Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

Lattice Design of the Collider Ring for CEPC CDR

Yiwei Wang
for the CEPC Accelerator Physics Group

The Institute of High Energy Physics, Chinese Academy of Sciences

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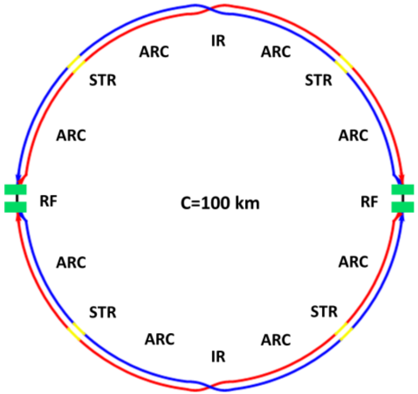
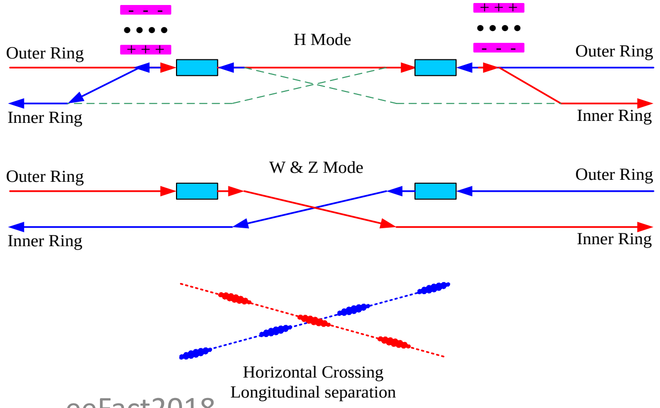
- Summary

Introduction

- The circumference of CEPC collider ring is **100 km.**
- In the RF region, the **RF cavities are shared by two rings for H mode**.
- **Twin-aperture of dipoles and quadrupoles is adopt in the arc region** to reduce the their power. The distance between two beams is 0.35m.
- Compatible optics for H, W and Z modes
  - For the **W and Z mode**, the optics except RF region is got by **scaling down the magnet strength with energy**.
  - **For H mode, all the cavities will be used** and bunches will be filled in half ring.
  - **For W & Z modes, bunches will only pass half number of cavities** and can be filled in full ring.



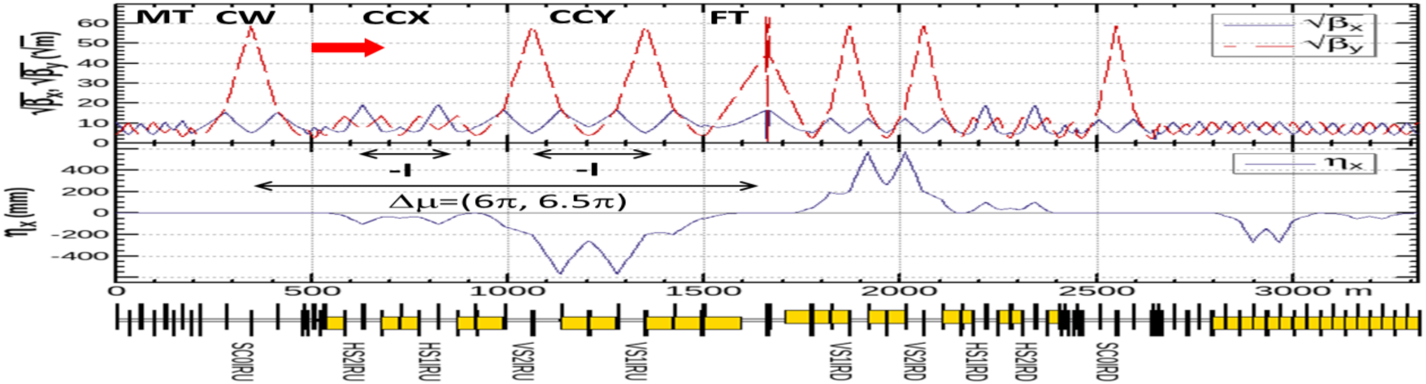


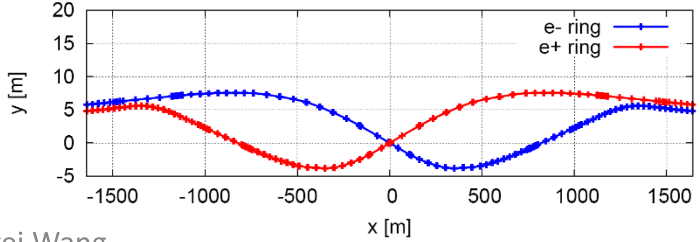
by D. WANG

	Higgs	*W*	*Z*（*3T*）	*Z*（*2T*）
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	**100**			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	**16.5×2**			
Piwinski angle	**3.48**	**7.0**	**23.8**	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x* / β_y* (m)	**0.36/0.0015**	**0.36/0.0015**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	**0.018/0.109**	**0.013/0.123**	**0.004/0.06**	**0.004/0.079**
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	4.4	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.46	0.75	**1.94**	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	**1.35**	**0.90**	**0.49**	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime* (min)	80/80	>400		
Lifetime (hour)	**0.43**	**1.4**	**4.6**	**2.5**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**10.1**	**16.6**	**32.1**

