Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

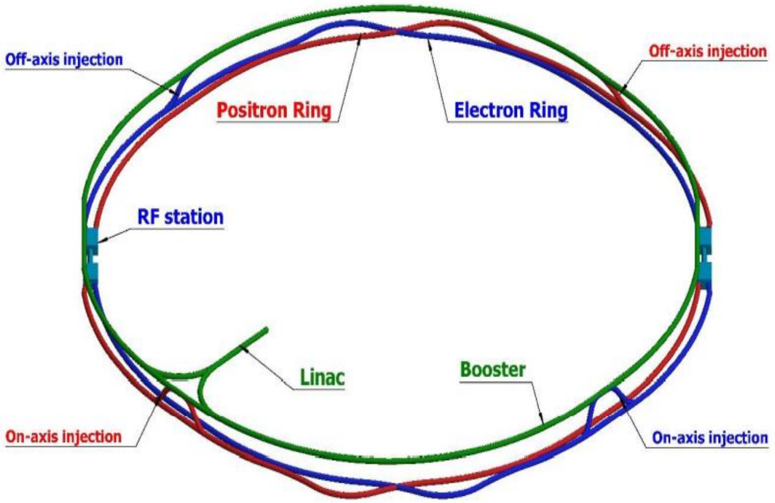
CEPC Collider ring lattice design

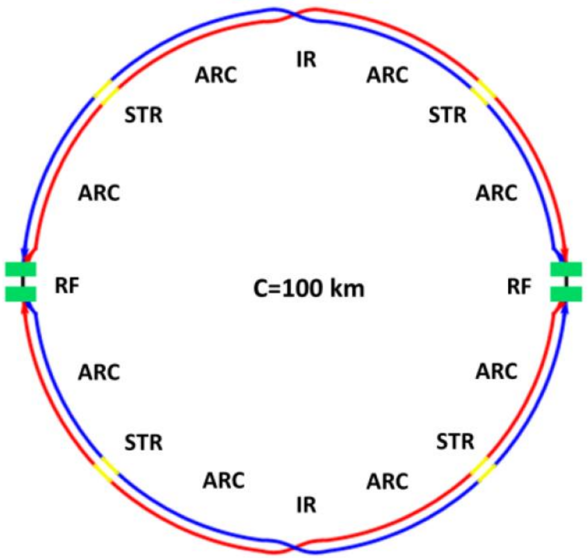
Yiwei Wang
for the CEPC Accelerator Physics Group
The Institute of High Energy Physics, Chinese Academy of Sciences

The 2022 International Workshop on the High Energy Circular Electron Positron Collider
24 Oct. 2022, IHEP, Beijing

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
  - on/off axis injection regions for different modes
  - beam dumping
- 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); A. Milanese, PRAB 19, 112401 (2016);

