Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

CEPC collider ring lattice design for the high luminosity scheme

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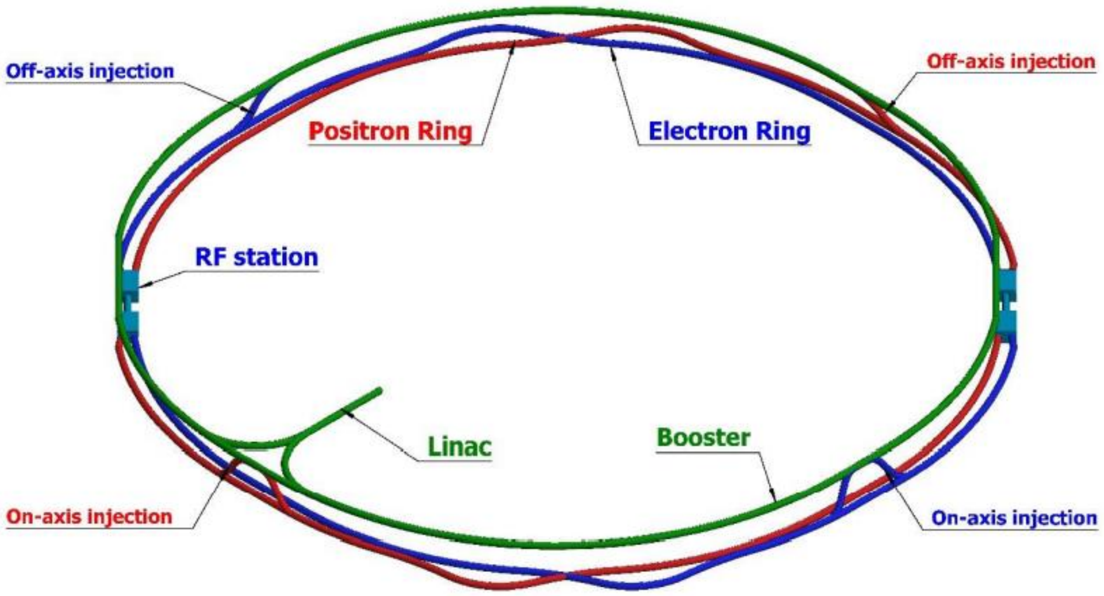
Design requirement of the CEPC collider ring

- SR power 30MW (50 MW upgradable), 100km, 2 IPs
- Crab waist collision
- Local chromaticity correction for the interaction region
- Non-interleaved sextupoles
- Correction of sawtooth orbit
- Shared cavities for two beam @ tt, Higgs
- Dual aperture dipole and quadrupole magnets
- Spin polarized beam @ Z
- Asymmetric interaction region
- Compatible of $t\bar{t}$/H/W/Z modes
- Compatible with SPPC

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



Key parameters of high luminosity scheme

C. Yu, Y. W. Wang, Y. Zhang, S. Bai, Y. Zhu, D. Wang, J. Gao et al

Key parameters of CDR scheme for Higgs

- **L*=2.2m, θc=33mrad, βx*=0.36m, βy*=1.5mm, Emittance=1.2nm**
  - Strength requirements of anti-solenoids B_z~7.2T
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 136T/m)

Key parameters of high luminosity scheme for Higgs

- **L*=1.9m, θc=33mrad, βx*=0.33m, βy*=1.0mm, Emittance=0.64nm**
  - Strength requirements of anti-solenoids B_z~7.2T (6.8T with a shorter solenoid)
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 141T/m) with room temperature vacuum chamber & Iron yoke

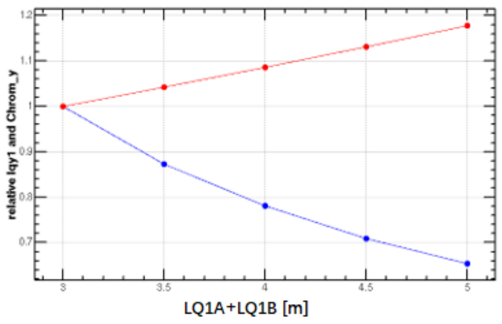
Reduction of the length from IP to 1st quadrupole **without changing the front-end position of the FD cryo-module**

- To make the lattice robust and provide good start point for DA

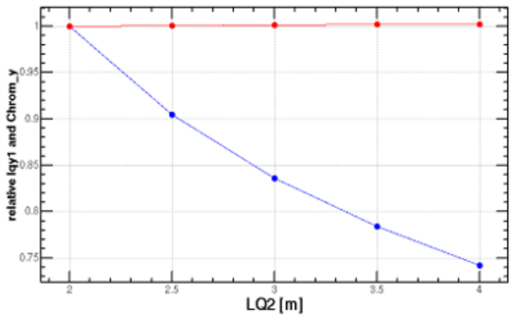
Optimization of final doublet design for Higgs

- CEPC is mainly optimized at Higgs energy. The final doublet design was mainly optimized for Higgs.
  - Status of the FD @ Higgs： L*=1.9m, LQ1=2.5m, LQ2=1.5m, d=0.3m, KQ1A=142T/m, KQ1B=85T/m, KQ2=96T/m
    - Minimum of radiation power occurs at KQ1B/KQ1A≈0.6
    - Strength, length of Q1, Q2 and their distance are mainly constrained by superconducting, mechanical installation, vacuum technologies in the MDI.

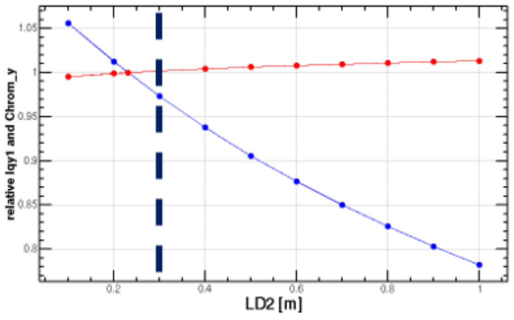
Length of Q1



Length of Q2



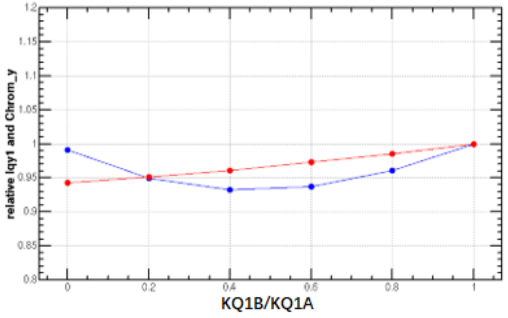
Distance of Q1 and Q2



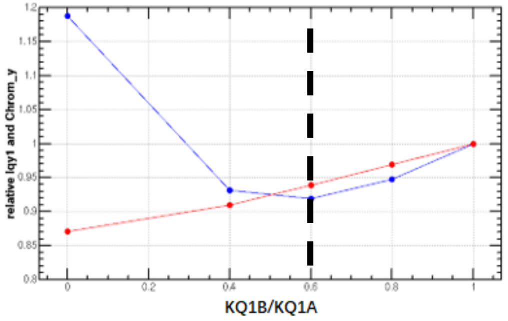
—relative chromaticity on y plane
—relative radiation power on y plane