Optics of Interaction region

- local chromaticity correction of both plane, asymmetric layout 1), crab-waist collision 2)
- L^*=2.2m, θ_C =33mrad, G_{QD0} =136T/m, G_{QF1} =111T/m, L_{QD0} =2.0m, L_{QF1} =1.48m
- IP upstream of IR: Ec < 120 keV within 400m, last bend Ec = 45 keV
- IP downstream of IR: Ec < 300 keV within 250m, last bend Ec = 97 keV



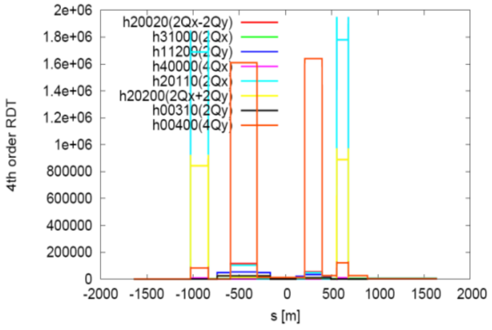


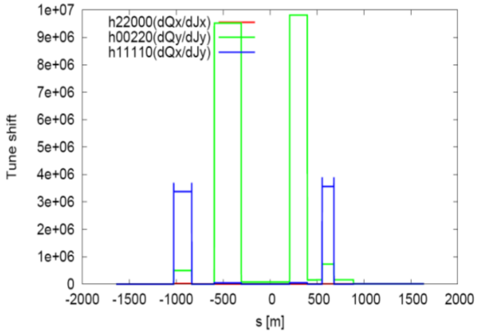
	Higgs	W	Z (3T)	Z(2T)
Vertical emittance [pm·rad]	0.16	0.53	2.9	0.45
Normalized Vertical Emittance Budget	6.7%	33%	71%	28%
Emittance Coupling Budget	0.2%	0.3%	2.2%	0.89%

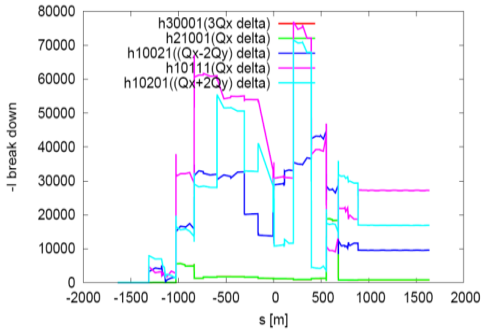
1) K. Oide et al., ICHEP16.
2) M. Zobov et al., Phys. Rev. Lett. 104, 174801(2010).

Nonlinearity correction of Interaction region

- Local chromaticity correction with sextupoles pairs separated by –I transportation
  - all **3rd and 4th RDT** (in Lie operator f3 and f4) due to sextupoles almost cancelled 1)
  - **up to 3rd order chromaticity** corrected with main sextupoles, phase tuning and additional sextupole pair 2,3)
  - **tune shift** due to finite length of main sextupoles corrected with additional weak sextupoles 3,4)
  - Break down of -I due to energy deviation corrected with ARC sextupoles



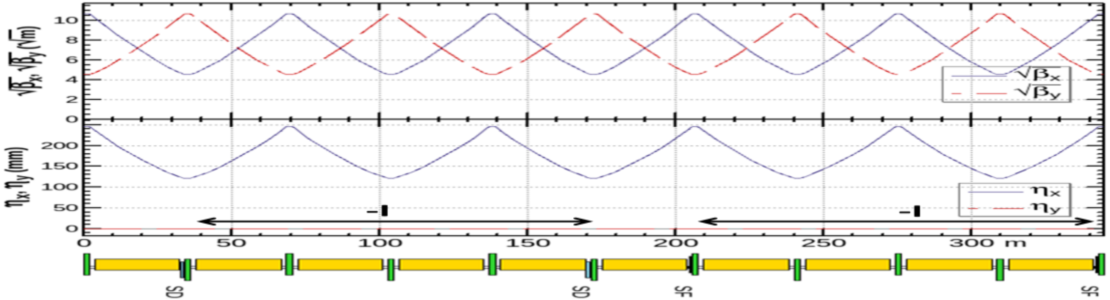


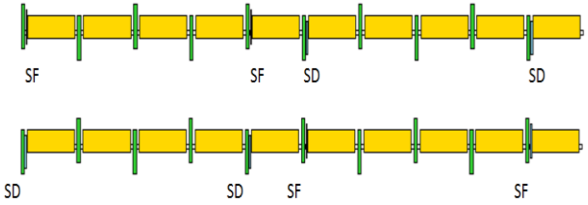


1) K. Brown
2) Brinkmann
3) Y. Cai
4) A. Bogomyagkov

Optics design of ARC region

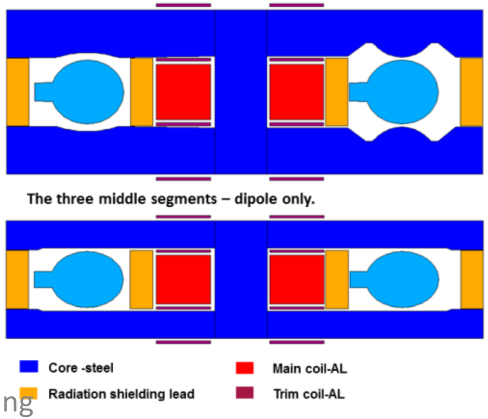
- FODO cell, 90°/90°, non-interleaved sextupole scheme, period =5cells

