Lattice design for the CEPC collider ring*

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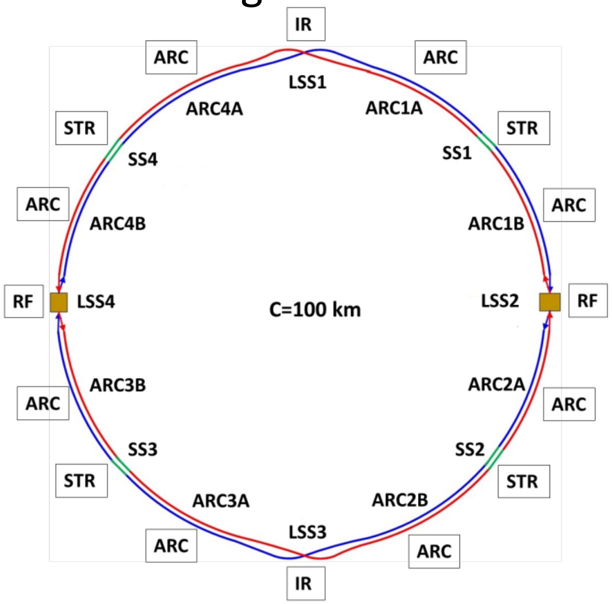
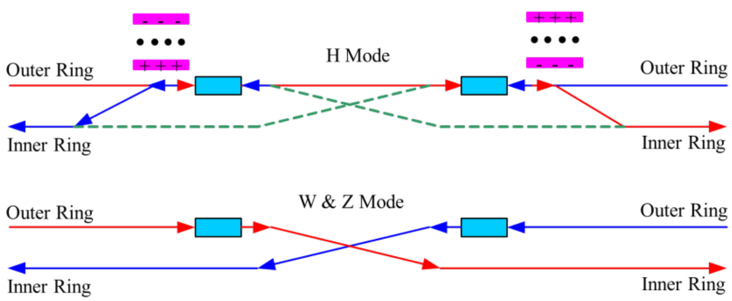
Outline

- Introduction
- Lattice design of the collider ring
  - Interaction region
  - Arc region
  - RF region
  - Straight section region
- Dynamic aperture
- Performance with errors
- 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.





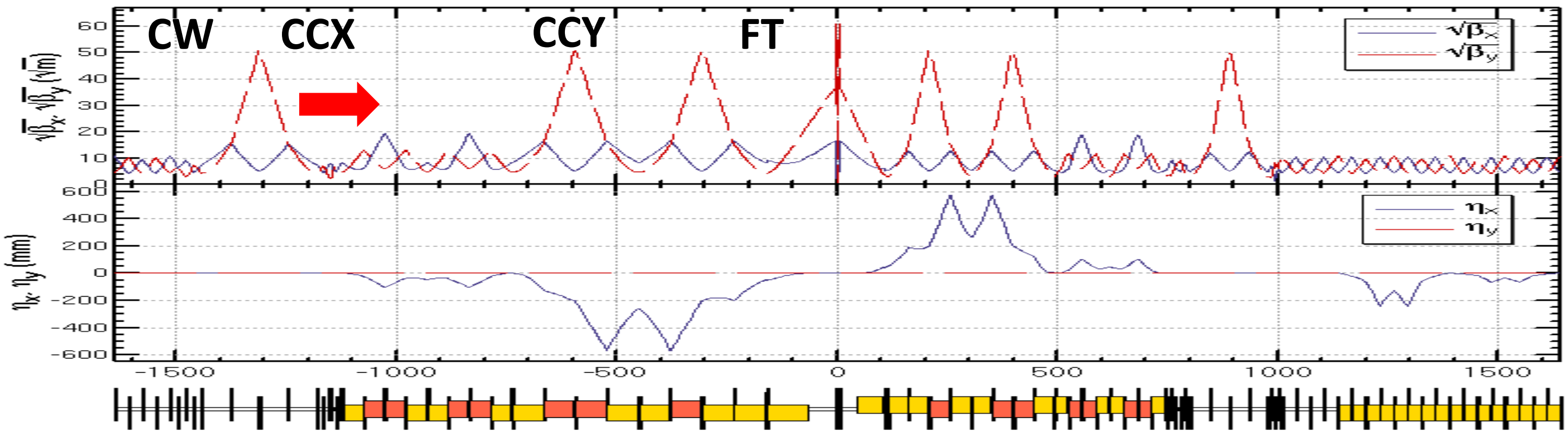
Parameters of CEPC collider ring

	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.73	0.34	0.036
Half crossing angle (mrad)	16.5		
Piwinski angle	2.58	4.29	16.8
N_e/bunch (10^{10})	15	5.4	4.0
Bunch number (bunch spacing)	242 (0.68us)	3390 (98ns)	8332 (40ns)
Beam current (mA)	17.4	88.0	160
SR power /beam (MW)	30	30	5.73
Bending radius (km)	10.6		
Momentum compaction (10^{-5})	1.11		
β_{IP} x/y (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.17/0.004
Transverse σ_{IP} (um)	20.9/0.068	13.9/0.049	5.9/0.078
ξ_x/ξ_y/IP	0.031/0.109	0.0148/0.076	0.0041/0.039
V_{RF} (GV)	2.17	0.47	0.054
f_{RF} (MHz) (harmonic)	650 (216816)		
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.26	3.62	6.0
HOM power/cavity (kw)	0.54 (2cell)	0.47(2cell)	0.49(2cell)
Energy spread (%)	0.1	0.066	0.038
Energy acceptance requirement (%)	1.52		
Energy acceptance by RF (%)	2.06	1.47	0.76
Photon number due to beamstrahlung	0.29	0.16	0.28
Lifetime due to beamstrahlung (hour)	1.0		
Lifetime (hour)	0.33 (20 min)		
F (hour glass)	0.89	0.94	0.99
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.93	7.31	4.1