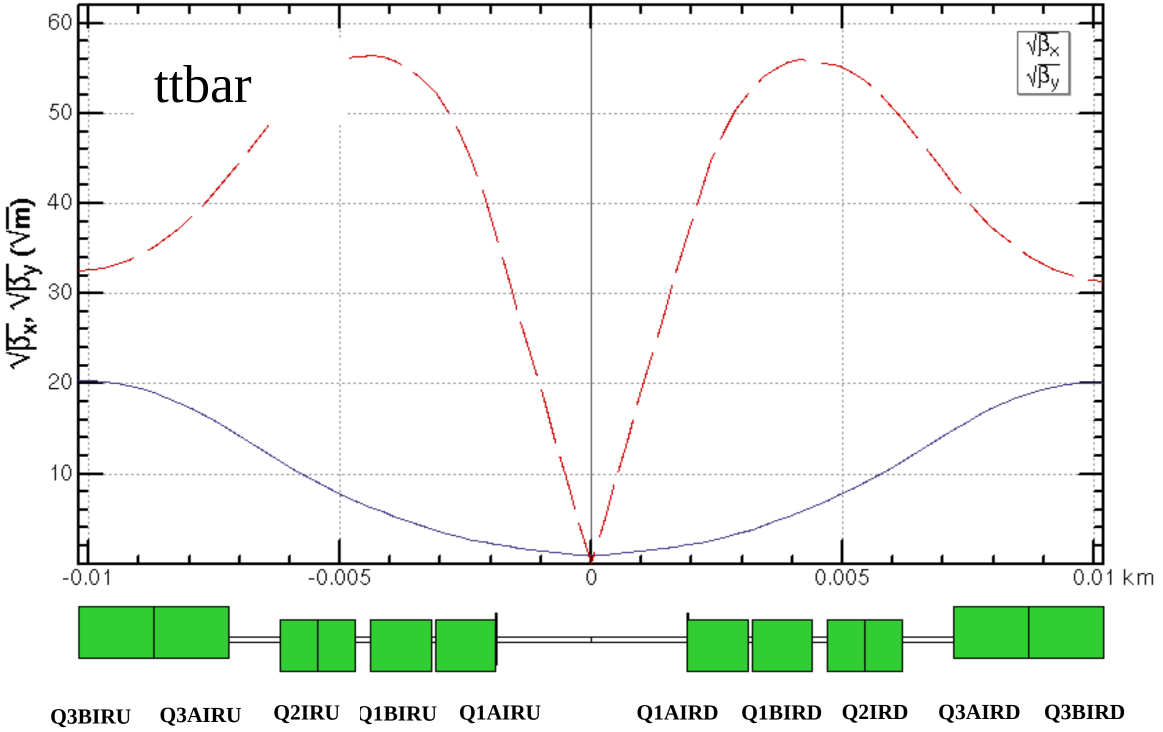
Machine parameters of CEPC

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

Interaction region for all modes

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



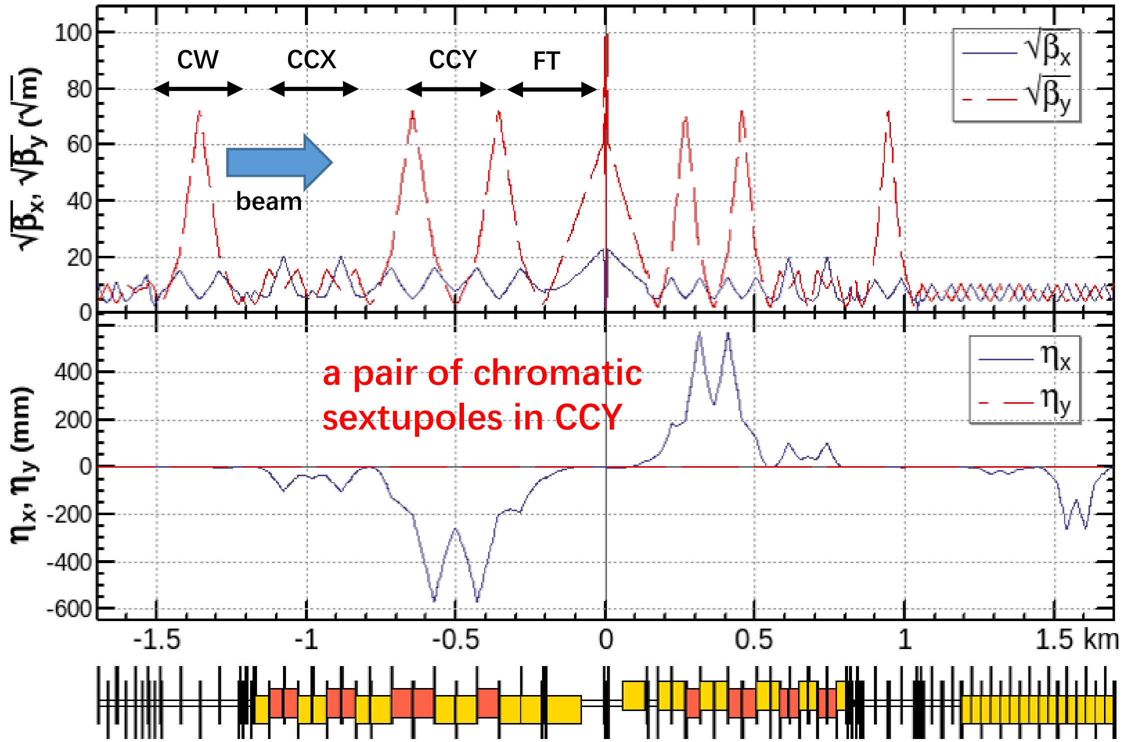
	L [m]	Strength [T/m]			
		ttbar	Higgs	W	Z
Q1AIRU	1.21	-141	-141	-94	-110
Q1BIRU	1.21	-59	-85	-56	+65
Q2IRU	1.5	-51	+95	+63	0
Q3AIRU	1.5	+40	0	0	+2
Q3BIRU	1.5	+40	0	0	+2
Q1AIRD	1.21	-142	-142	-95	-110
Q1BIRD	1.21	-64	-85	-57	+65
Q2IRD	1.5	-47	+96	+64	0
Q3AIRD	1.5	+40	0	0	+2
Q3BIRD	1.5	+40	0	0	+2

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

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

Interaction region for all modes (cont.)

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



	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

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

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

*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);

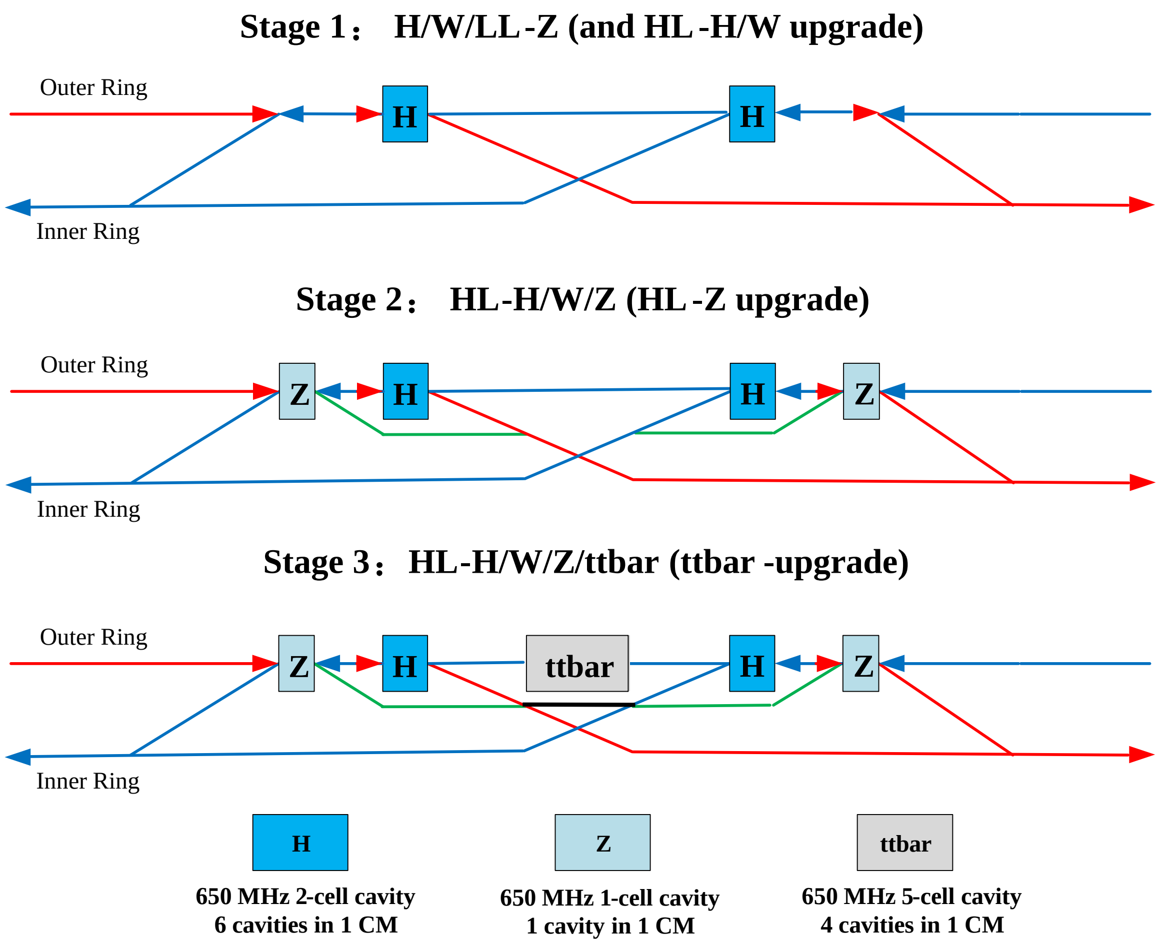
CEPC TDR New RF Layout

- Higgs first priority. And aiming for all modes seamless switching in whole project lifecycle without hardware movement
- Maximize performance and flexibility for future circular electron positron collider
- Add center connection line (short black line) for Higgs operation after ttbar upgrade. Need to check if the dipole SR light will hit the cavity after effective shielding

Peak luminosity at different stages with SR power **up to 50MW/beam**

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

more details in Jiyuan ZHAI, CEPC SRF system design and R&D progress, 16:40 - 17:00, 25 Sep 2022



*not fully implemented in the lattice yet

ARC region for all modes

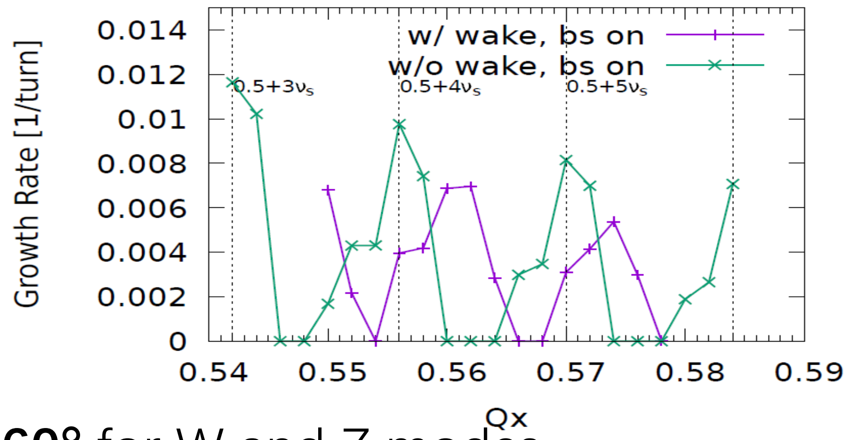
- Z and W modes need larger momentum compaction factor αp and thus larger emittance εx, Qs
  - To suppress the impedance induced instability at Z mode
  - To increase stable tune area if considering beam-beam effect and impedance consistently at W and Z modes