Different **strength ratio of Q1A and Q1B**
Different **length ratio of Q1A and Q1B** when keep total length of Q1A+Q1B

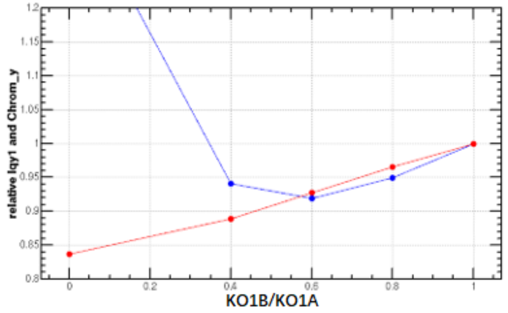
LQ1B/LQ1A=0.36



LQ1B/LQ1A=1



LQ1B/LQ1A=1.5

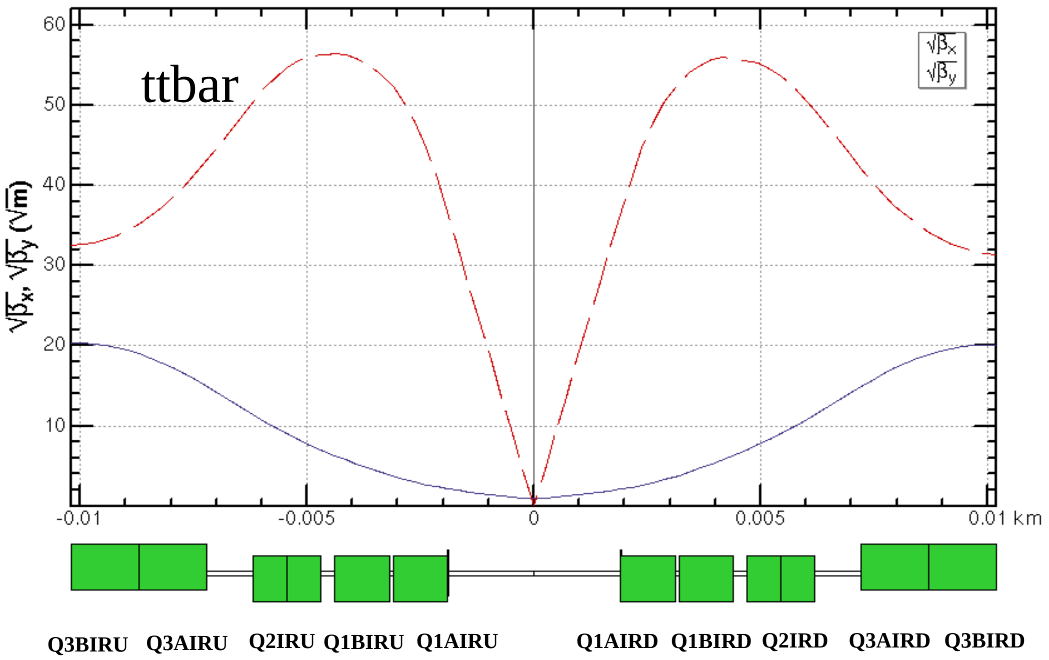


- Minimum of radiation power occurs at **KQ1B/KQ1A≈0.6**
- Different length of Q1A and Q1B doesn't affect much on the minimum of the power and chromaticity. This provides more freedom of the FD technical design.

Interaction region for all modes

- For the interaction region, the IP beta functions are refitted with the different combination of final doulets and the matching quadruples.

*ref: FCC-ee CDR



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

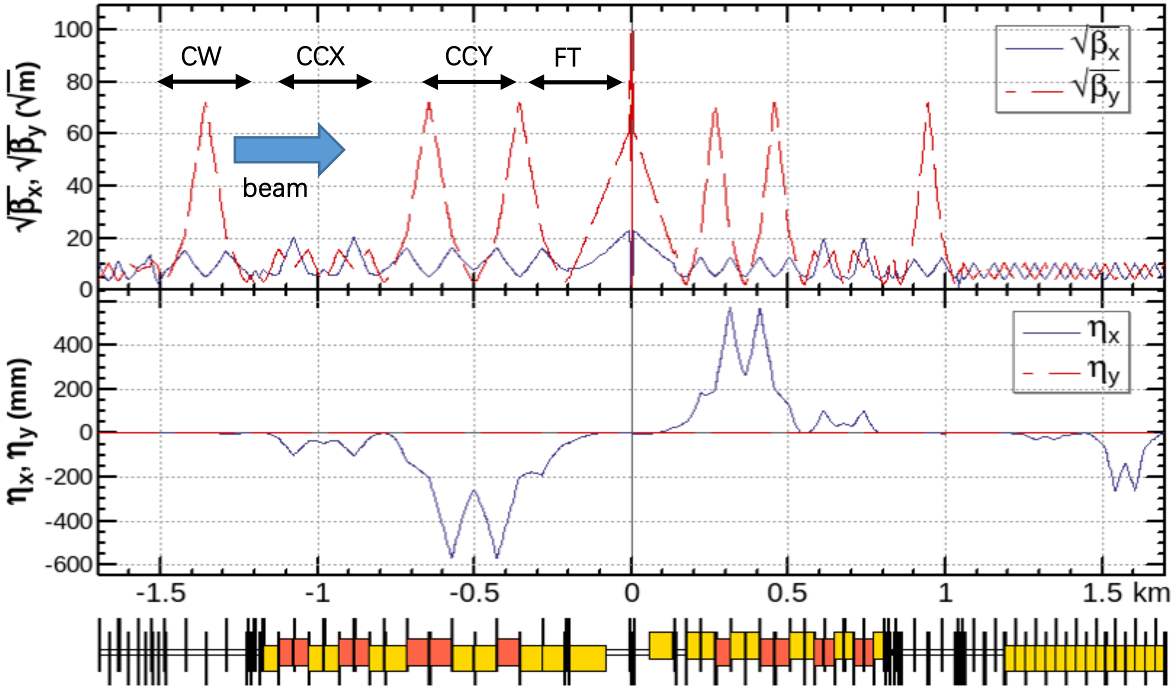
	L [m]	Strength [T/m]			
		ttbar	Higgs	W	Z
Q1AIRU	1.21	-141	-141	-94	-110
Q1BIRU	1.21	-59	-85	-56	+65
Q2IRU	1.5	-51	+95	+63	0
Q3AIRU	1.5	+40	0	0	+2
Q3BIRU	1.5	+40	0	0	+2
Q1AIRD	1.21	-142	-142	-95	-110
Q1BIRD	1.21	-64	-85	-57	+65
Q2IRD	1.5	-47	+96	+64	0
Q3AIRD	1.5	+40	0	0	+2
Q3BIRD	1.5	+40	0	0	+2

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

Interaction region for all modes (cont.)