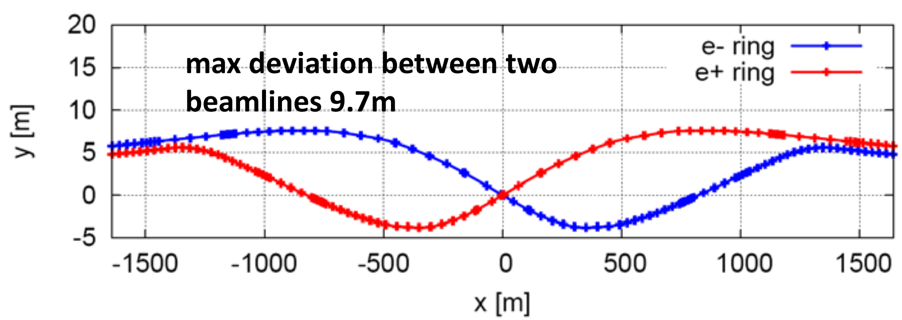
by D. Wang

Linear optics of Interaction region

- Provide local chromaticity correction of both plane
- **L*=2.2m, θc=33mrad, GQD0=136T/m, GQF1=111T/m**
- 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
- The vertical emittance growth due to solenoid coupling is less than 4%.
- Relaxed optics for injection can be re-matched easily as the **modular design**.



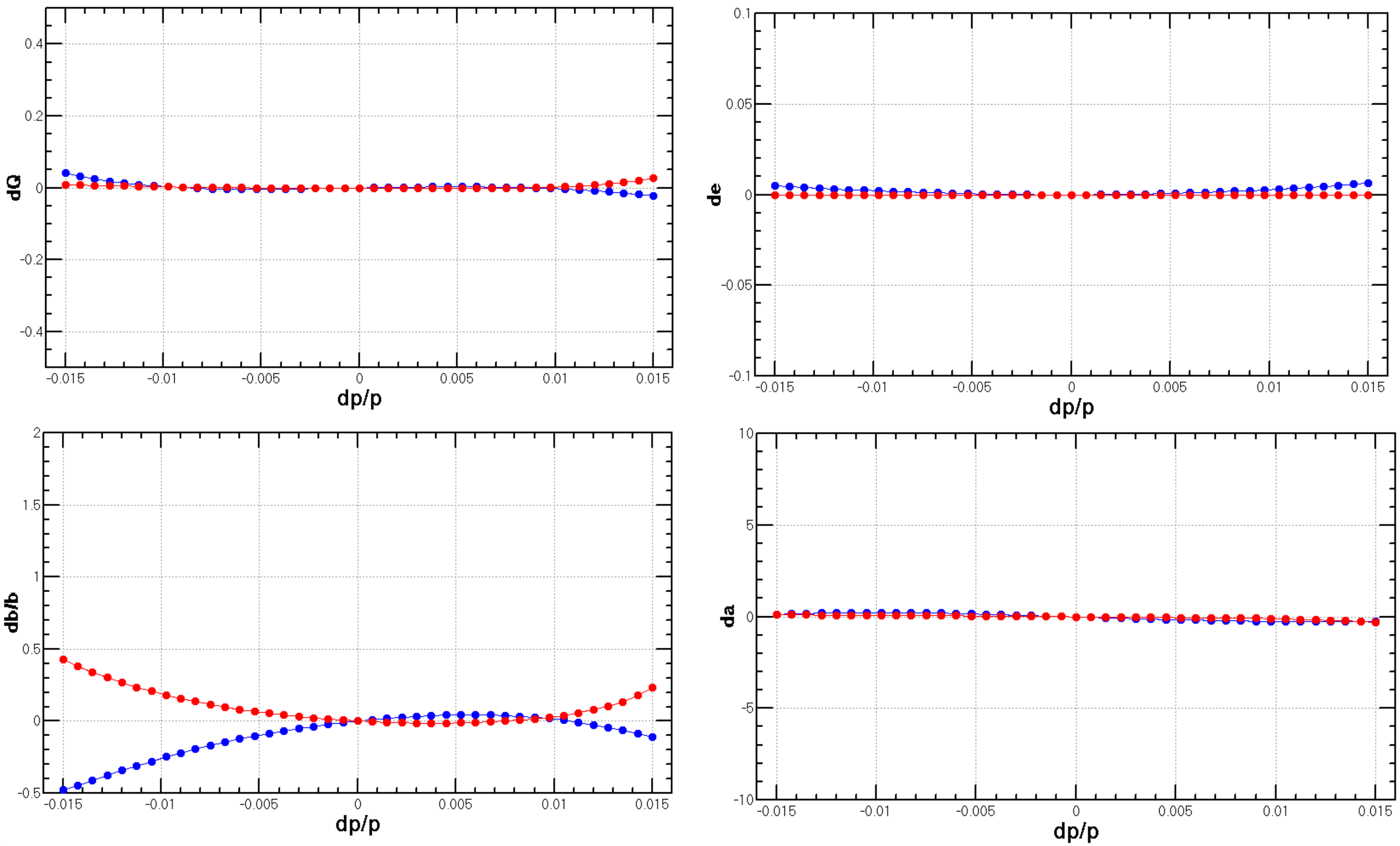
L*= 2.2m
βx*= 0.36mm
βy*= 1.5mm
GQD0≅-136T/m
GQF1≅111T/m
LQD0=2.0m
LQF1=1.48m



asymmetric IR layout*
*ref: K. Oide, ICHEP16.