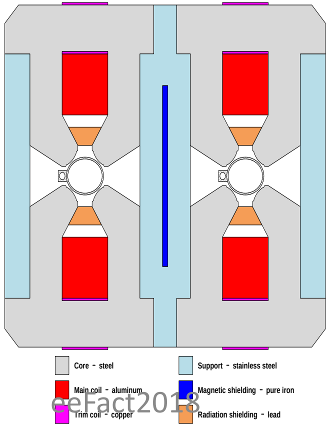


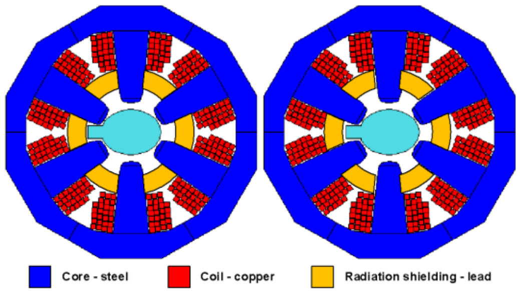


- **Twin-aperture of dipoles and quadrupoles*** is adopt in the arc region to reduce the their power. The distance between two beams is 0.35m.

*Ref: A. Milanese, PRAB 19, 112401 (2016)



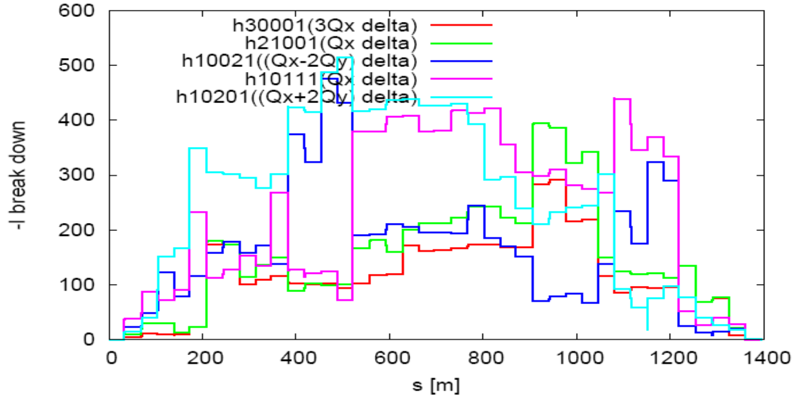




magnets designed by
F. Chen, M. Yang, X. Sun et al.

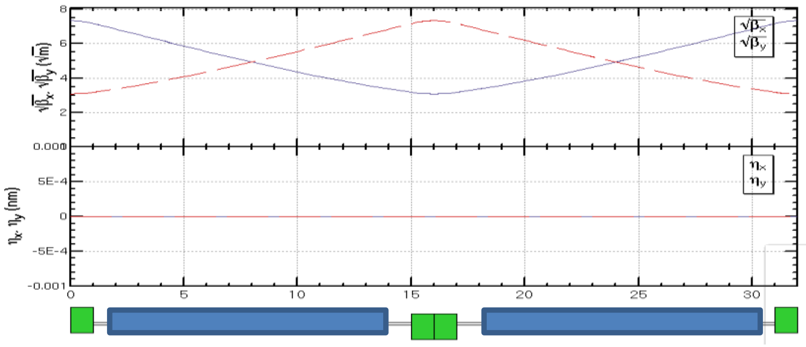
Nonlinearity correction of ARC region

- FODO cell, 90°/90°, non-interleaved sextupole scheme, period =5 cells
- With 2 families of sextupoles in each 4 periods, i.e. 20 cells
  - all 3rd and 4th resonance driving terms (in Lie operator f3 and f4) due to sextupoles cancelled, except small 4Qx, 2Qx+2Qy, 4Qy, 2Qx-2Qy
  - break down of -I due to energy deviation cancelled
  - thus cells numbers equal to 20*N in each ARC region, 32 families of ARC sextupoles used to optimize DA



FODO cell for cryo-module

- Get a smallest average beta function to reduce the multi-bunch instability caused by RF cavities especially for the Z mode
  - 90/90 degree phase advance
  - The distance between quadrupoles is 13.7 m which allow a cryo-module with length of 12m.
  - average beta function 30 m
- 336 / 6 / 2RF stations / 2 sections / 2= 7 cells in each section