- For the interaction region, the IP beta functions are refitted with the different combination of final doulets and the matching quadruples.

*ref: FCC-ee CDR

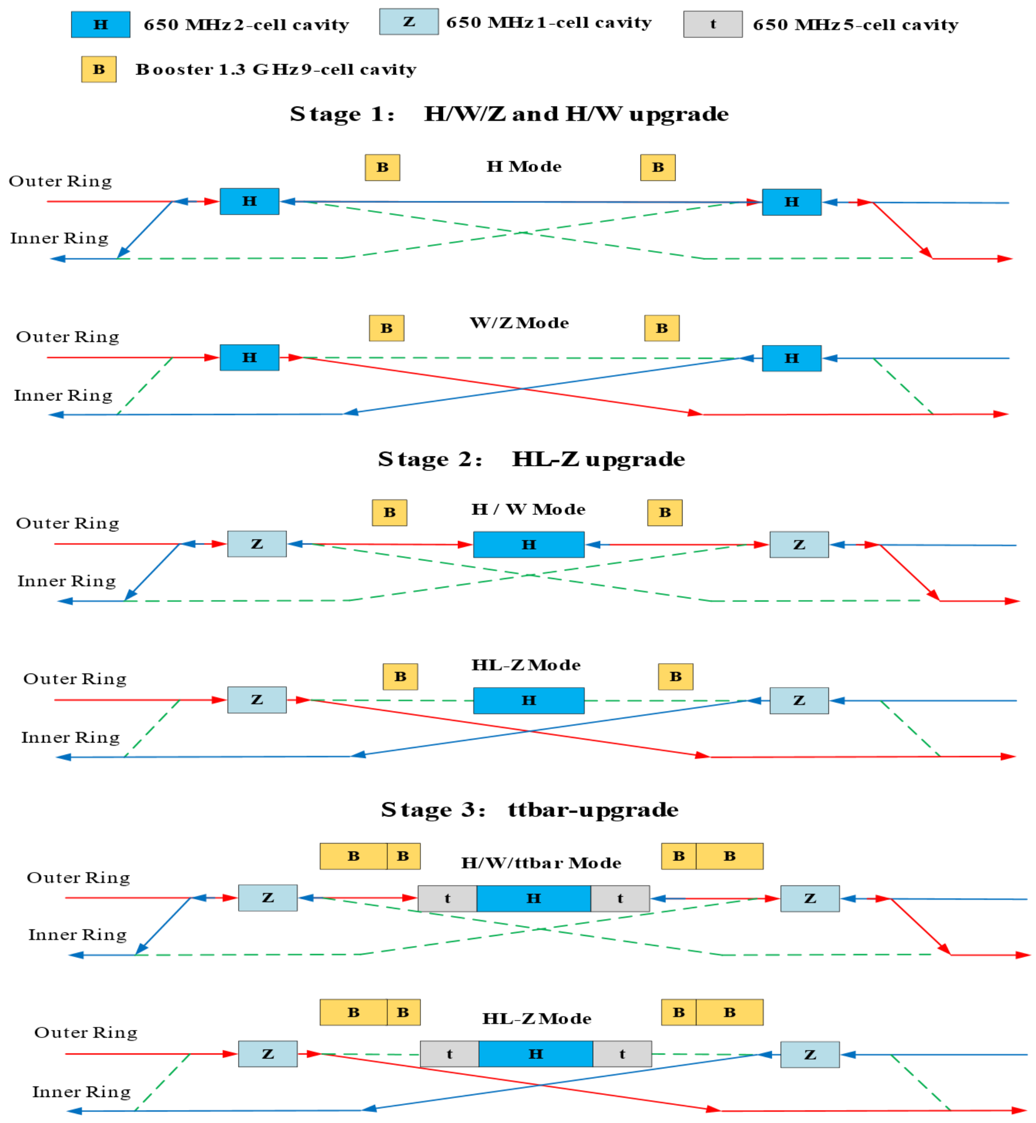


	QD	QF
Z	Q1A	Q1B
W/H	Q1A+Q1B	Q2
ttbar	Q1A+Q1B+Q2	add quad Q3A and Q3B

	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.

RF staging for compatible modes



by J. Y. Zhai, Yiwei Wang

- 1st priority of the Higgs running and flexible switching
- Low cost at early stage
- Get high luminosity for all modes

Stage 1 (H/W run)

- Layout and parameters are same with CDR except longer central part
- Medium or low luminosity at Z

Stage 2 (HL-Z upgrade)

- **Move Higgs cavities to center and add high current Z cavities.**
- **By-pass low current H cavities.**

Stage 3(ttbar upgrade):

- Add ttbar cavities (low current, high gradient, high Q)
- Nb3Sn@4.2 K or others to significant reducing the cost of cryo-system and AC power.

ARC region for all modes

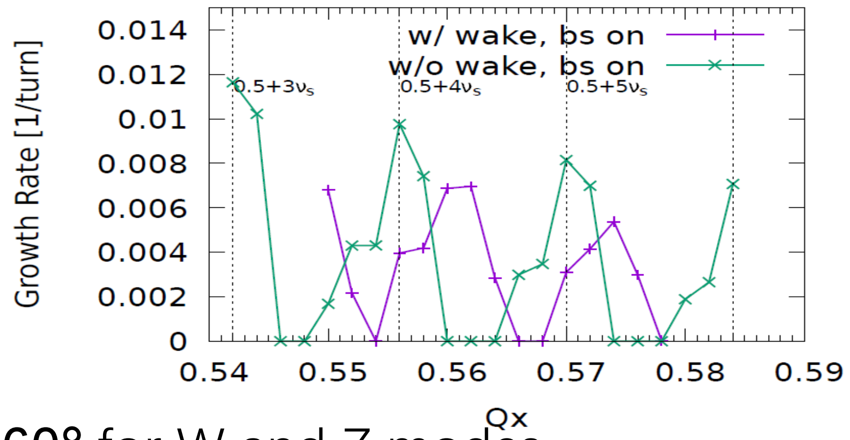
- Z and W modes need larger momentum compaction factor αp and thus larger emittance εx, Qs
  - To suppress the impedance induced instability at Z mode
  - To increase stable tune area if considering beam-beam effect and impedance consistently at W and Z modes