Microwave instability

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

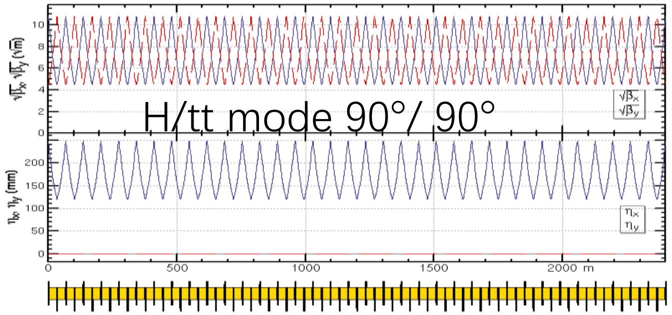
Na Wang,
CEPC Day, March 2020

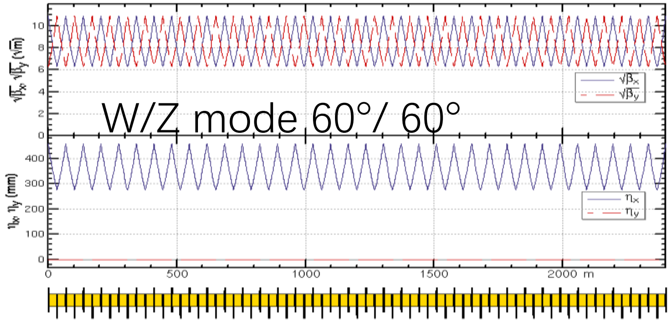
stable tune area with both beam-beam and impedance (Z mode 90/90)



Yuan Zhang

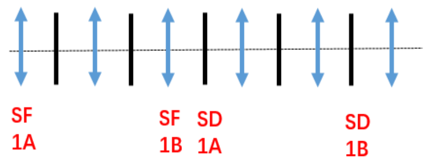
- **Phase advance reduced from 90° to 60°** for W and Z modes



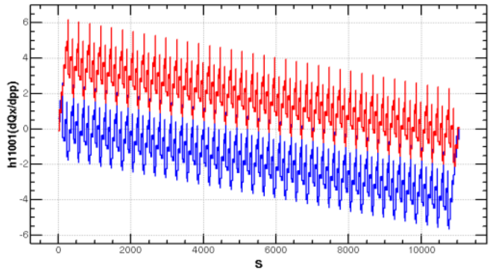


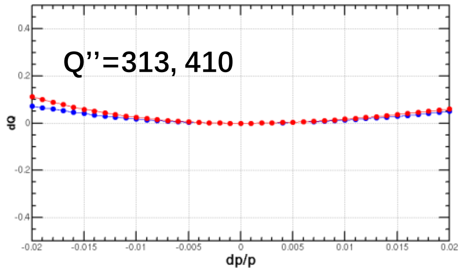
Optimization of ARC aberration for Higgs/ttbar modes

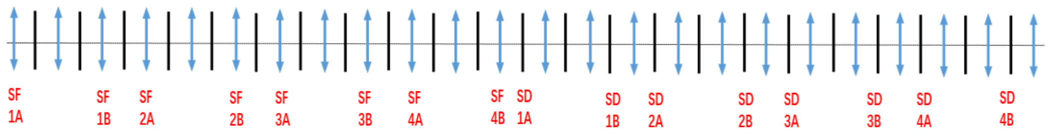
- 2^{nd} order chromaticity is a main aberration for the optimization of momentum acceptance with **one –I sextupole pair scheme**.
    - In previous versions, 2^{nd} order chromaticity generated in the ARC region are corrected with IR knobs (phase advance or K1).
    - However, the IR knobs will generate 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



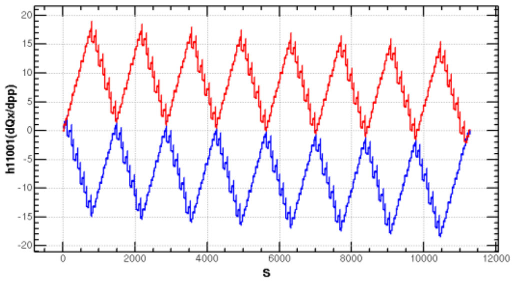
Scheme with **one –I sextupole pair**
Proposed by K. Oide

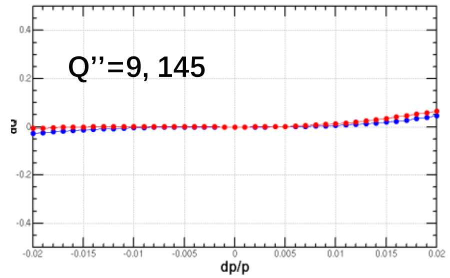






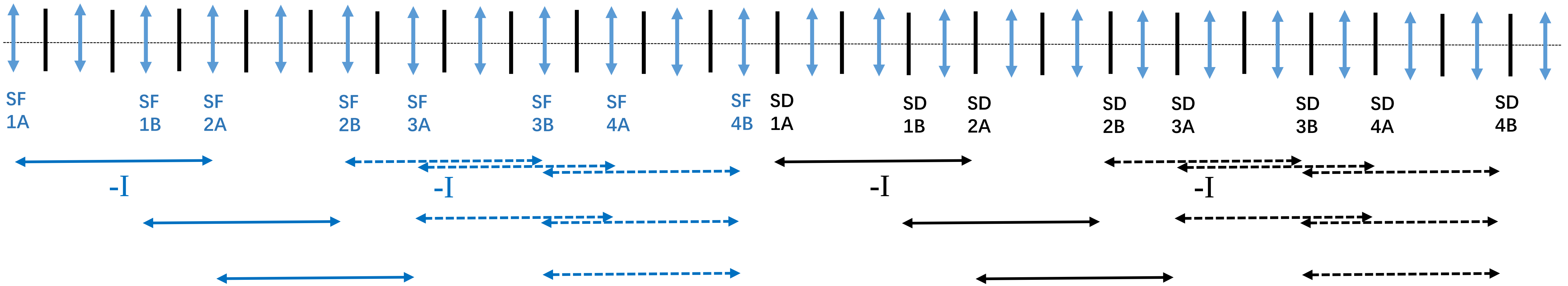
Scheme with **four –I sextupole pairs**
Proposed by Tianjian Bian





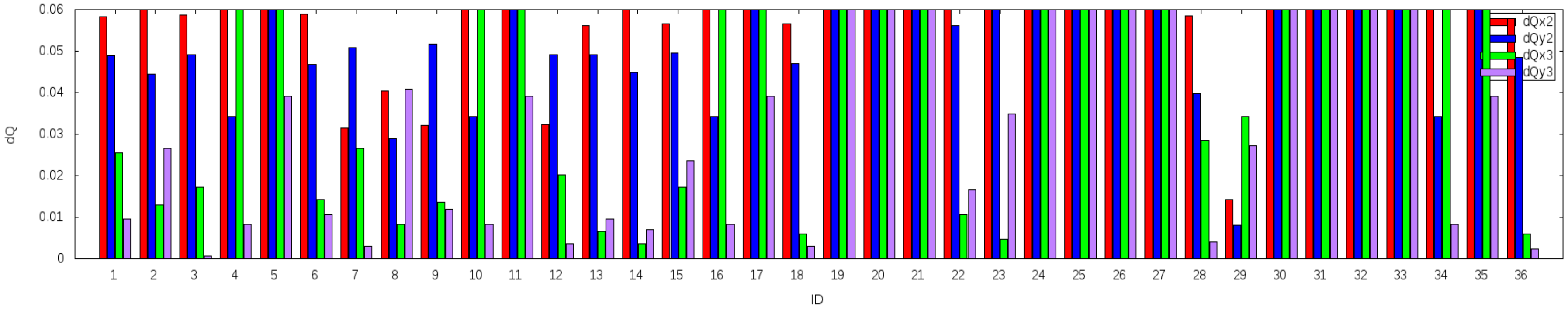
Optimization of ARC aberration for W/Z modes