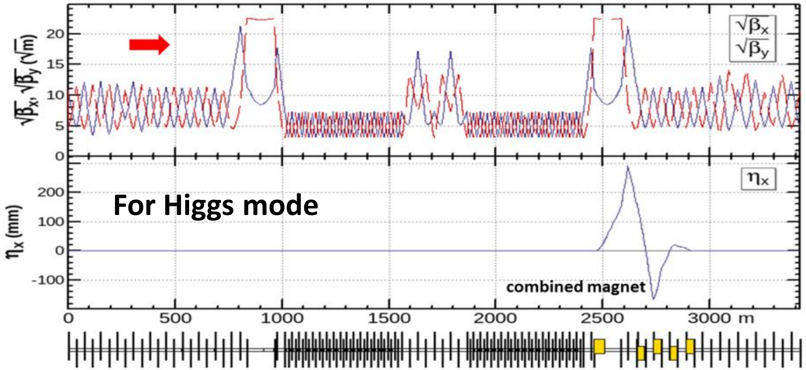


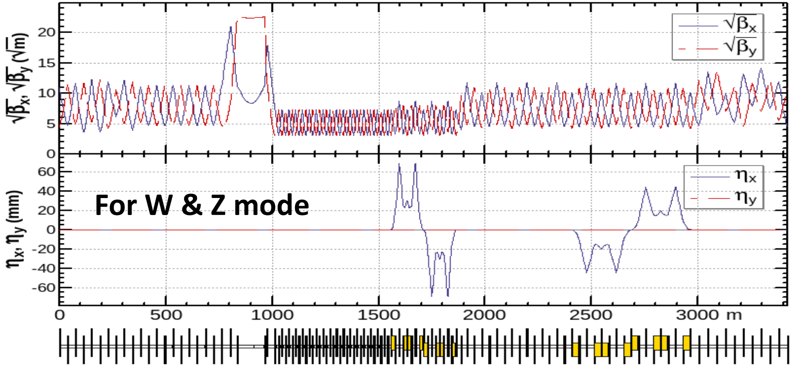
cryo-module quadrupole

90/90 deg
Half cell: 13.7m+2.3m
βmax: 53.8 m
βmin: 9.5 m

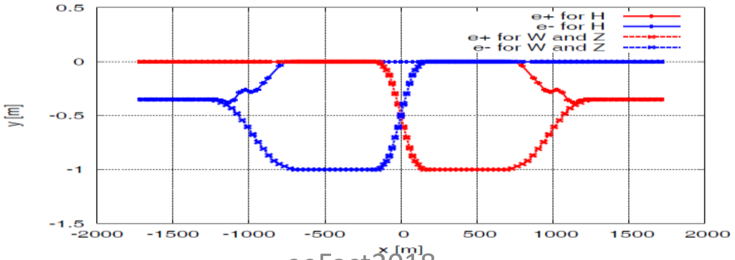
Optics design of RF region

- **Common RF cavities** for e- and e+ ring (Higgs)
- An electrostatic separator combined with a dipole magnet to avoid bending of incoming beam (ref: K. Oide, ICHEP16)
- **RF region divided into two sections for bypassing half numbers of cavities in Z mode**



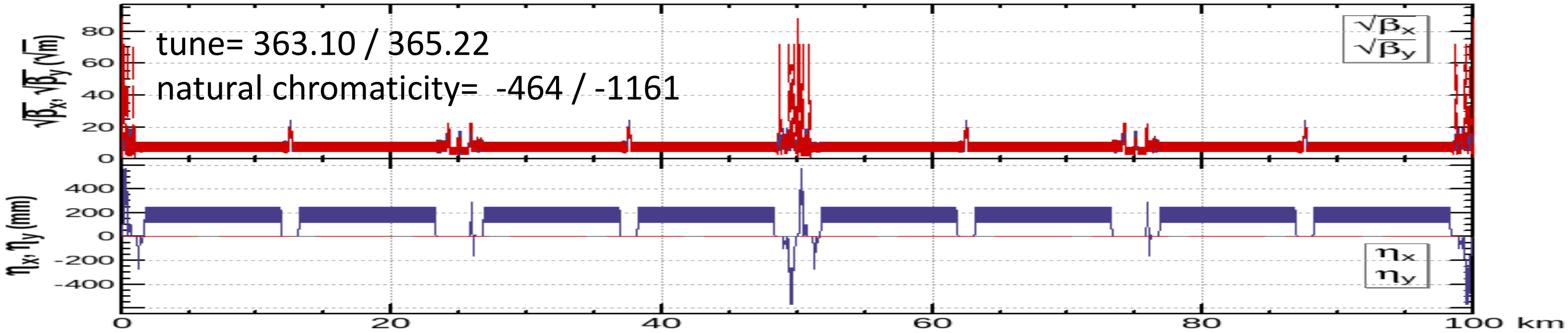


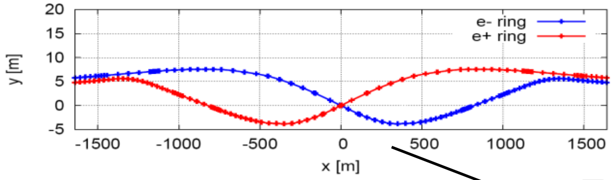
Esep= 2.0 MV/m
Lsep= 4 m×10
Δx= 10 cm at entrance of quad

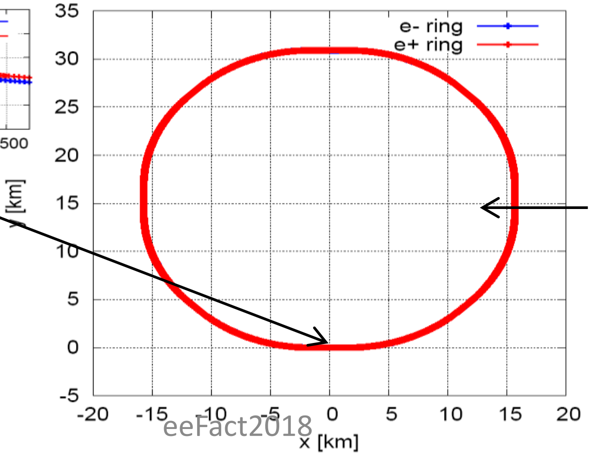


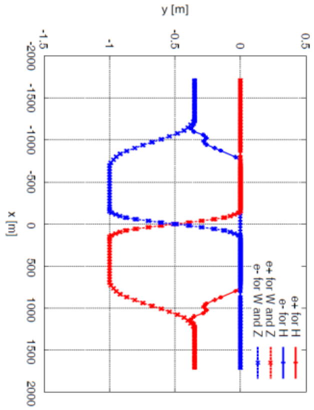
Optics of the collider ring

- An optics fulfilling requirements of the parameters list, geometry, photon background and key hardware.