Microwave instability

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

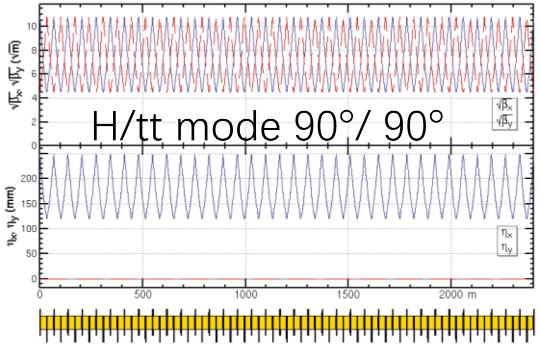
Na Wang,
CEPC Day, March 2020

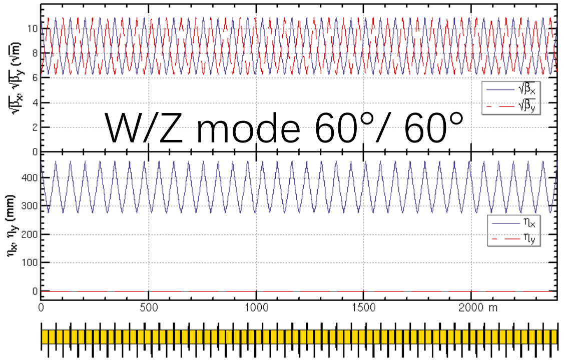
stable tune area with both beam-beam and impedance (Z mode 90/90)



Yuan Zhang

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





Status of beam parameters

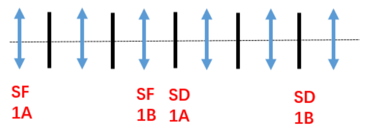
	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch spacing [ns]	4524	636	257	25 (10% gap)
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Longitudinal tune Qs	0.078	0.049	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	39/40	60/700	80/18000
Beam lifetime [min]	18	20	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

Y.W. Wang, D. Wang, Y. Zhang, J. Y. zhai, S.Bai, Y.D. Liu, N. Wang, C. X. Cui, C.H. Yu, J. Gao et al

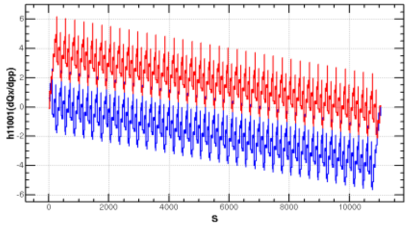
*Yiwei Wang et al, IPAC21, WEPAB033

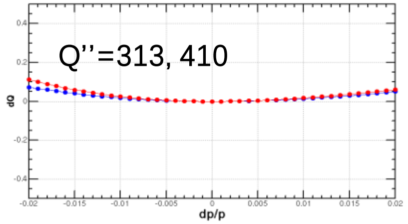
Optimization of the ARC aberration at ttbar and Higgs modes

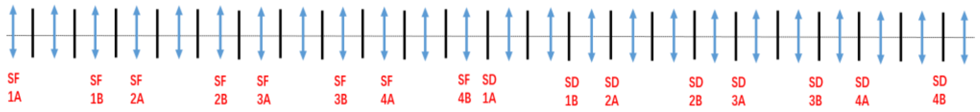
- 2nd order chromaticity is a main aberration for the optimization of momentum acceptance with **2-repeated sextupole scheme**.
  - In previous versions, 2nd order chromaticity generated in the ARC region are corrected with IR knobs (phase advance or K1).
  - However, the IR knobs will generate distortions at IP (beta, alfa and dispersion) **especially for the horizontal plane**.
- A lattice with **8-repeated sextupoles scheme**
  - much less 2nd order chromaticity for the horizontal plane



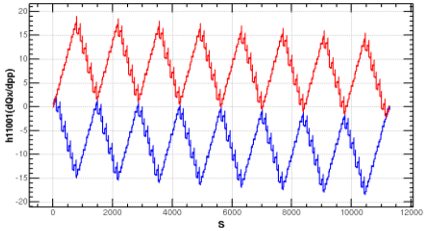
Scheme with **2 repeated sextupoles**
Proposed by K. Oide

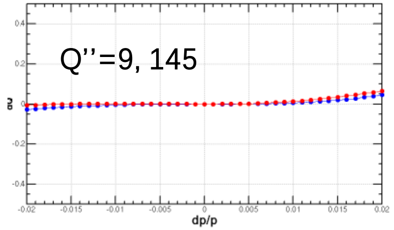






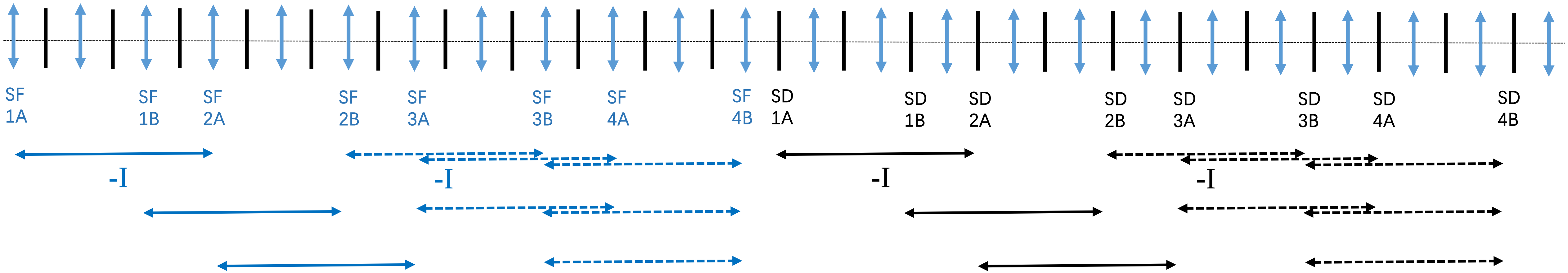
Scheme with **8 repeated sextupoles**
Proposed by Tianjian Bian



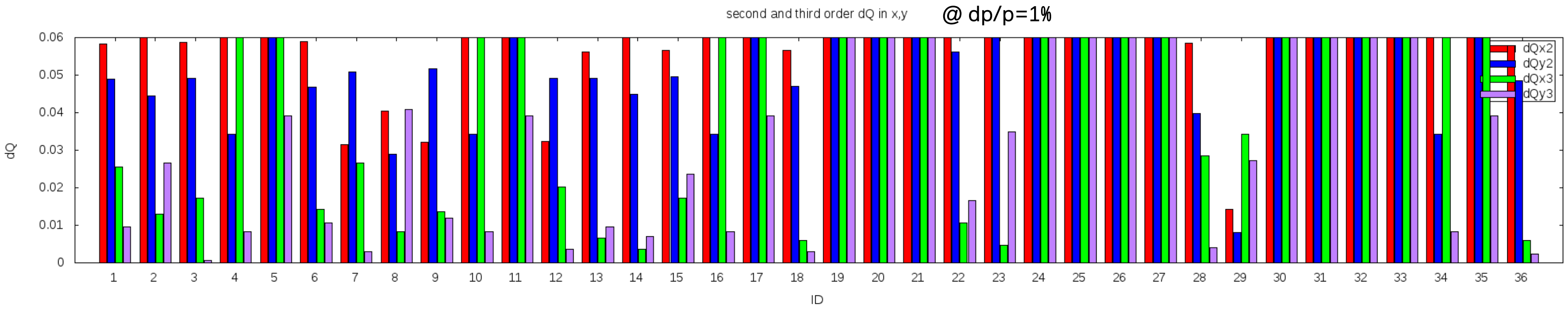


Optimization of the ARC aberration at W and Z modes

- 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)

