response matrix and SVD method.
- Dispersion correction
  - With dispersion free steering (DFS): orbit manipulation by knob correctors.
- Beta-beating correction
  - Correct the beta functions with sextupoles turned on based on AT LOCO
- Coupling correction
  - 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.

Error assumption

- With assumption of 100 um transverse misalignments
- BPMs placed at each quadrupoles
- H/V correctors placed beside focusing/defocusing quadrupoles

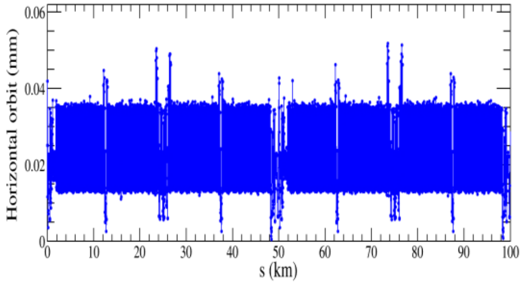
Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.02%
IR Quadrupole	0.10	0.10	0.10	0.02%
Sextupole	0.10*	0.10*	0.10	0.02%

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

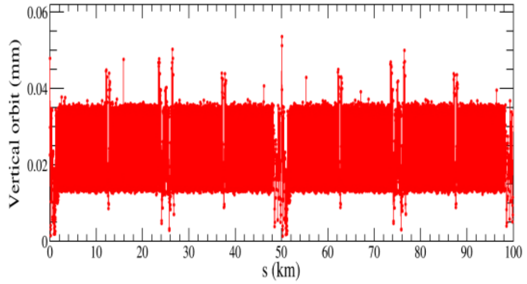
- with a large beta* lattice
- with quadrupole coils in the sextupoles
- 10um is possible as O(BPM resolution)=1um

Result of Higgs and Z lattice functions

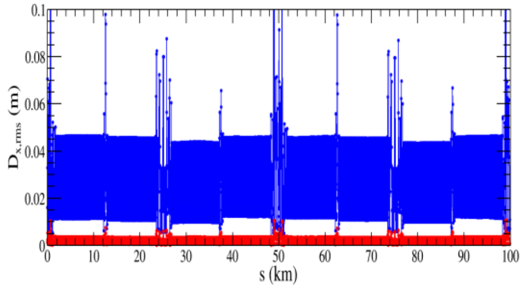
- The RMS orbit, dispersion and beta-beating of the whole ring are controlled after the global corrections.



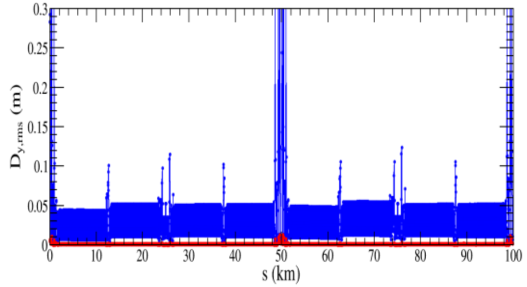
ΔX decreased to max 50um



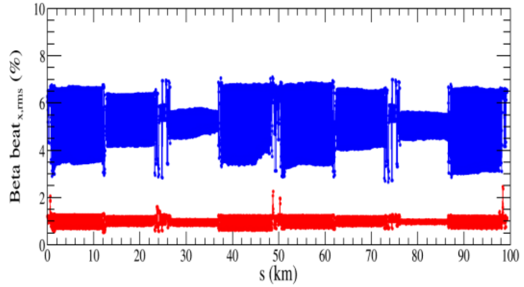
ΔY decreased to max 50um



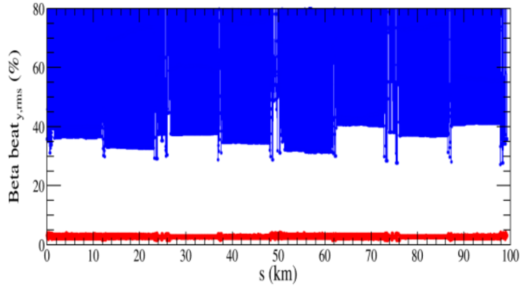
$\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm