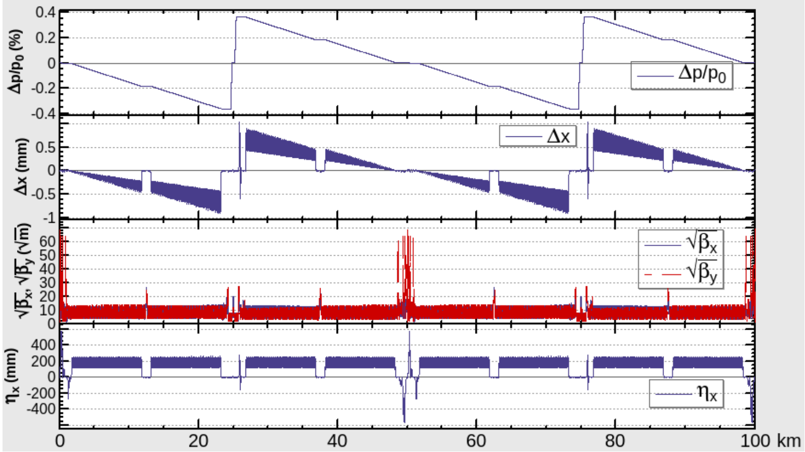


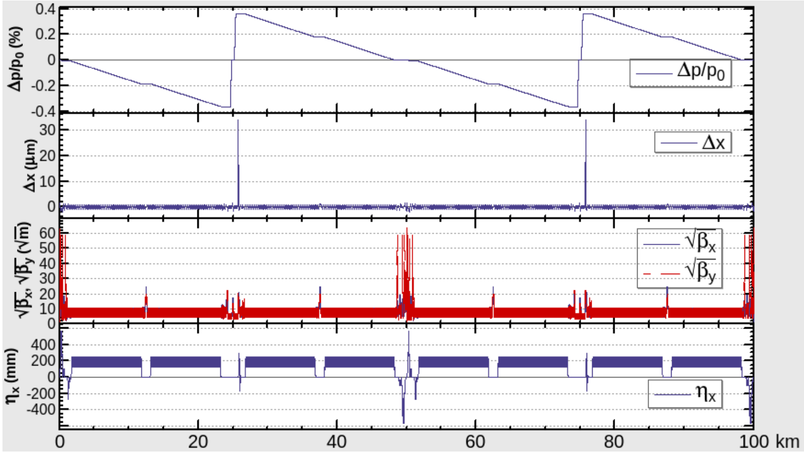




Energy sawtooth effects and correction

- With only two RF stations, the energy sawtooth is around ±0.35 %
- The closed orbit distortion in CEPC collider ring is around 1 mm and becomes 1um after tapering the magnet strength with beam energy.
  - adjusting range of magnets strength ±1.5%





Dynamic aperture requirements

- Dynamic aperture requirements

	Higgs	W	Z
with on-axis injection	$8\sigma_x \times 15\sigma_y \times 1.35\%$	-	-
with off-axis injection	$13\sigma_x \times 15\sigma_y \times 1.35\%$	$15\sigma_x \times 9\sigma_y \times 0.9\%$	$17\sigma_x \times 9\sigma_y \times 0.49\%$

- Start point of the optimization

"On-axis injection", Xiaohao Cui, 15:20-15:40, 25 Sep

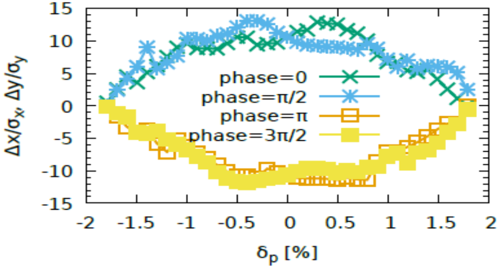
  – Nonlinearity optimized term by term with 10 families of sextupoles in the IR and 4 families of sextupoles in the ARC.
- Optimize dynamic aperture directly with MODE (Y. ZHANG, IHEP)
  – With **10 families of sextupoles in the IR, 32 families of sextupoles in ARC and 8 phase advances**

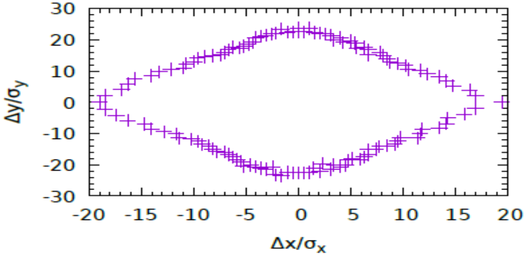
Dynamic aperture result (w/o errors)

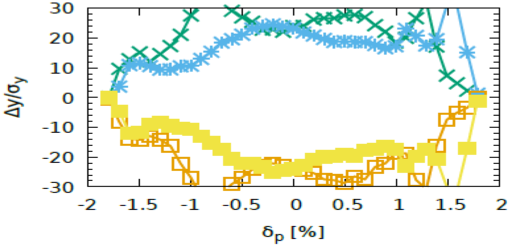
by Y. ZHANG, et al

Tracking in SAD w/ synchrotron radiation damping, fluctuation(100 samples), energy sawtooth and tapering, 145/475/2600 turns(H/W/Z, 2 damping times), 4 initial phases