Nonlinearity correction of Interaction region

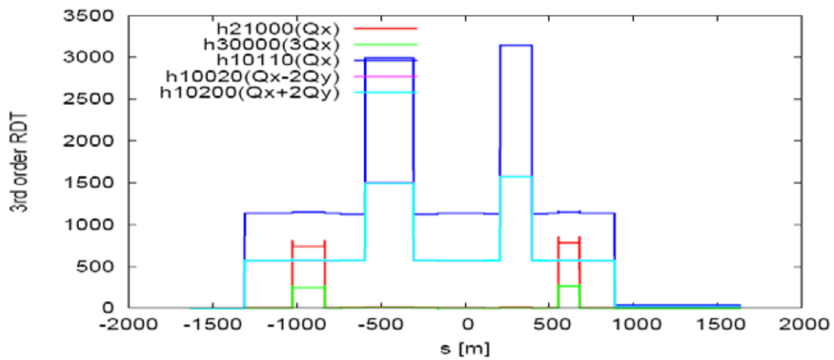
- **Local chromaticity correction** with sextupoles pairs separated by –I transportation
  - **up to 3rd order chromaticity** corrected with main sextupoles, phase tuning and additional sextupole pair 2,3) Ref: 2) Brinkmann 3) Y. Cai
  - higher order chromaticities can be corrected with higher order multipoles 3)

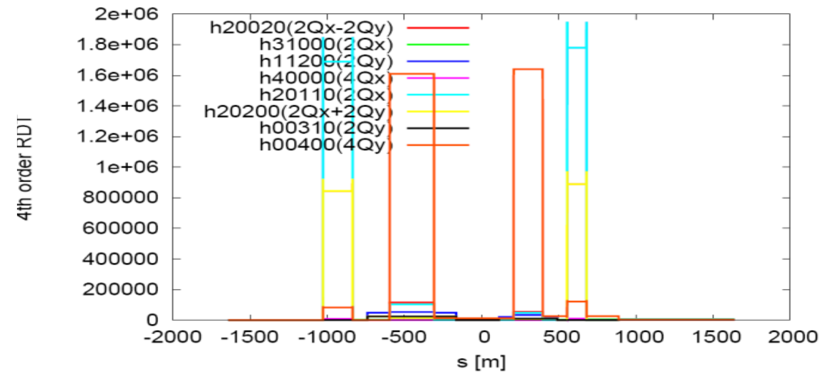


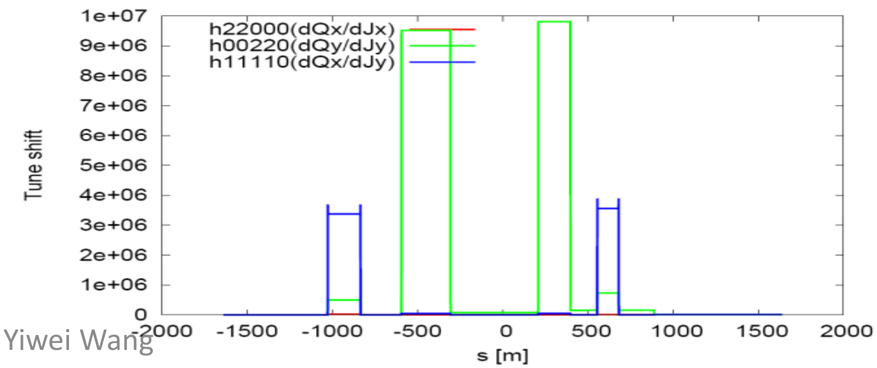
Nonlinearity correction of Interaction region

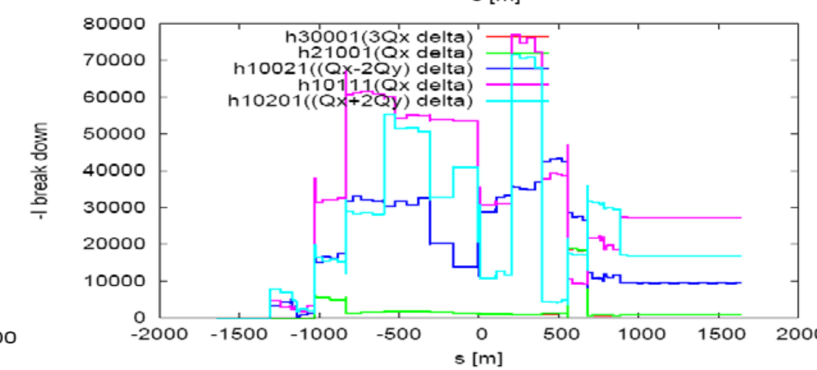
- **Local chromaticity correction** with sextupoles pairs separated by –I transportation
  - all **3rd and 4th RDT** due to sextupoles almost cancelled 1)
  - **tune shift dQ(Jx, Jy)** due to finite length of main sextupoles corrected with additional weak sextupoles 3,4)
  - **Break down of -I due to energy deviation** corrected with ARC sextupoles
    - could be further optimized with odd dispersion scheme 5), Brinkmann sextupoles 2) or pair of decapoles 3)

Ref:
1) **K. Brown**
2) **Brinkmann**
3) **Y. Cai**
4) **Anton**
5) **K. Oide**
6) **J. Bengttson's**