- 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)



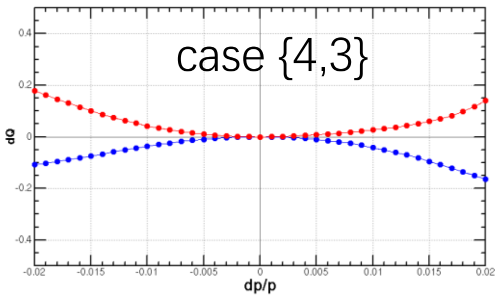
1st pair	2nd pair		
(1A, 2A)	(2B,3B)	(3A,4A)	(3B,4B)
(1B, 2B)	-	(3A,4A)	(3B,4B)
(2A, 3A)	-	-	(3B,4B)

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

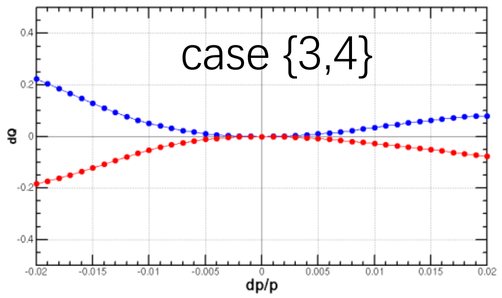


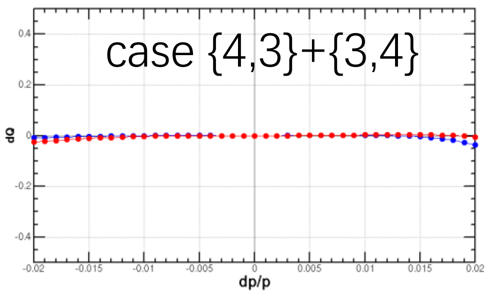
Optimization of ARC aberration for Z/W modes (cont.)

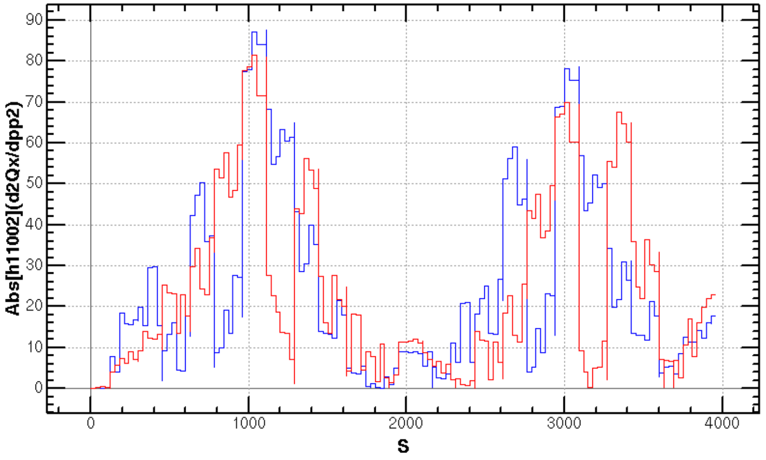
- Cancellation of main aberration has period of 23*3 cells.