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

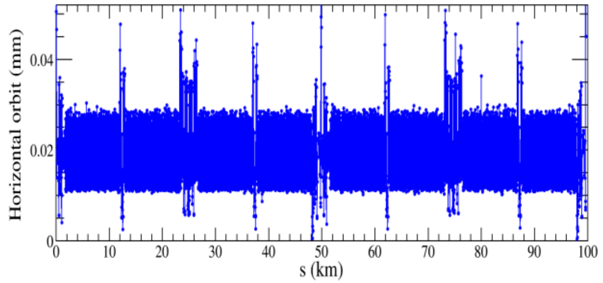


$\Delta\beta/\beta_{x,rms}$ decreased from 5.2% to 1.0%

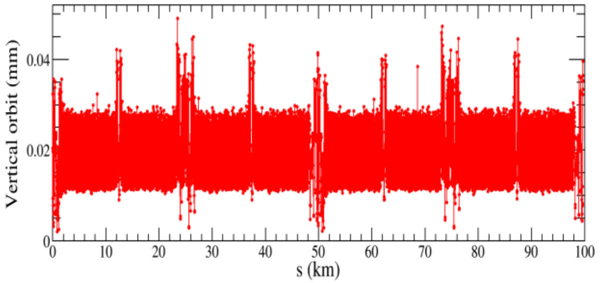


$\Delta\beta/\beta_{y,rms}$ decreased from 83.2% to 2.8%

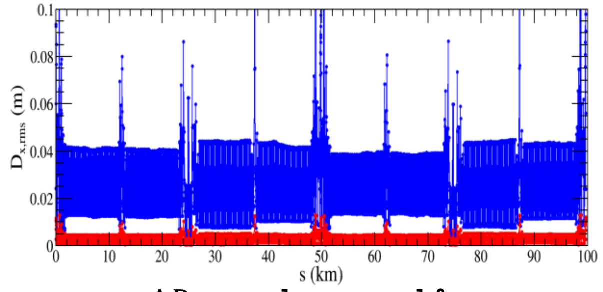
Higgs



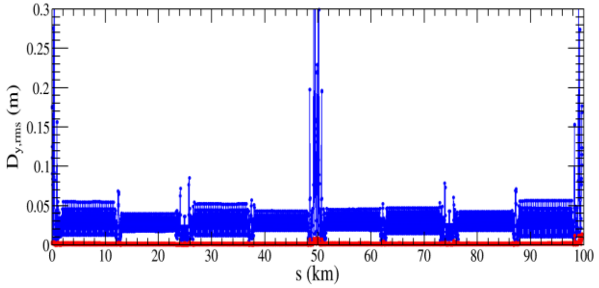
ΔX decreased to max 50um



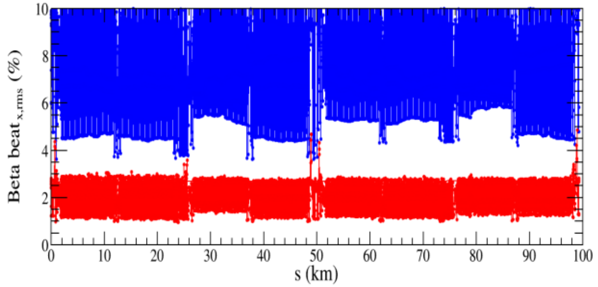
ΔY decreased to max 50um



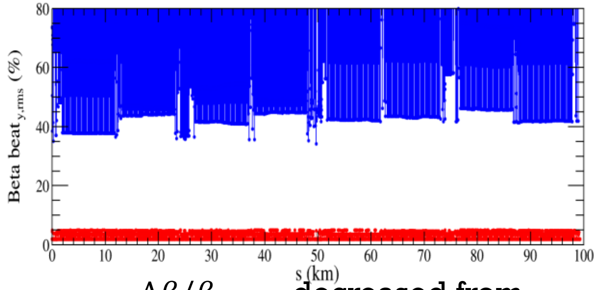
$\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm