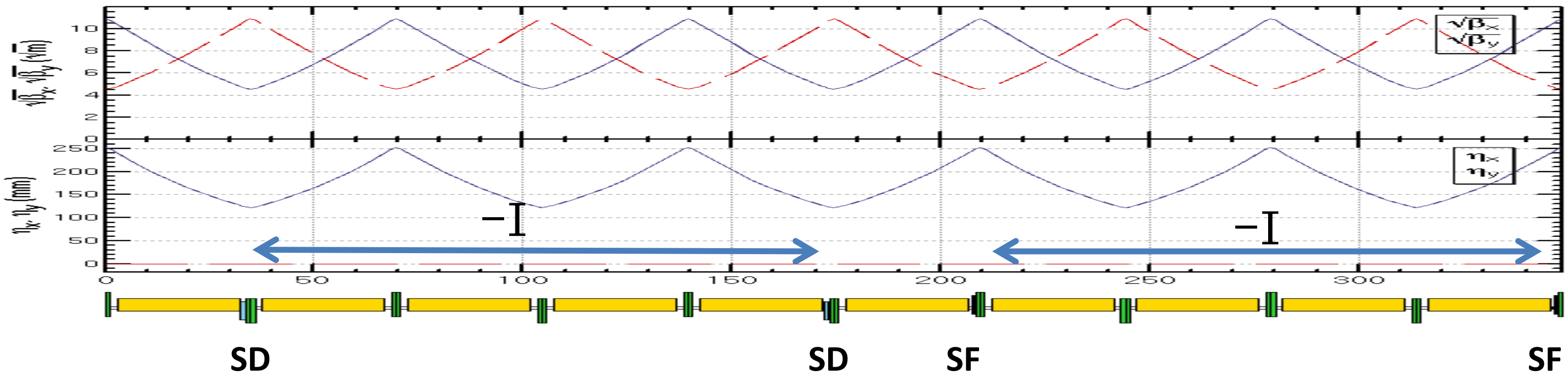




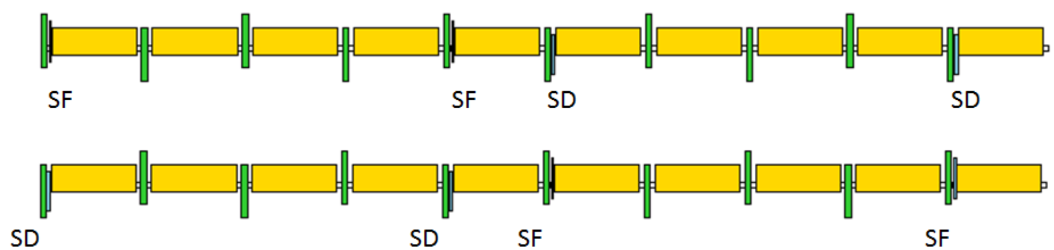


Linear optics design of ARC region

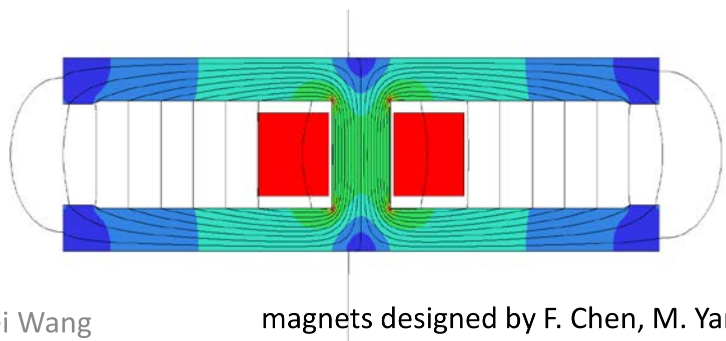
- **FODO cell, 90°/90°, non-interleaved sextupole scheme, period =5cells**

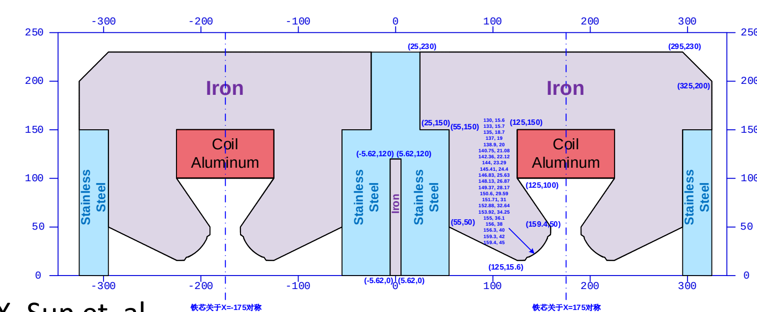


- **Twin-aperture of dipoles and quadrupoles* is adopt in the arc region** to reduce the their power. The distance between two beams is 0.35m.



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

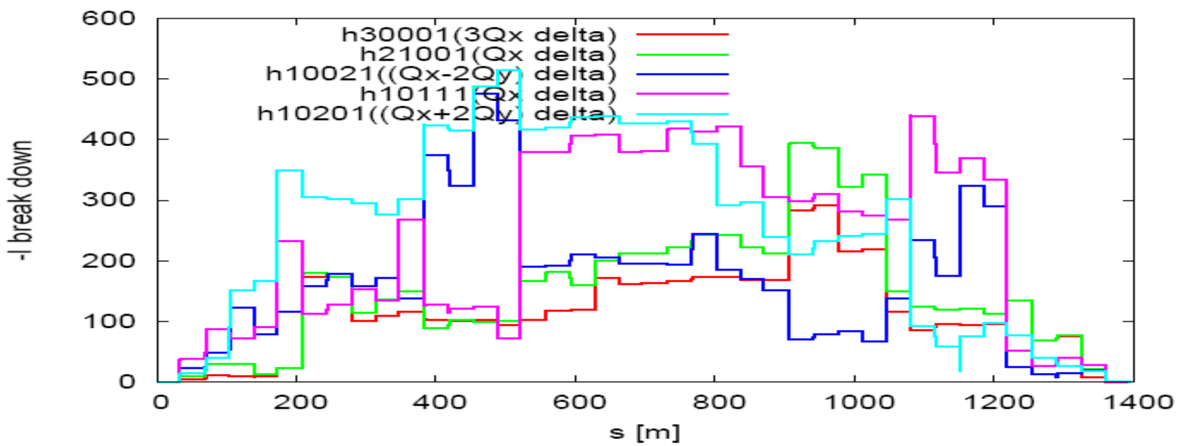




magnets designed by F. Chen, M. Yang, X. Sun et al.