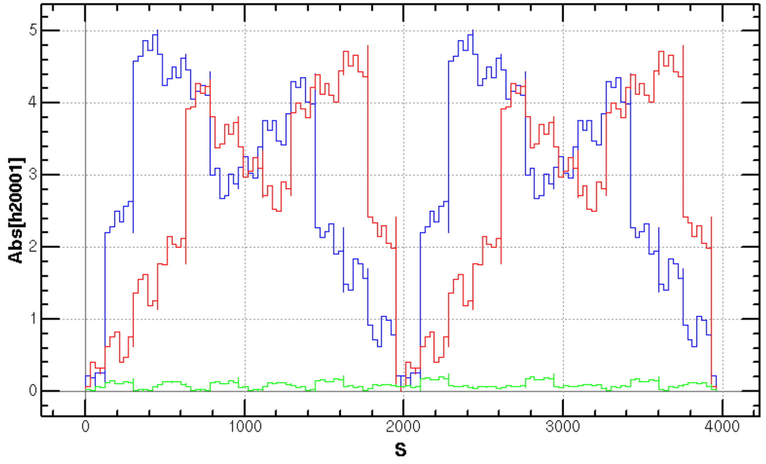


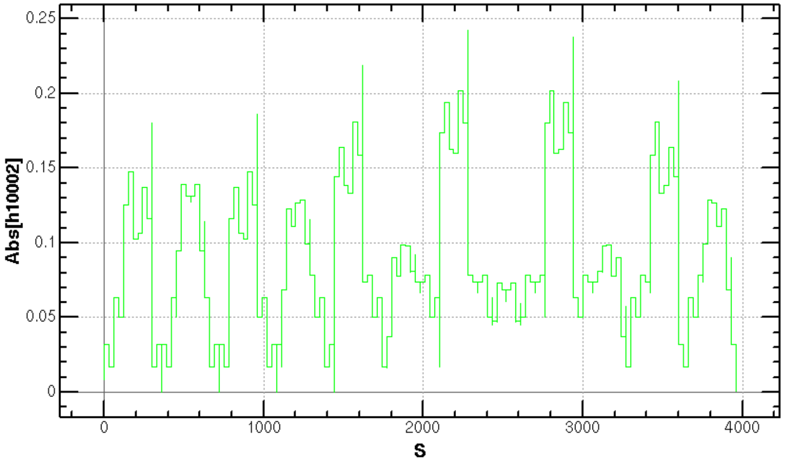
+

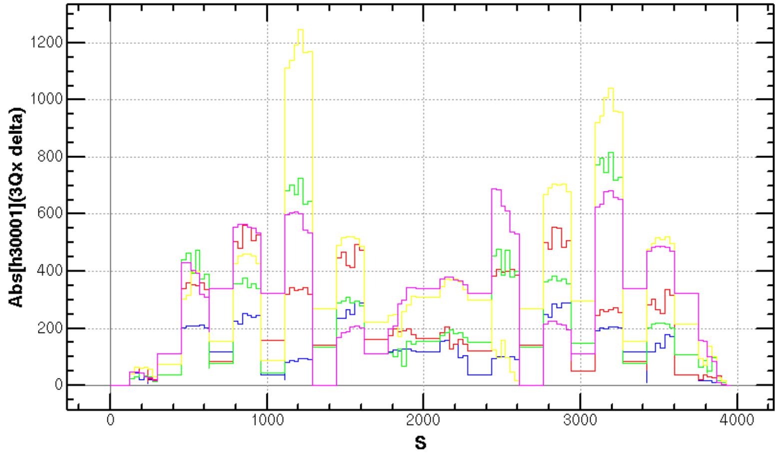




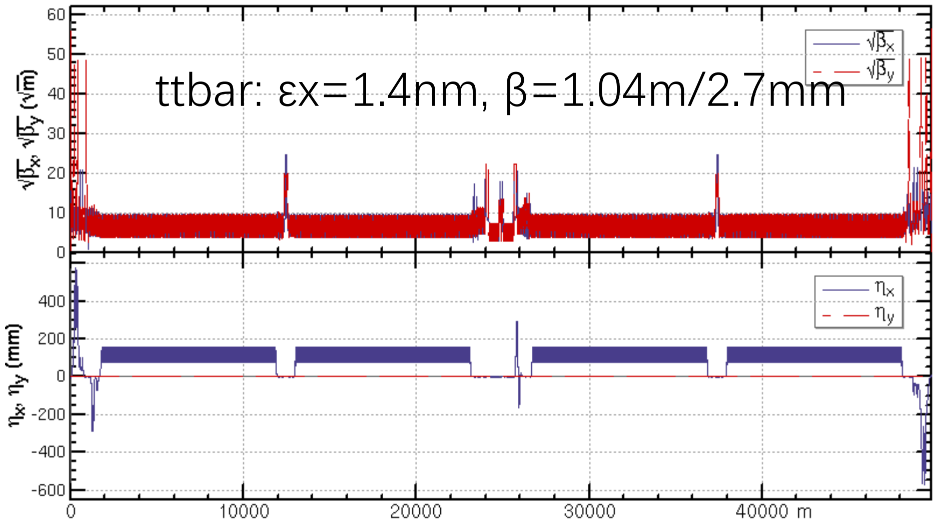


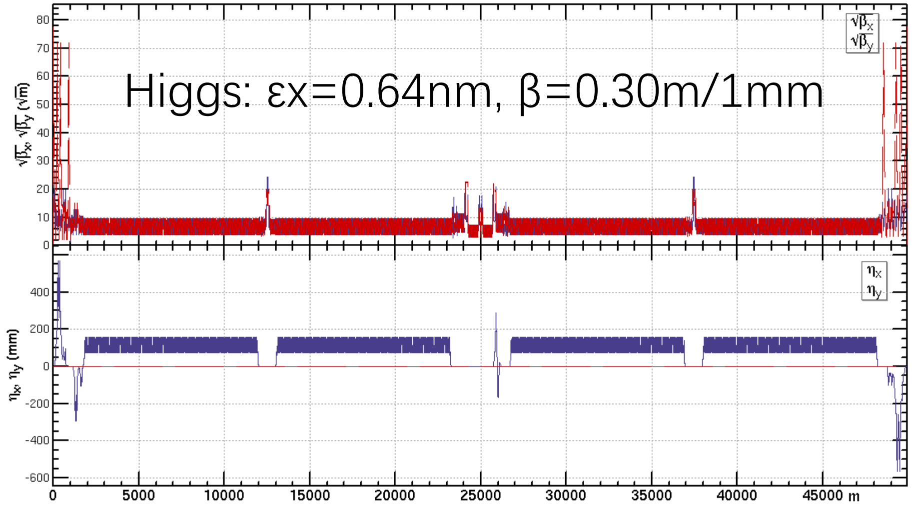


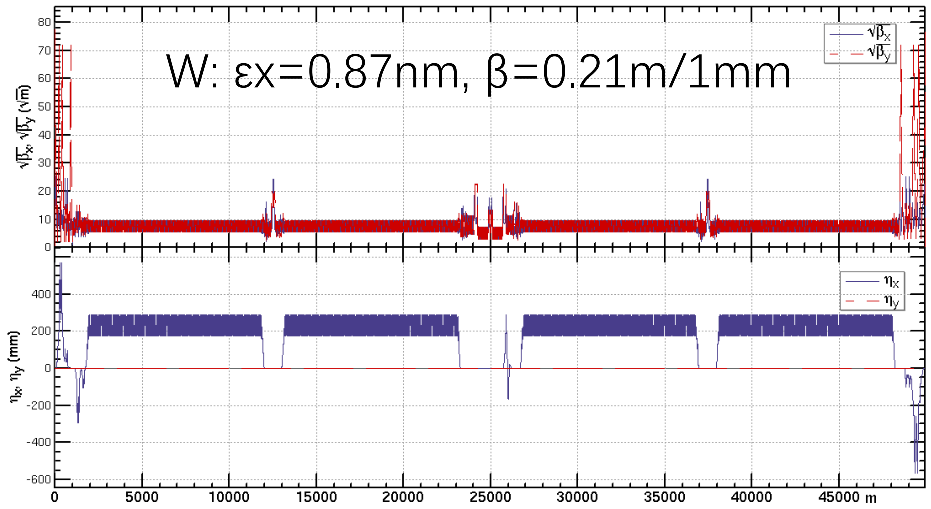


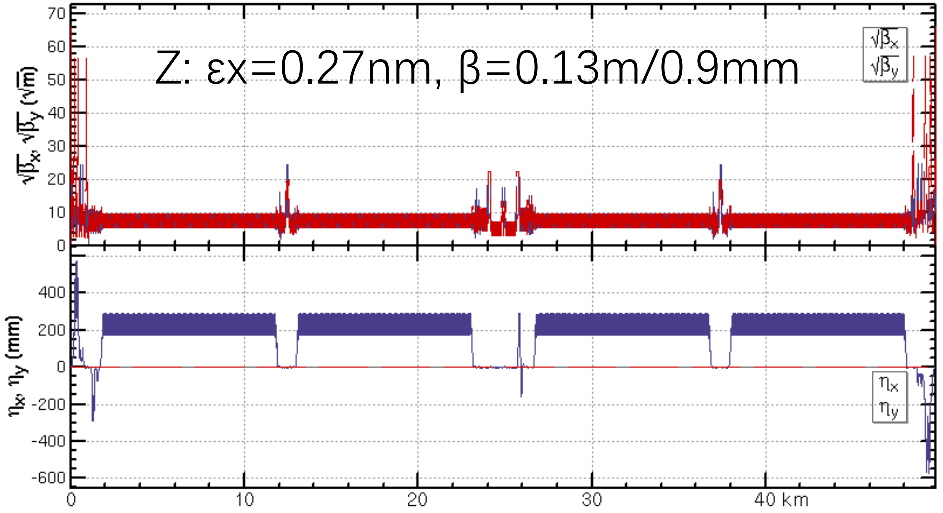


Lattice of half ring









Dynamic aperture requirement

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

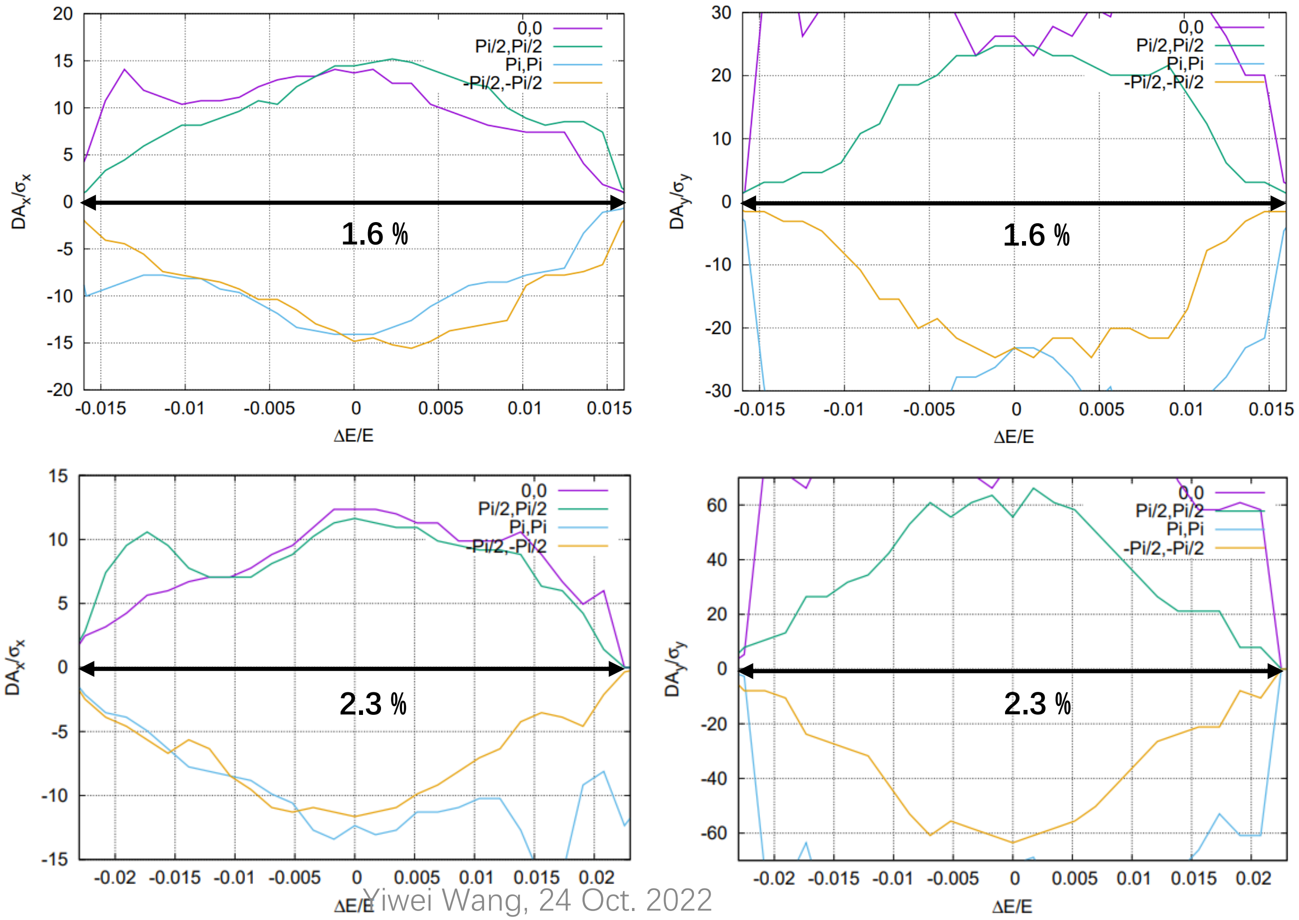
	ttbar	Higgs	W	Z
Horizontal Emittance in collider/booster [nm]	1.4 / 2.83	0.64 / 1.26	0.87 / 0.56	0.27 / 0.19
DA requirement from injection	$13.9\ \sigma_x \times 7\ \sigma_y$ off axis	$14.4\ \sigma_x \times 7\ \sigma_y$ off axis $7\ \sigma_x \times 7\ \sigma_y$ on axis	$10.5\ \sigma_x \times 5\ \sigma_y$ 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	1.7	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