$\Delta D_{y,rms}$ 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%

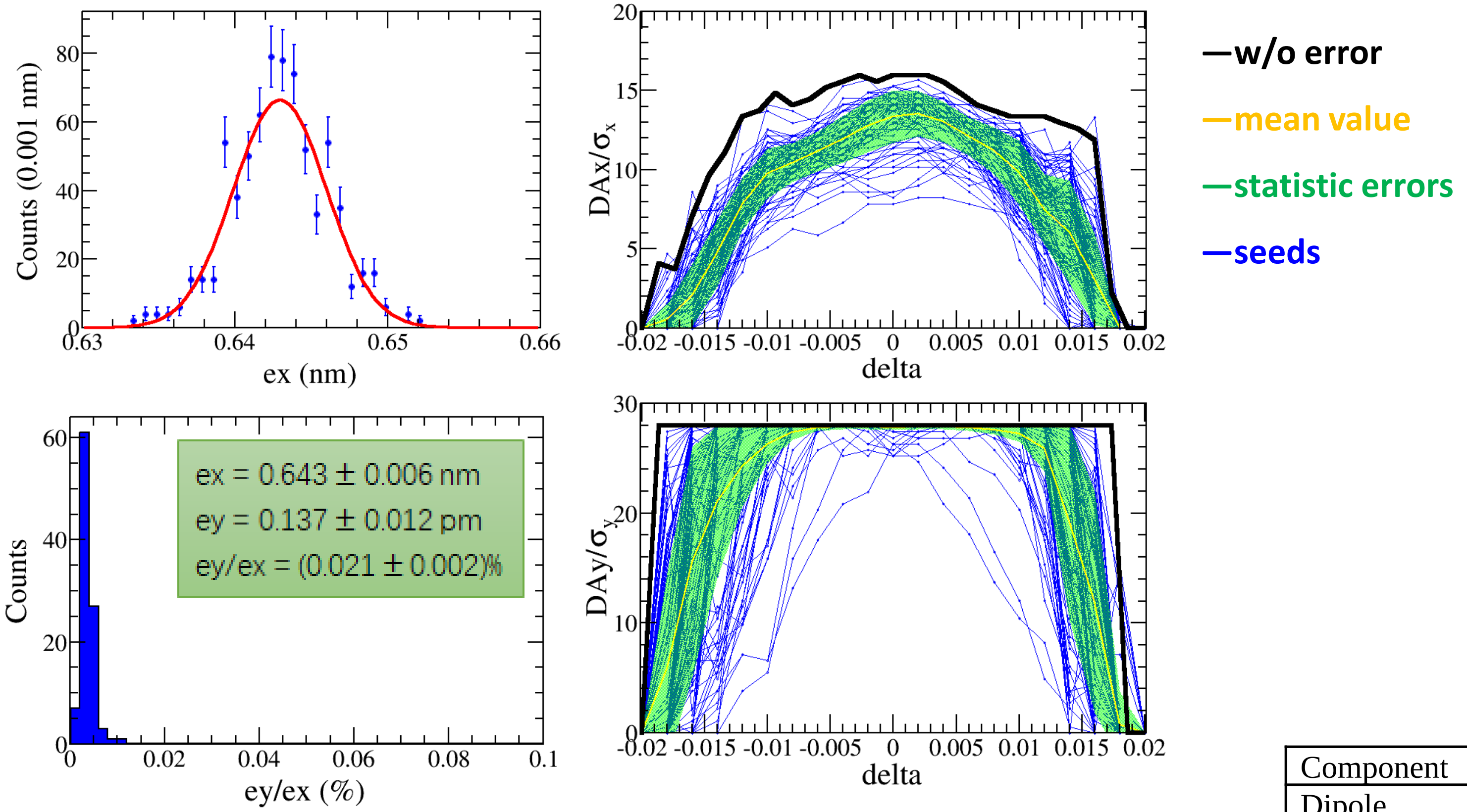
Z

Orbit and optics after corrections

- The RMS orbit, dispersion and beta-beating of the whole ring for the Higgs/Z/W/ttbar modes are controlled after the global corrections.