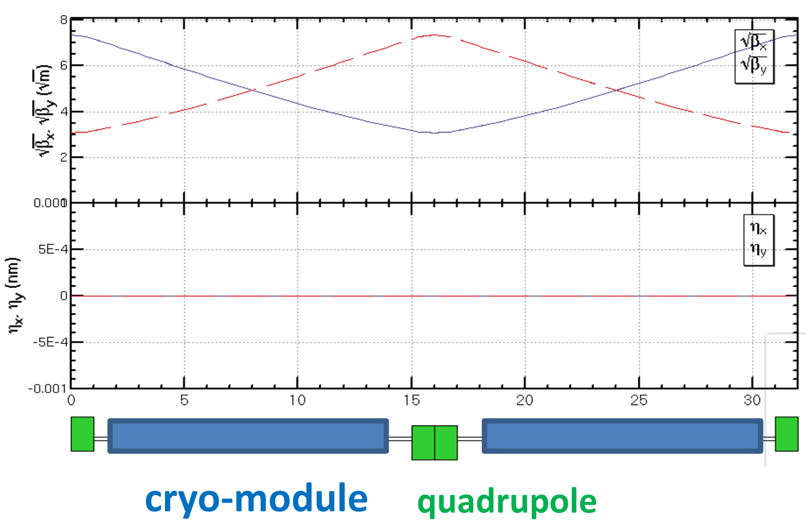
Nonlinearity correction of ARC region

- **FODO cell, 90°/90°, non-interleaved sextupole scheme, period =5 cells**
  - **tune shift dQ(Jx, Jy) is very small**
    - DA on momentum: large
  - **Chromaticity dQ(δ) need to be corrected with many families**
    - DA off momentum: with many families to correct dQ(δ)
  - With 2 families of sextupoles in each 4 periods i.e. 20 cells
    - all 3rd and 4th resonance driving terms (RDT) 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**



FODO cell for cryo-module

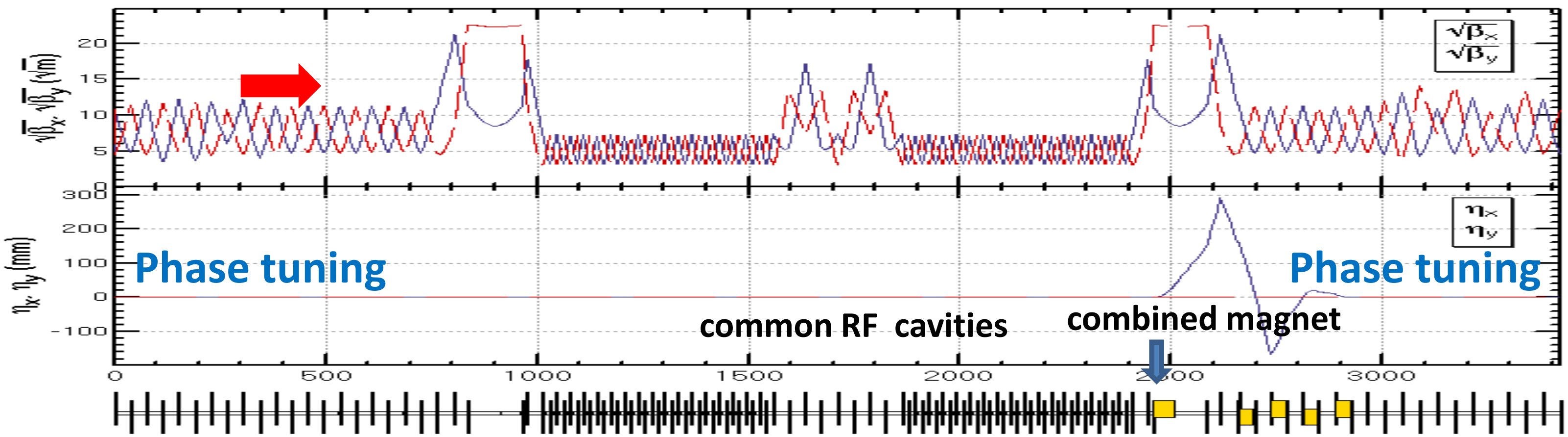
- Get a smallest average beta function to reduce the multi-bunch instability caused by RF cavities (compatible for Z mode)
  - 90/90 degree phase advance
  - as short as possible distance between quadrupoles, but should be larger than a module length (12m)
  - **Filling factor of module is 75 %.**
- 336 / 6 / 2RF stations / 2 sections / 2= 7 cells in each section



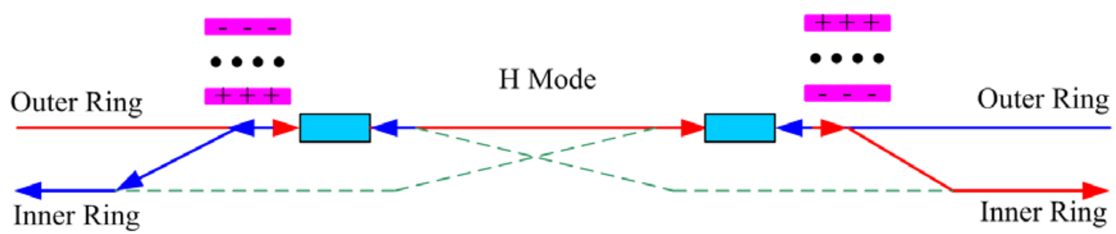
90/90 deg
Half cell: 13.7m+2.3m
βmax: 53.8 m
βmin: 9.5 m