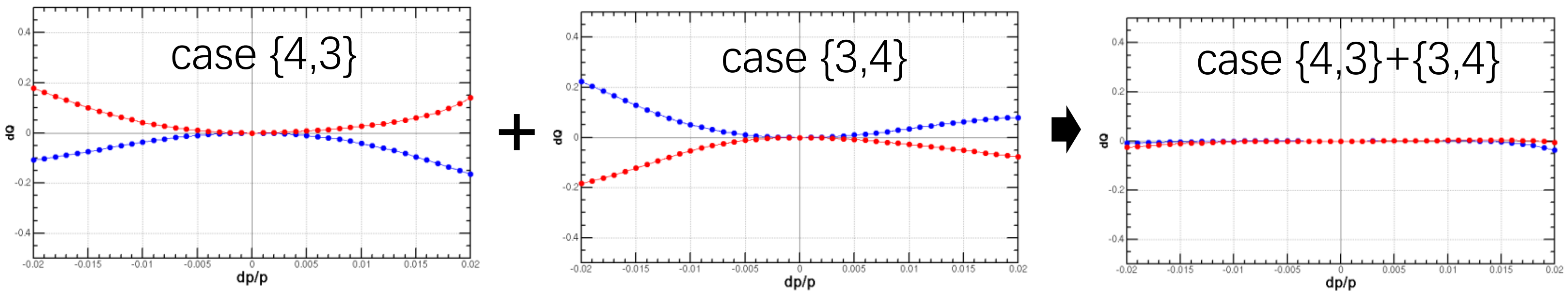


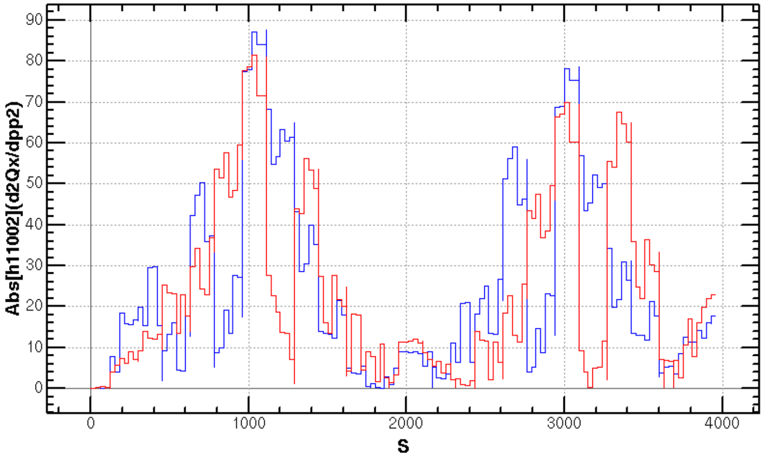
1st pair	2nd pair		
(1A, 2A)	(2B,3B)	(3A,4A)	(3B,4B)
(1B, 2B)	-	(3A,4A)	(3B,4B)
(2A, 3A)	-	-	(3B,4B)

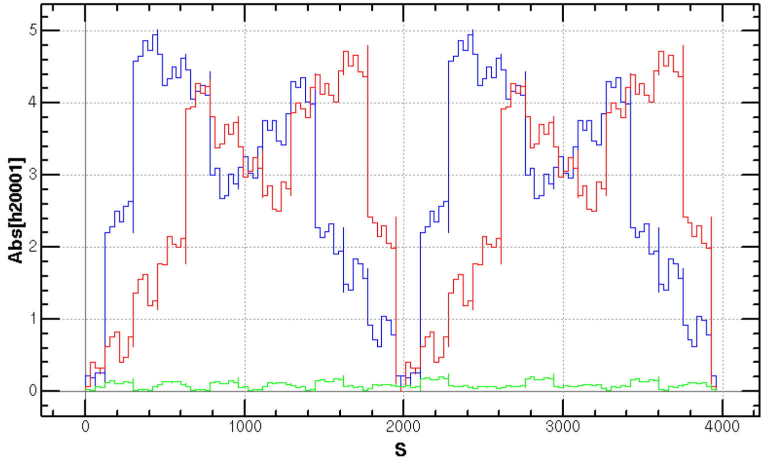


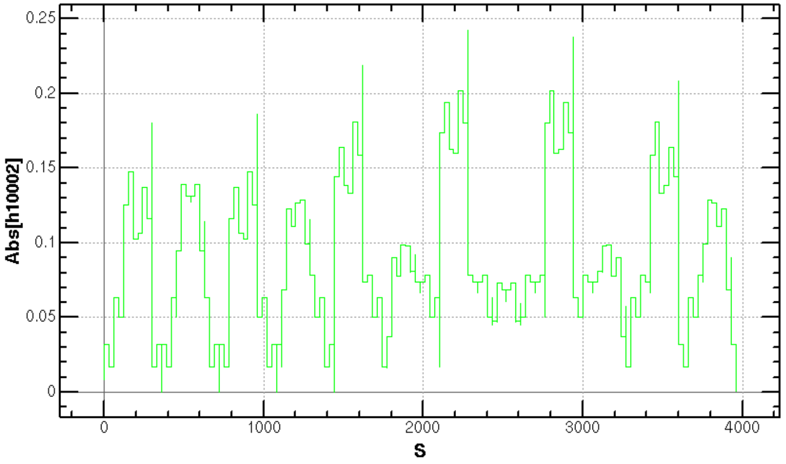
Optimization of the ARC aberration at W and Z modes (cont.)