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

Emittance and dynamic aperture with error @ Higgs

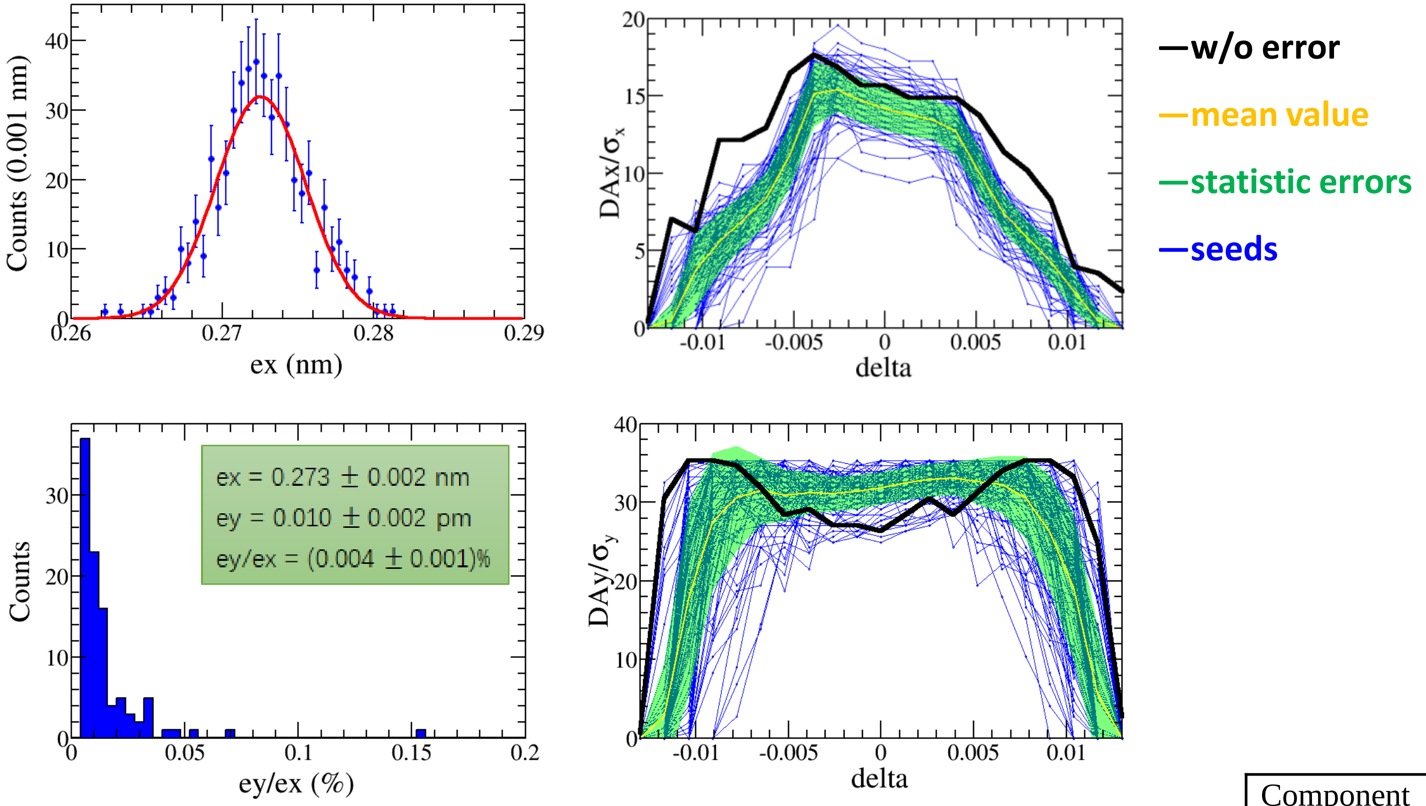


Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole

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%

- The emittance coupling fulfill the requirement (<0.2%)
- All of 100 lattice seeds with errors are corrected.
- 90% lattice seeds with error correction achieve $11\sigma_x \times 27\sigma_y \times 1.6\%$ after global correction.
- Correction with more errors and the IR tuning are undergoing.