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**

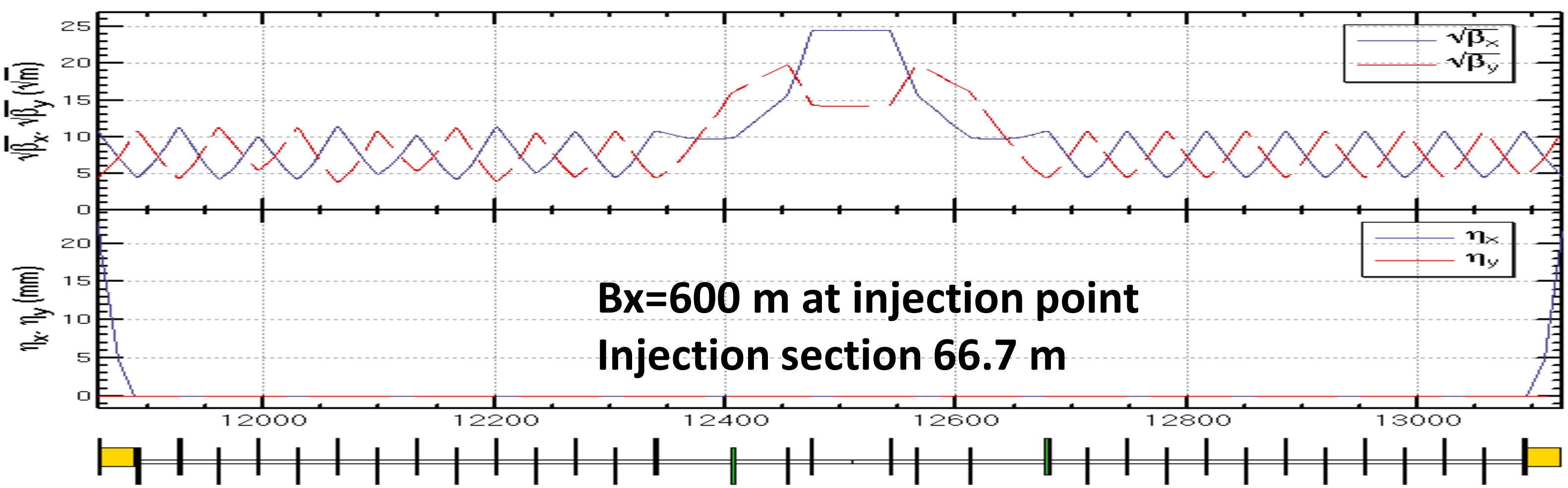


Esep=1.8 MV/m
Lsep=50m
Ldrift=75m
Δx=10 cm at entrance of quad



Optics design of Straight section region

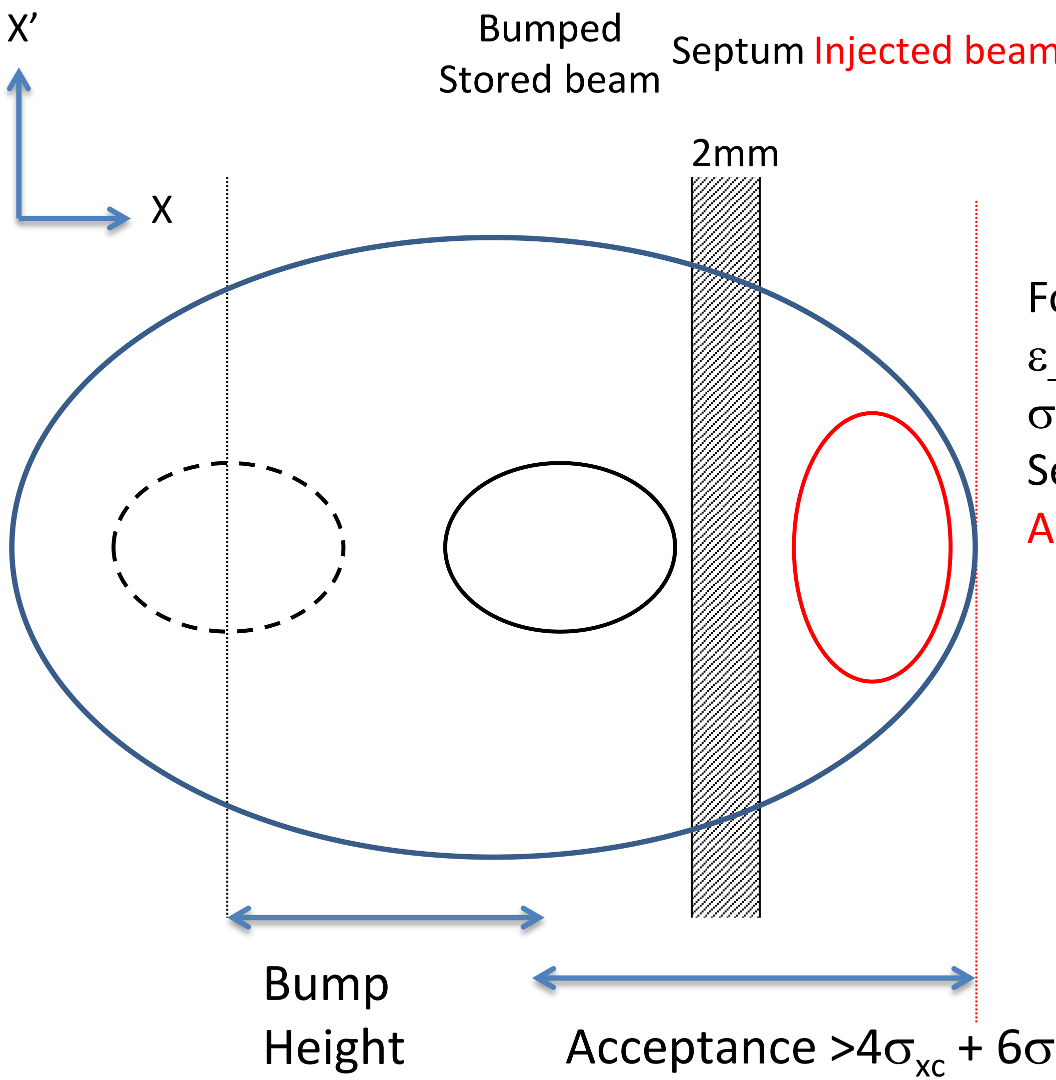
- The function of the straight section is phase advance tuning and injection.
  - Independent magnets for two rings
  - 0.3m of longitudinal distance between two quadrupoles of two rings allows a larger size of quadrupoles