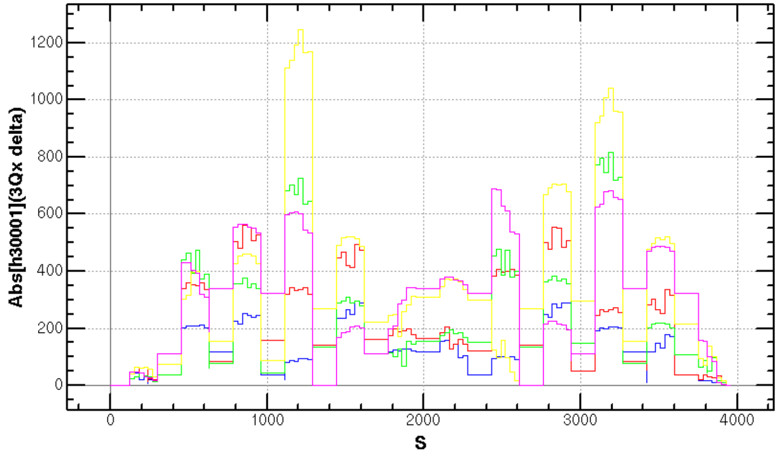
- Cancellation of main aberration has period of 23*3 cells.



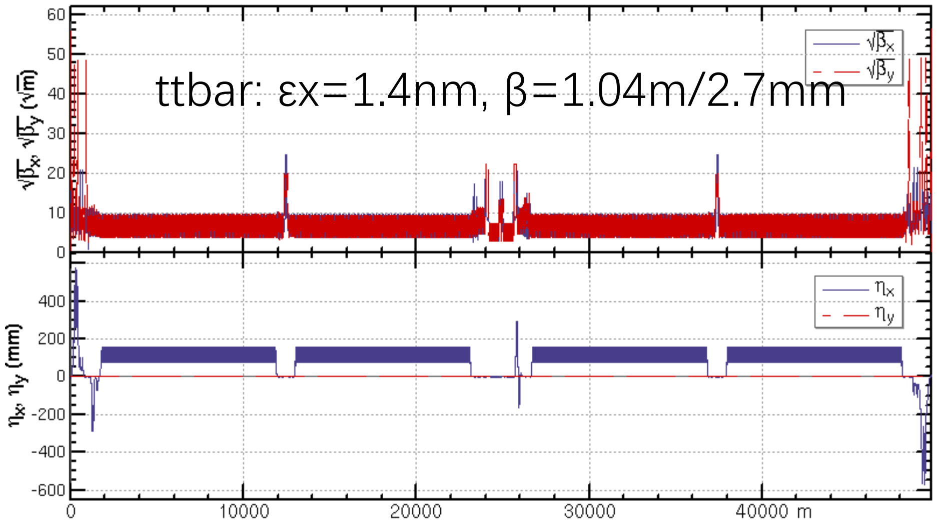


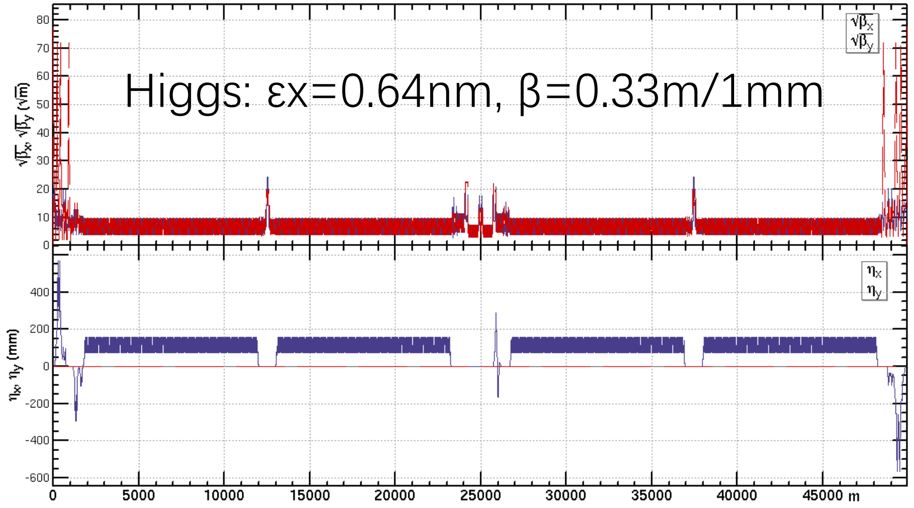


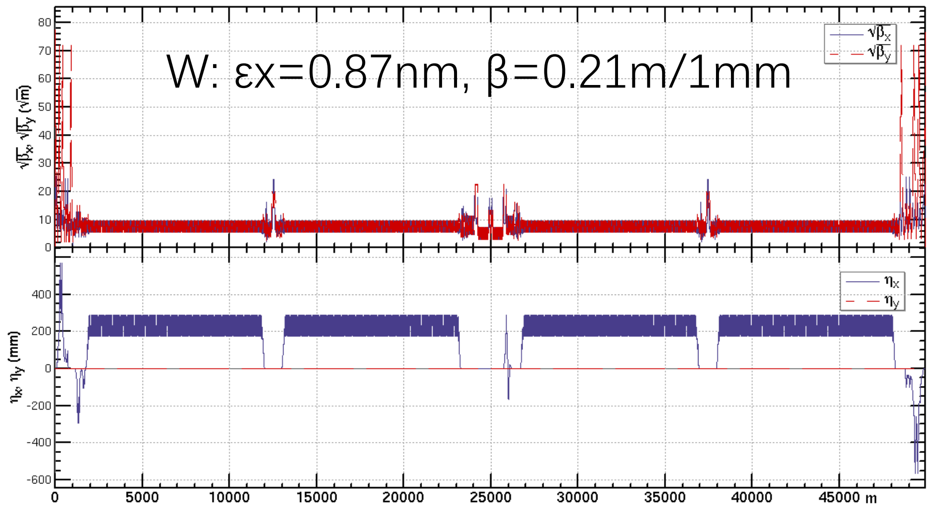


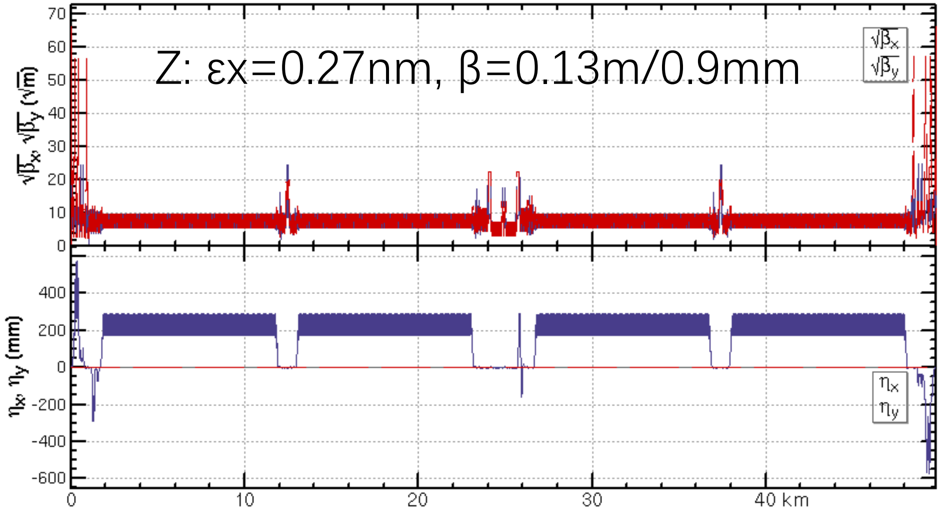


Lattice of half ring









The new RF layout has not been implemented in these lattices.