Higgs

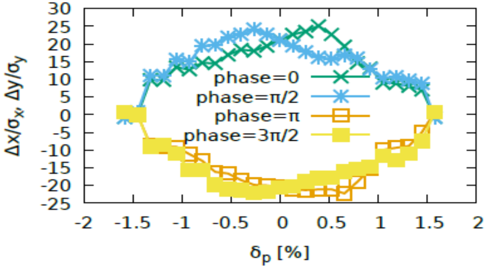


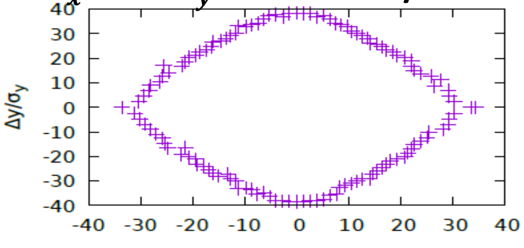


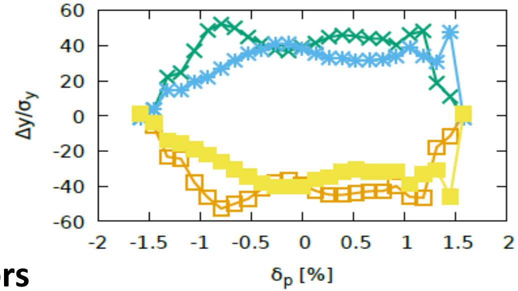


$20\sigma_x \times 23\sigma_y$ & 0.018 w/o errors

W

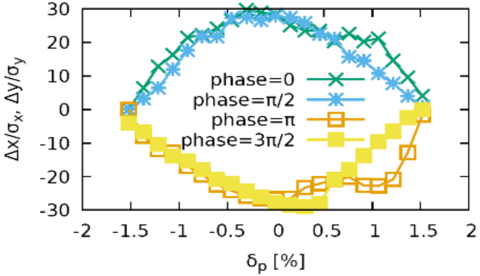


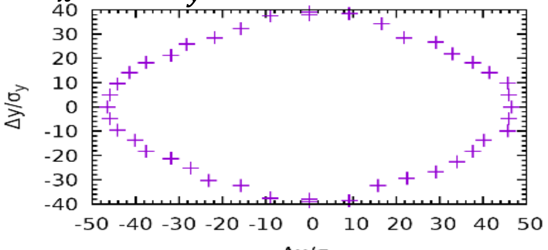


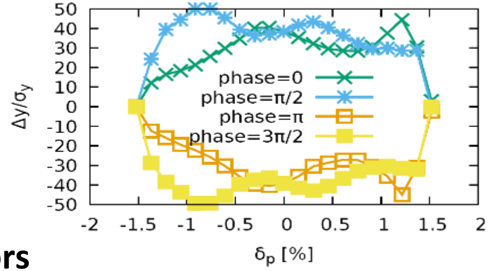


$32\sigma_x \times 40\sigma_y$ & 0.015 without errors

Z







$46\sigma_x \times 40\sigma_y$ & 0.015 without errors

Performance with errors

by Yuanyuan WEI, et al

- LOCO based on AT is used to correct distortion of closed orbit, beta, dispersion and coupling.

    1. correct distortion of closed orbit w/o sextupole
    2. correct the beta and dispersion w/ sextupole
    3. correct coupling

Component	Δx (mm)	Δy (mm)	Δz (mm)	$\Delta\theta_x$ (mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.05	0.05	0.15	0.2	0.2	0.1	0.01%
Quadrupole	0.03	0.03	0.15	0.2	0.2	0.1	0.02%

Further study with larger tolerance of misalignment is undergoing and the goal for Δx and Δy is 100 μm.

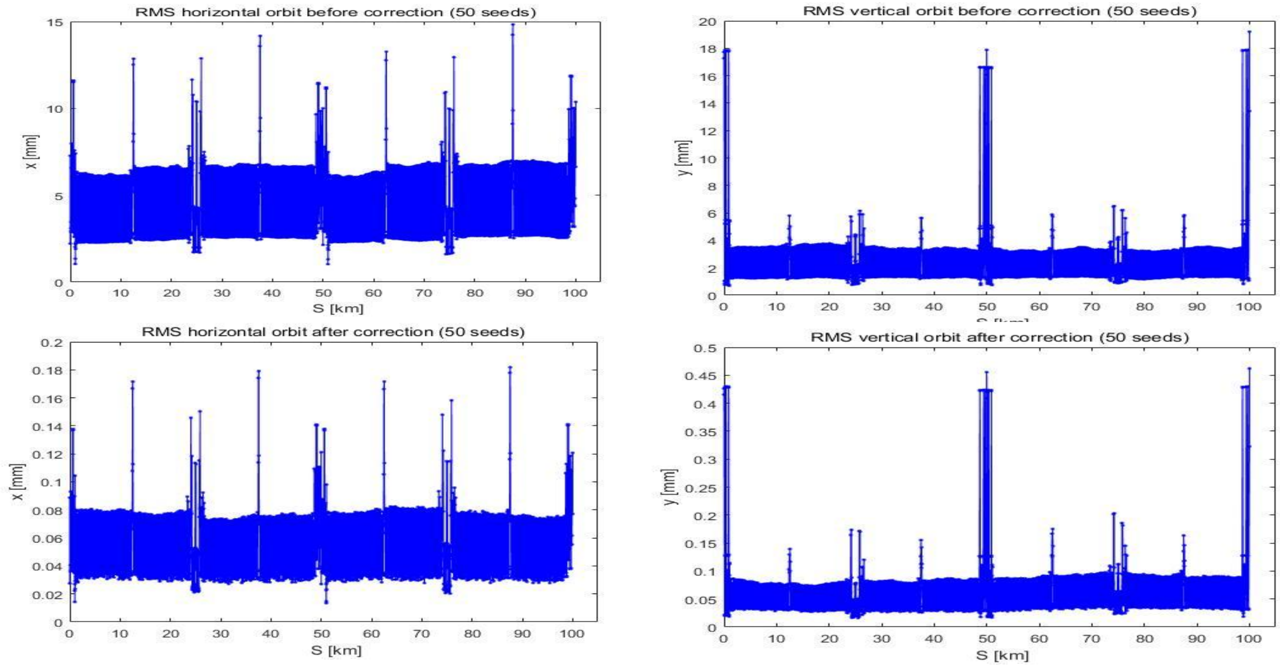
Correct distortion of closed orbit w/o sextupole