Phase tuning **Injection** **Phase tuning**

Injection

conventional off axis injection
4 kicker for local bump in the collider

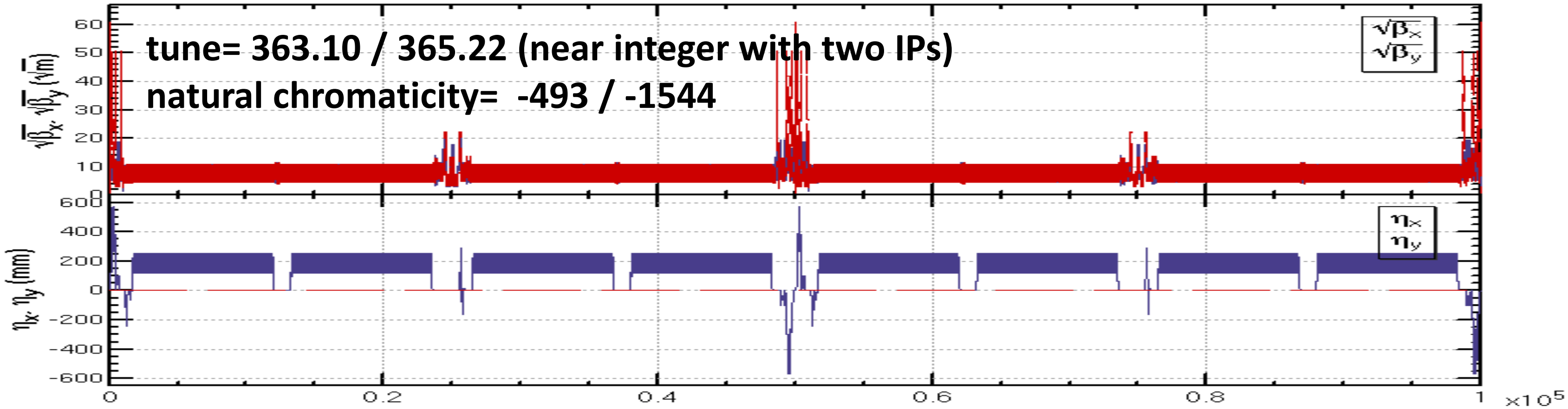


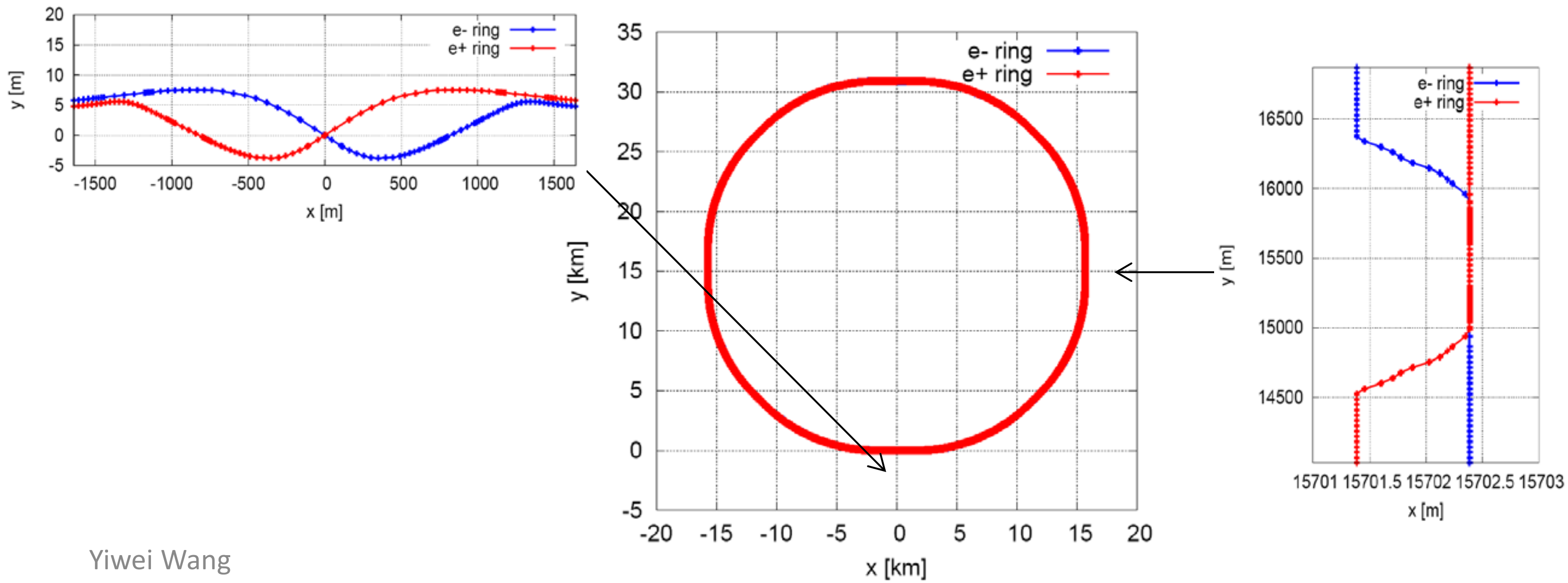
For Higgs:
ε_x = 1.21 nm.rad; ε_inject = 3.58 nm.rad
σx = 0.85 mm, σ_inject = 0.94 mm
Septum = 2 mm
Acceptance > 13 σ