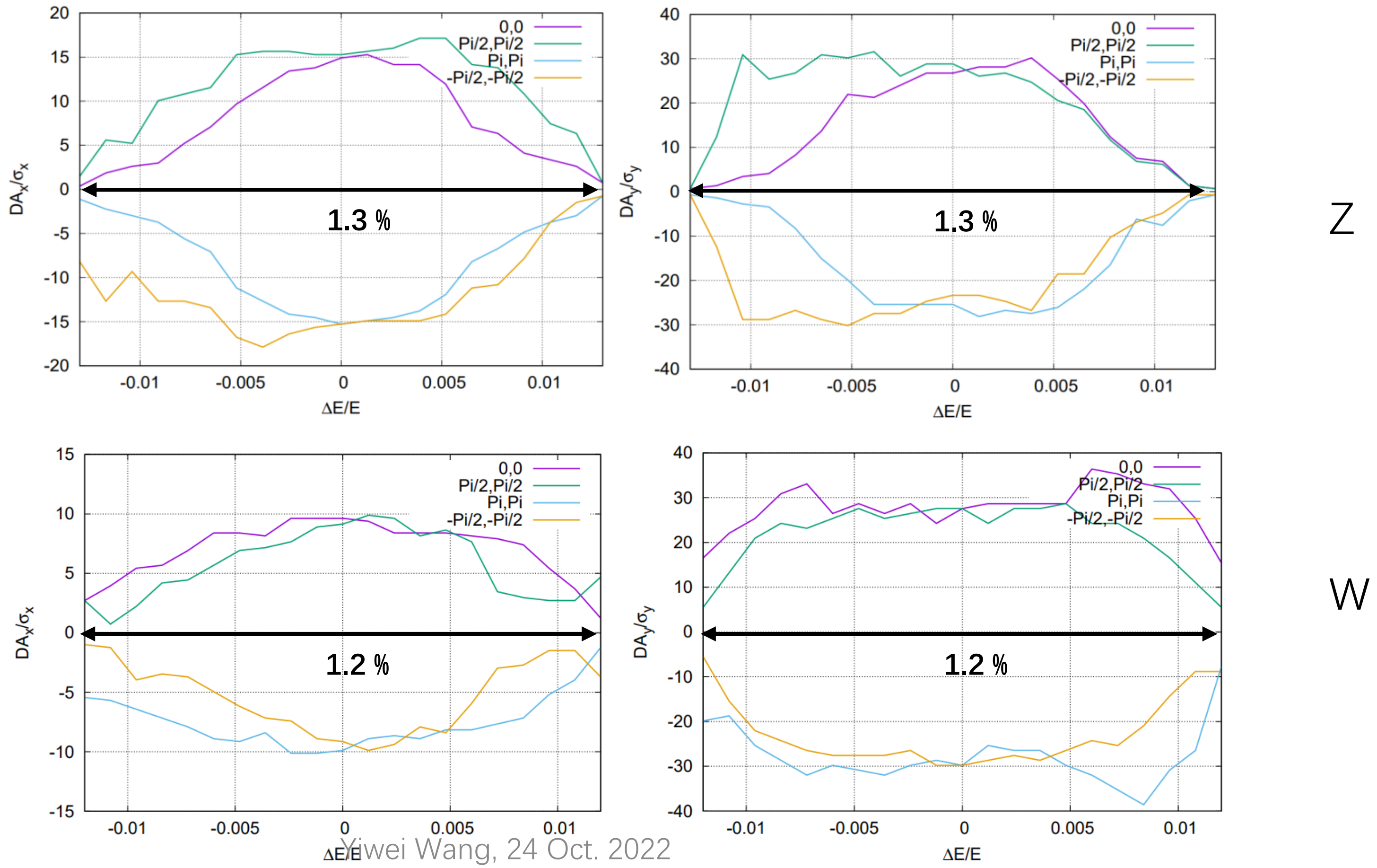
Higgs

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



Dynamic aperture with errors @ Higgs

by B. Wang, Y. Y. Wei, Y. W. Wang

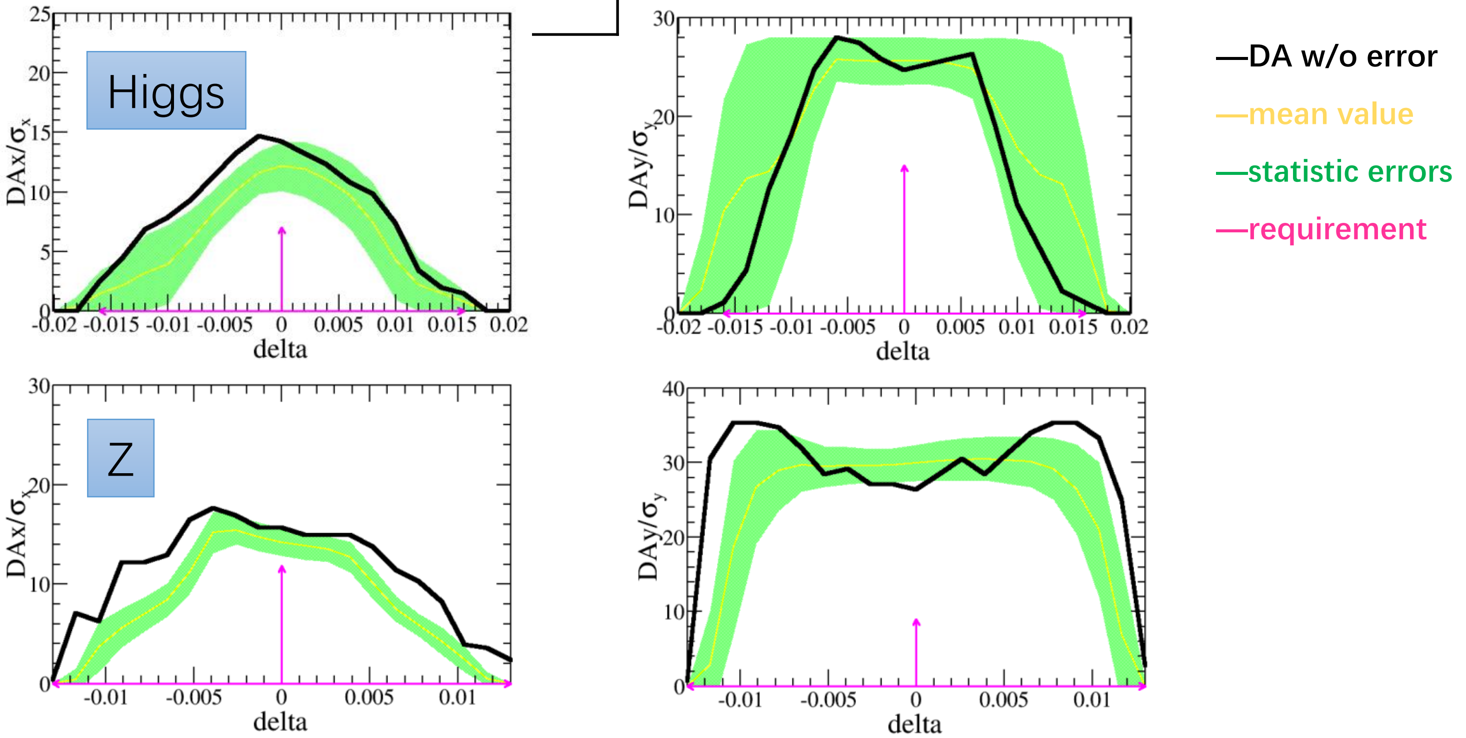
more details in Bin Wang, Orbit correction and error analysis, 10:40 - 11:00, 24 Sep 2022

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*			

*reduced to 10 um with movers

w/o misalignment of the girder, main field errors of the sextupole

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



- ...ttices with errors are corrected for Higgs and Z respectively.
- The DA with error correction are tracked and satisfy the on-axis injection requirement.

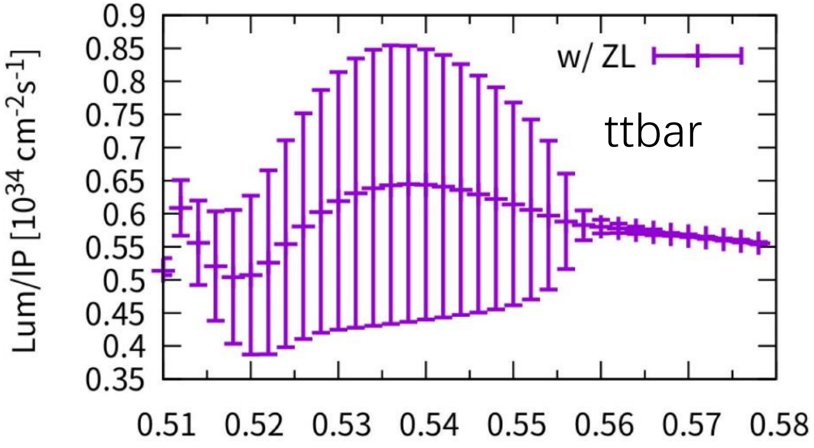
Summary

- 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: New aberration correction scheme in ARC region. 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.
- Dynamic aperture w/ main errors for Higgs and Z modes achieve the requirements.