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	1.7	1.2	1.3

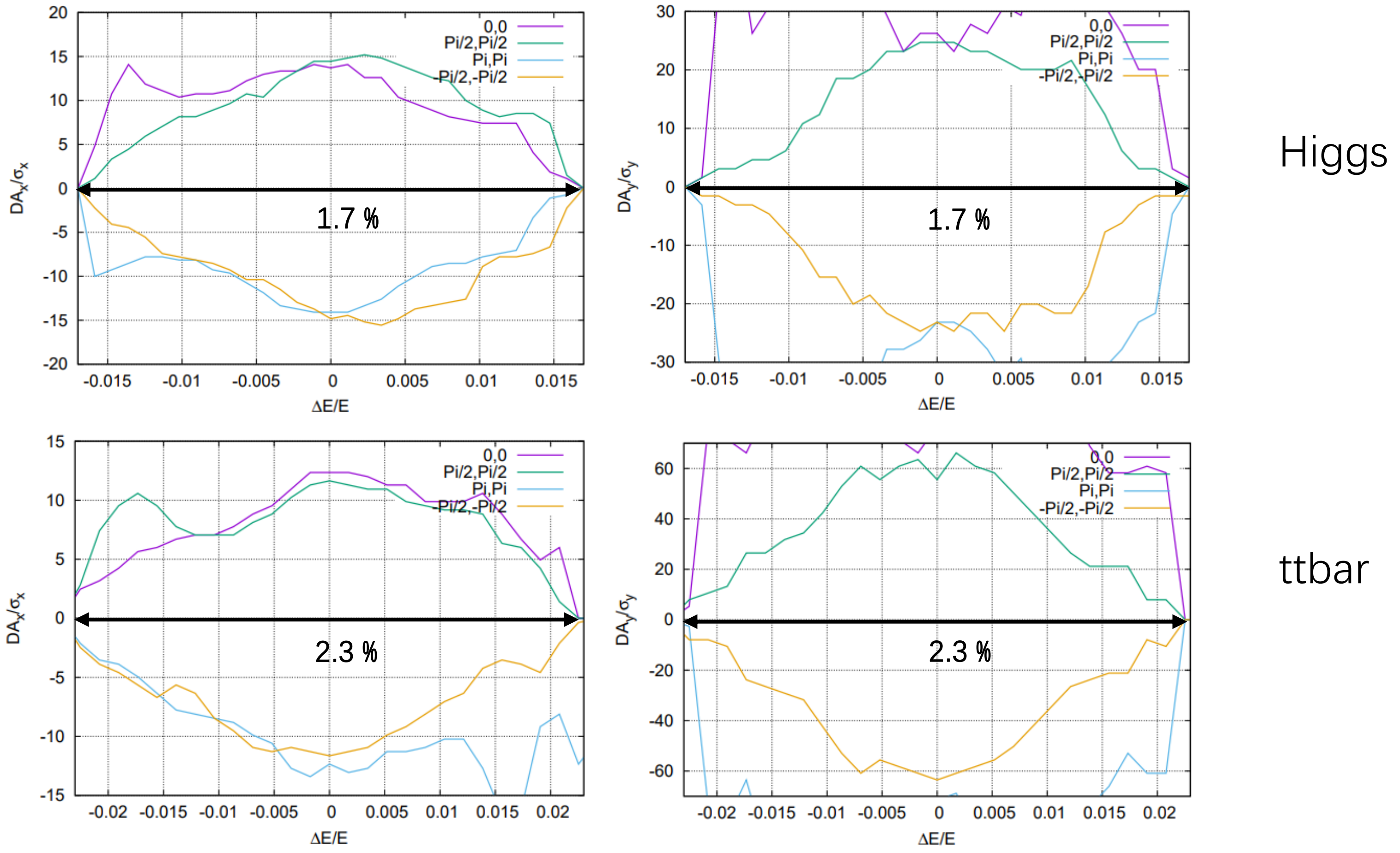
DA requirement	ttbar	Higgs	W	Z
with on-axis injection	-	$7\sigma_x \times 15\sigma_y \times 1.7\%$	-	-
with off-axis injection	$13.9\sigma_x \times 20\sigma_y \times 2.3\%$	$14.4\sigma_x \times 15\sigma_y \times 1.7\%$	$10.5\sigma_x \times 9\sigma_y \times 1.2\%$	$11.8\sigma_x \times 9\sigma_y \times 1.3\%$

* need beam-beam simulation to check for y

Dynamic aperture status @ 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)
  - Further optimization is under going (totally 256 arc families)