- About 1500 BPMs, horizontal and vertical correctors are used (4 per one betatron wave).

50 samples

before

after



$\sigma_{COD} \leq$ 6 / 4 mm (x/y) before correction except for IR regions

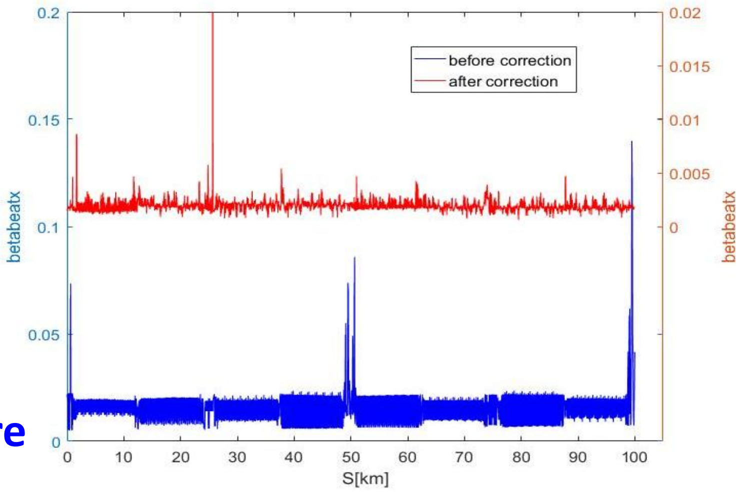
$\sigma_{COD} \leq$ 100 um (x/y) after correction except for IR regions

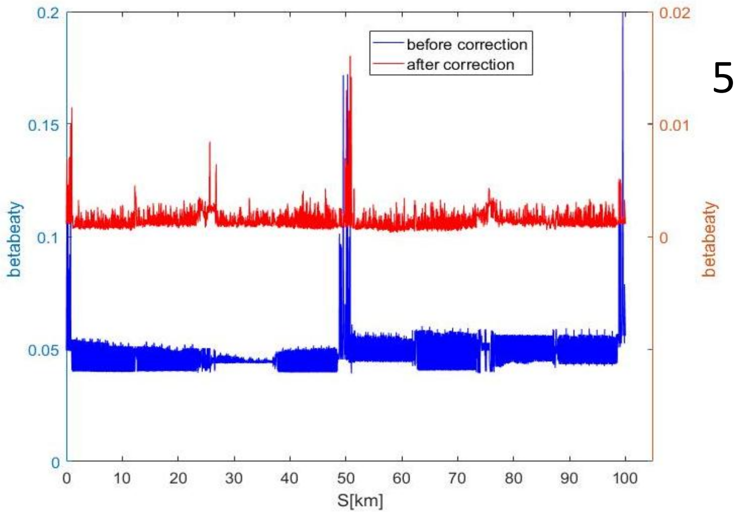
Correct the beta and dispersion w/ sextupole

- Strength of 1/5 quadrupoles (~600 out of 3000 quadrupoles) are changed to restore beta functions