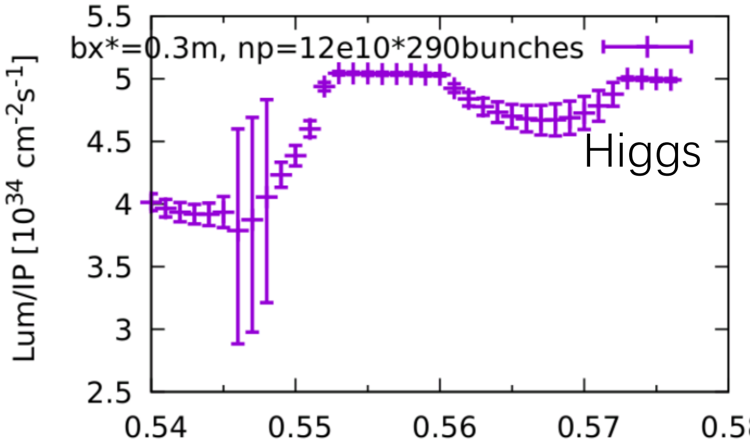
backup

CEPC TDR parameter luminosity checked by beam-beam simulations

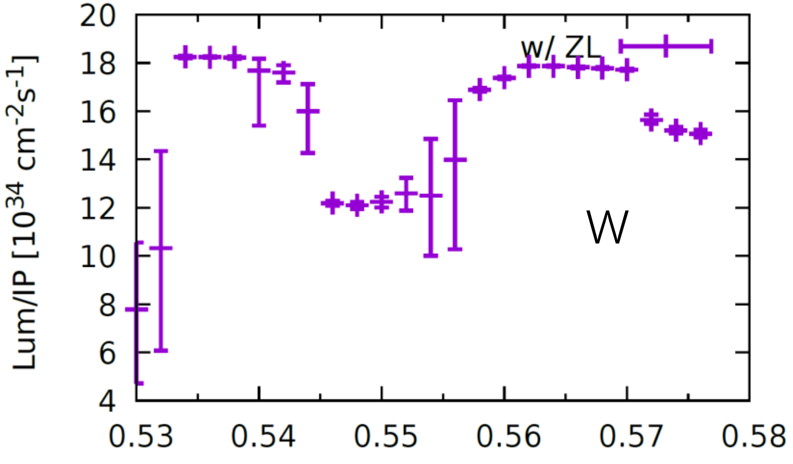
Y. Zhang



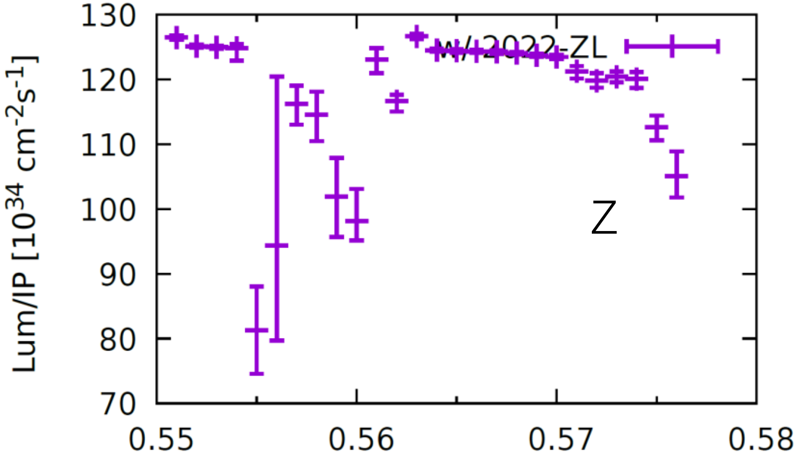
ttbar: 0.55* 10^34/cm^2/s (BB Simulation)
Parameter table:0.5*10^34/cm^2/s



Higgs : 5*10^34/cm^2/s (BB Simulation)
Parameter table:5*10^34/cm^2/s



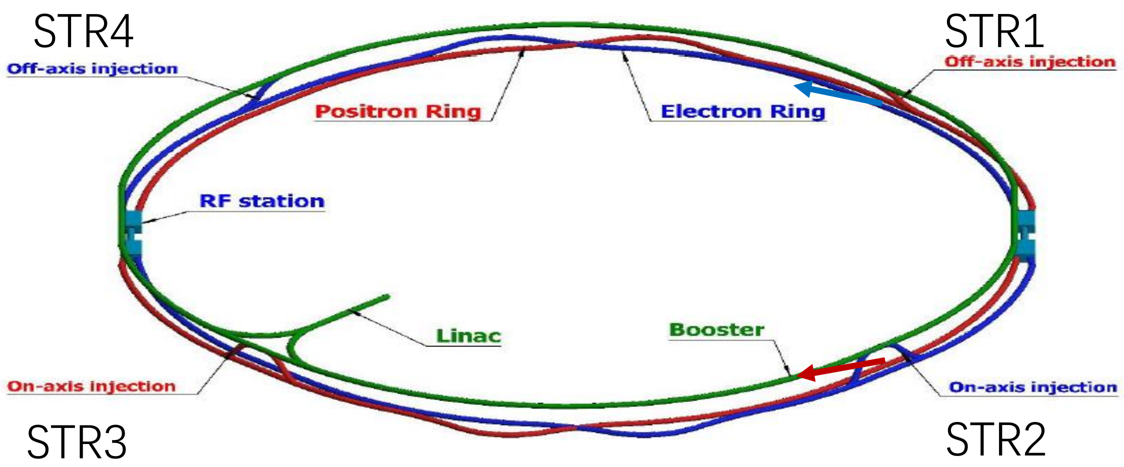
W-pole : 18*10^34/cm^2/s(BB Simulation)
Parameter table:16*10^34/cm^2/s

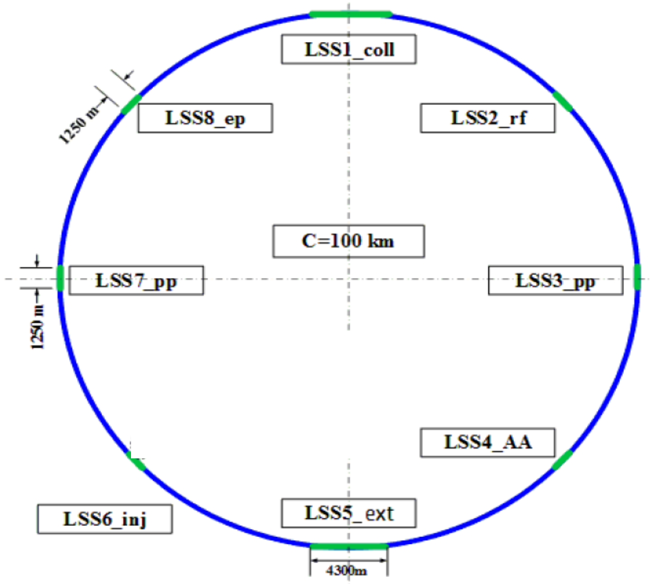


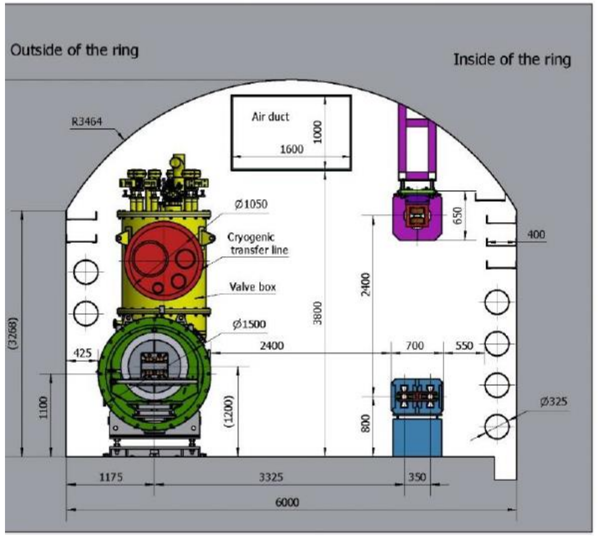
Z-pole : 125*10^34/cm^2/s (BB Simulation)
Parameter table:115*10^34/cm^2/s

Location of the dumping system

- Dumping system for collider ring
  - Seems not necessary to be close to IP
    - **Active machine protection** for the beam loss with time larger than **multi turns**
  - Located at **STR1 and STR2** or STR2 and STR3
    - At least one dump for each collider ring
    - STR4 for future option of ep collision
  - **Inner side of tunnel**
    - SPPC will locates outer side of CEPC
    - Maintenance of the dump
- Dumping system for booster ring
  - Low charge bunches can be dumped by collimator
  - Dumping for bunches of on axis injection can **share the dump with collider ring**







Layout of dumping system

- The layout near off-axis injection region