Emittance and dynamic aperture with error @ Z



Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
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Crab waist sextupole
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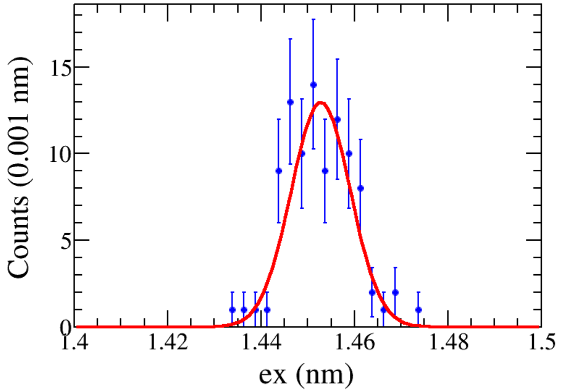
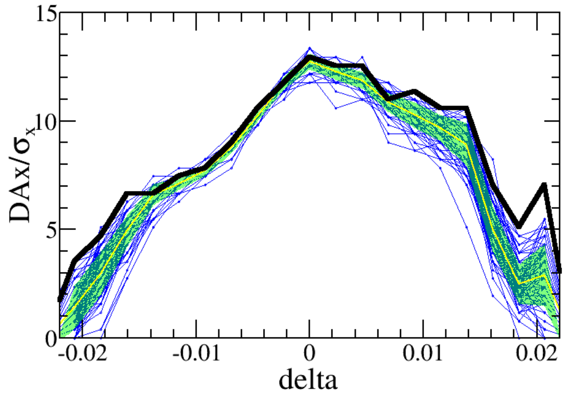
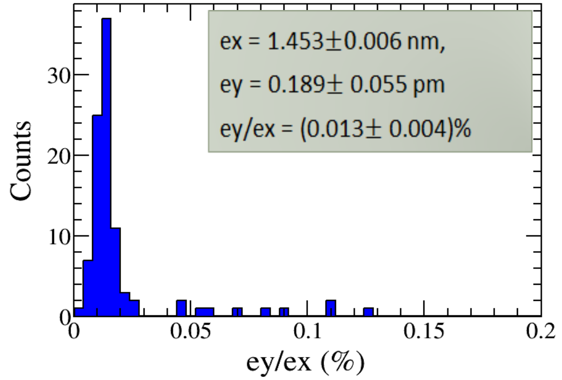
Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.02%
IR Quadrupole	0.10	0.10	0.10	0.02%
Sextupole	0.10*	0.10*	0.10	

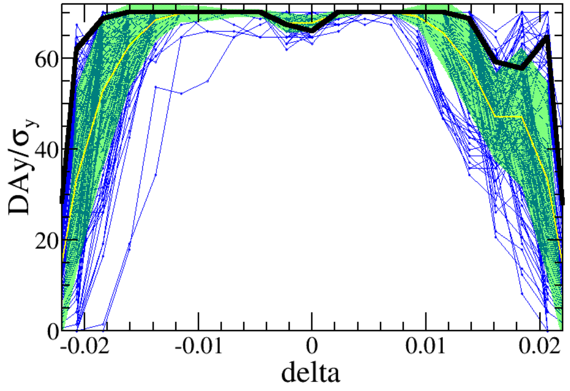
- The emittance coupling fulfill the requirement (<0.5%)
- All of 100 lattice seeds with errors are corrected.

Emittance and dynamic aperture with error @ ttbar









—w/o error

—mean value

—statistic errors

—seeds

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 (<0.34%)
- All of 100 lattice seeds with errors are corrected.

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	

Beam lifetime of lattice + beam beam+Beamstrahlung

Y. Zhang, Y. Wang, D. Wang, H. Geng, Z. Duan

- The beam lifetime including both beam-beam and lattice are optimized with large number of nonlinear knobs with algorithm of multi-objective differential evolution (MODE)#
- Further check of beam lifetime with bare lattice + beam beam (weak-strong) + beamstrahlung fulfill the requirements of the H/W/$t\bar{t}$ modes. Beam lifetime study of Z mode is on the way.

	ttbar	Higgs	W
Beam lifetime requirement for top-up injection [min]	18	18	21
Bhabha lifetime [min]	81	39	60
Required lattice + beambeam + beamstrahlung beam lifetime [min]	24	34	32
Simulated lattice + beambeam + beamstrahlung beam lifetime [min]	278	139	139
Crab sextupole strength [%]	49	80	80

#J. Wu, Y. Zhang, Q. Qin, Y. Wang, C. Yu, D. Zhou, NIMA 959 (2020) 163517.
J. Wu, Y. Zhang, Q. Qin, doi:10.18429/JACoW-IPAC2019-MOPGW051, IPAC19.
Y. Zhang et al, doi:10.18429/JACoW-eeFACT2018-TUYBA04, eeFACT2018.

Summary

- Lattice of the CEPC collider ring design fulfill the requirements of the parameters list, geometry and key hardware.
- Dynamic aperture w/ main errors for H/Z/$t\bar{t}$ modes achieve the requirements from the top-up injection. DA study of W mode is on the way.
  - Correction with more errors and the IR tuning are undergoing.
- Further check of beam lifetime with bare lattice + beam beam + beamstrahlung fulfill the requirements for the H/W/$t\bar{t}$ modes. Beam lifetime study of Z mode is on the way.

Backup