after

before



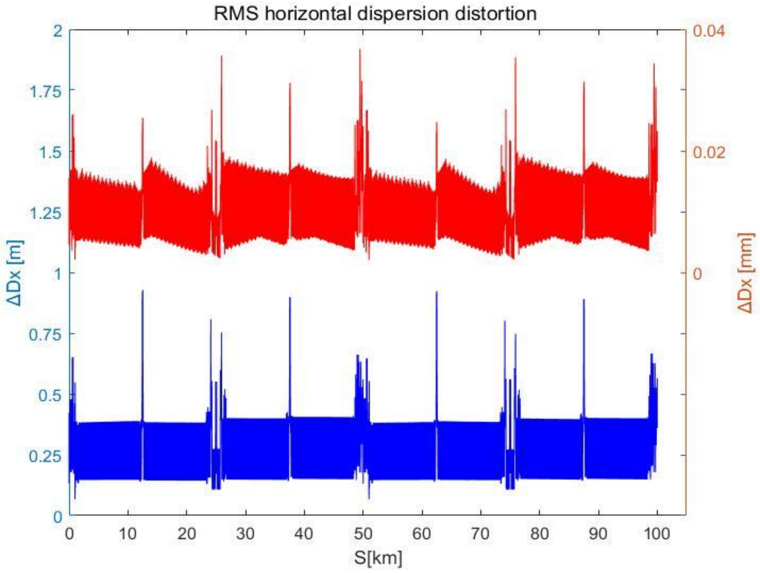


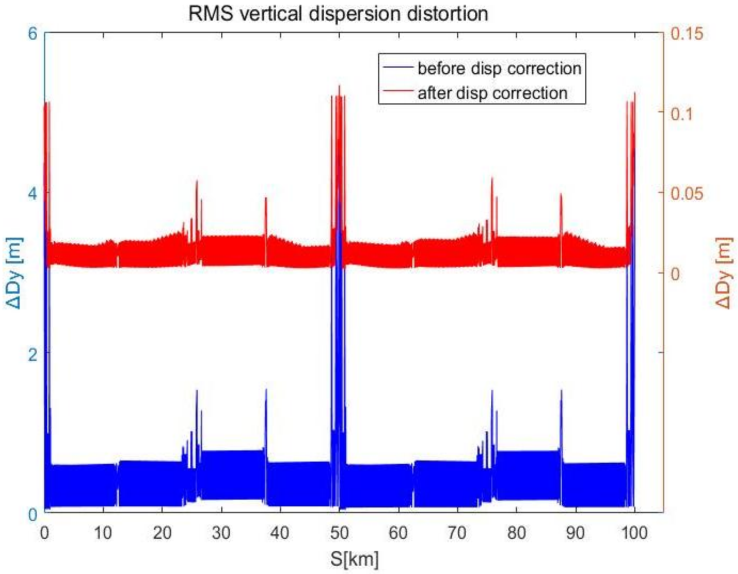
50 samples

$(\Delta\beta/\beta) \leq 3\% / 5\%$ (x / y) before correction except for IR regions

$(\Delta\beta/\beta) \leq 0.5\%$ (x / y) after correction except for IR regions

Dispersion distortion





50 samples

$std(Dx\_err)_{max}$ = 1 m before

$std(Dx\_err)_{max}$ = 0.04 m after

$std(Dy\_err)_{max}$ = 4 m before

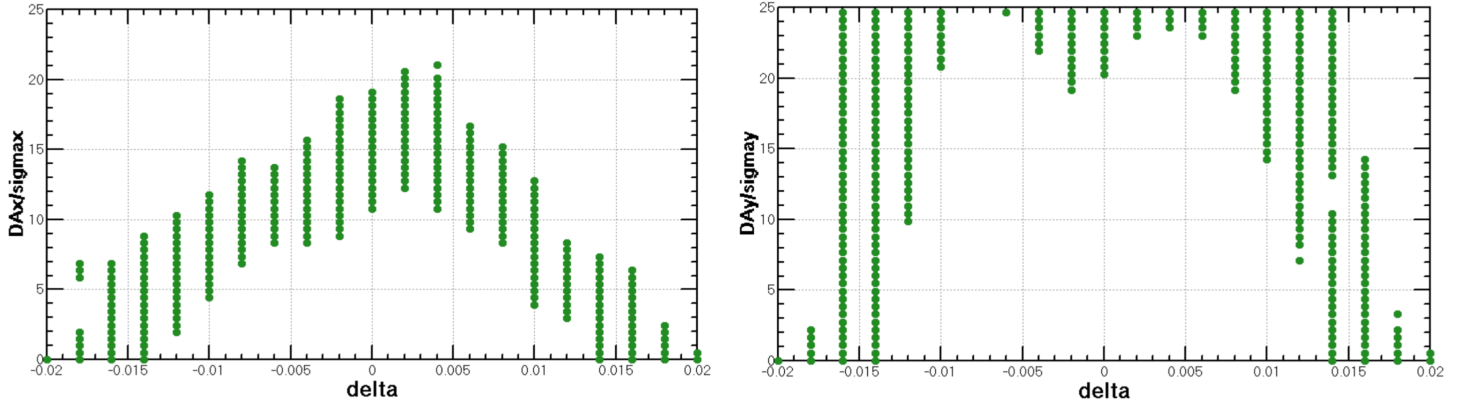
$std(Dy\_err)_{max}$ = 0.1 m after

Correct the coupling

- Quadrupole roll and the feed-down effect from sextupoles give rise to coupling.
- Skew coils on sextupoles and some independent skew quadrupoles are used to minimize the coupling response matrix by LOCO.
- Emittance growth is less than 0.15% after correction.

Dynamic aperture results (w/ errors)

- Dynamic aperture result for **Higgs mode**
  - Tracking in SAD w/ radiation damping, fluctuation, energy sawtooth and tapering, 145 turns(2 damping times), initial phases=0
  - Totally around 800 random seeds used
  - Horizontal dynamic aperture decreased significantly with errors. But it still fulfils the dynamic aperture requirement of on-axis injection.



$$20\sigma_x \times 23\sigma_y \,\&\, 0.018$$ **w/o errors**

$$11\sigma_x \times 19\sigma_y \,\&\, 0.014$$ **w/ errors**

Summary

- Linear optics of the CEPC collider ring designed fulfilling requirements of the parameters list, geometry, photon background and key hardware.
- Nonlinearity correction is made to give a good start point of dynamic aperture optimization and further optimization is made with MODE.
- For Higgs mode, the dynamic aperture with the errors currently considered fulfill the requirements of on-axis injection.
- Further study with larger tolerance of misalignment is undergoing and the goal for Δx and Δy is 100 μm.

Thank you!