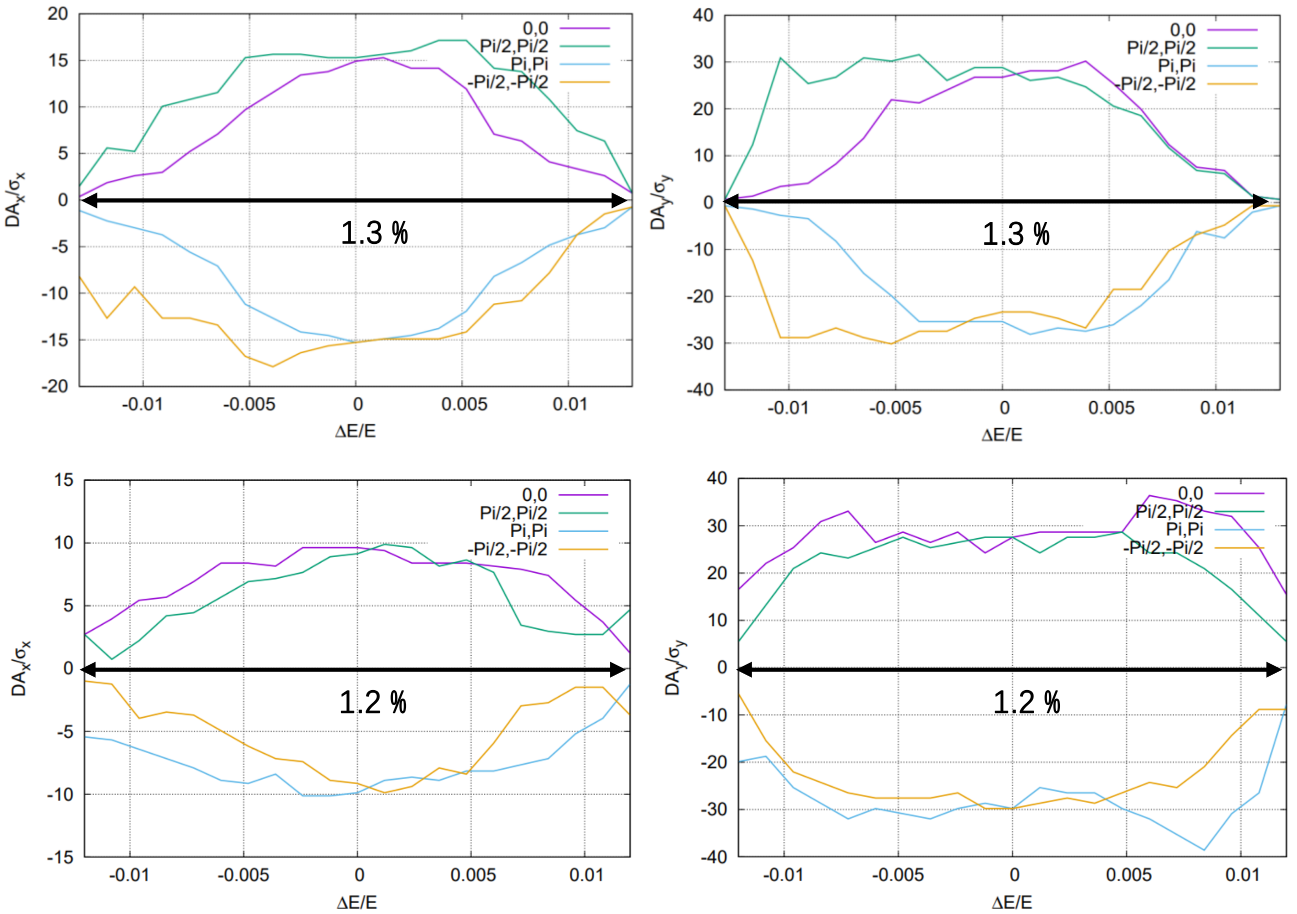
Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole



Dynamic aperture status @ 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)
  - Further optimization is under going (160 arc familes to be turned on)

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

Dynamic aperture with error @ Higgs

Bin Wang,
Yuanyuan Wei,
Yiwei Wang

- Error correction with 50 and 100 um misalignment in IR quadrupoles
  - closed orbit distortion (COD) and dispersion free steering (DFS) correction has been done
  - DA with 418 and 270 (out of 1000) error seeds satisfy the on-axis injection requirements
- Further optimization with 100 um misalignment in IR quadrupoles is undergoing.

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.1	0.01%
Arc Quadrupole	0.10	0.10	0.1	0.02%
IR Quadrupole	**0.05**	**0.05**	**0.05**	
Sextupole	0.10	0.10	0.1	

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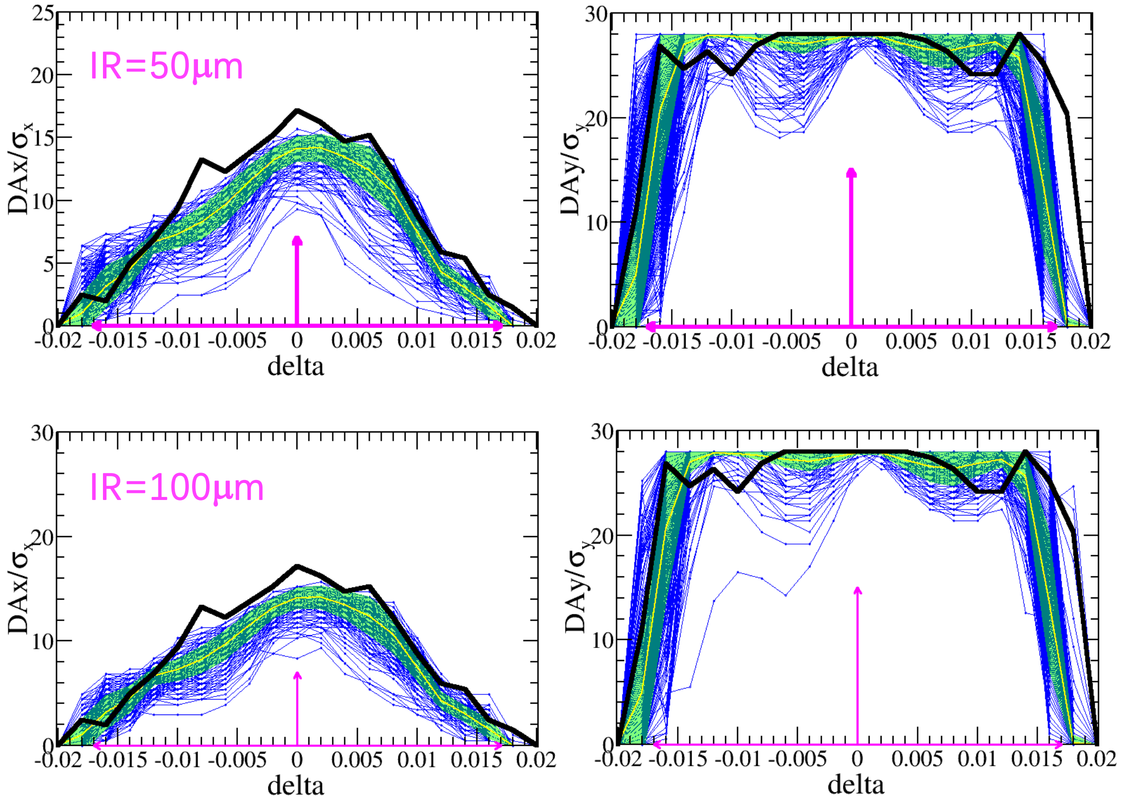
Arc Quadrupole	0.10	0.10	0.1	0.02%
IR Quadrupole	**0.10**	**0.10**	**0.10**	
Sextupole	0.10	0.10	0.1	

Lattice version cepc.lat.diff.8713.346.2p used
εx=0.64nm, β=0.33m/1mm, L*=1.9m

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



Summary

- The high luminosity scheme of CEPC collider ring with 30MW has been designed by mainly squeezing the β_y^* and emittance.
  - New aberration correction scheme in ARC region, compatible final quadrupoles in IR
  - Phase advance reduced from 90° to 60° for W/Z mode to suppress impedance instability and increase stable tune area
  - Dynamic aperture w/o error for four modes achieve the requirement of energy acceptance. The DA can be further optimized with more arc sextupole families.
- The imperfection correction to the high luminosity lattice is on going.
  - With transverse alignment of 50um and 100um for final quadrupoles and 100um for other magnets
  - The dynamic aperture @ Higgs with 418 and 270 out of 1000 error seeds satisfy the on-axis injection requirements