by Xiaohao Cui

Linear optics of the collider ring

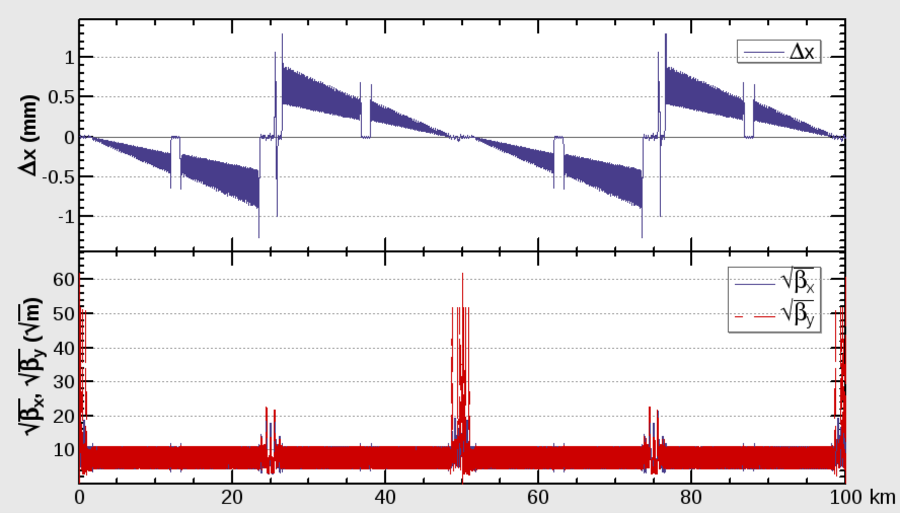
- An optics fulfilling requirements of the parameters list, geometry, photon background and key hardware.

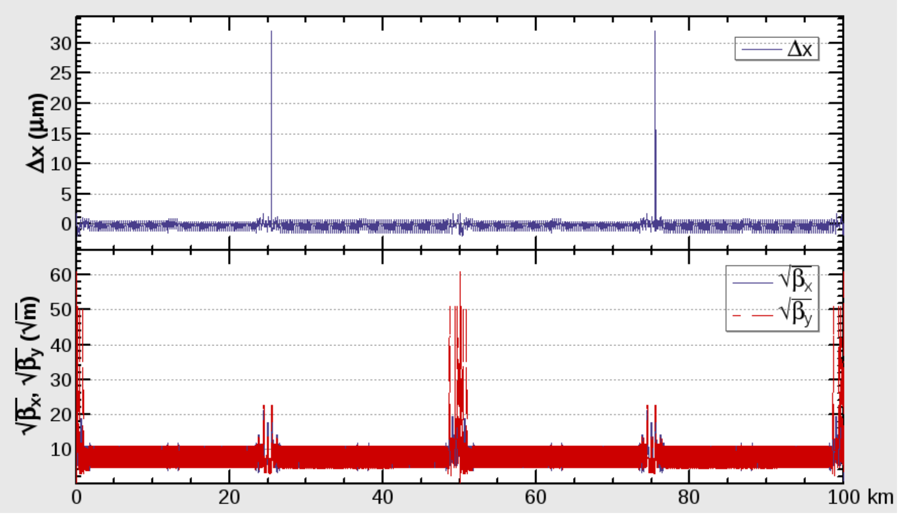




Sawtooth orbit correction

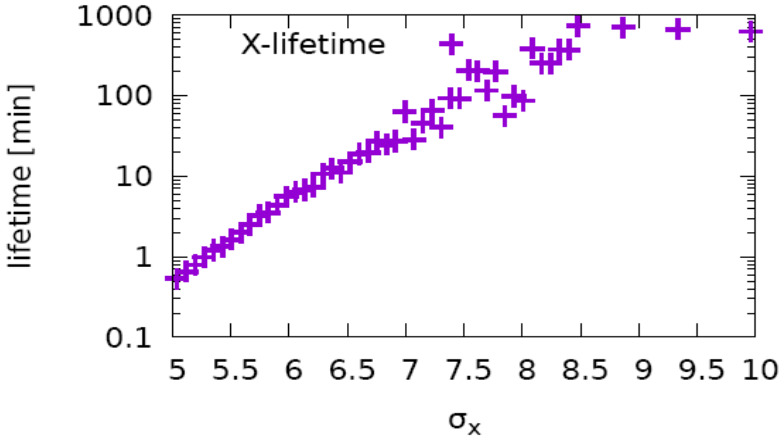
- With only two RF stations, the sawtooth orbit in CEPC collider ring around 1mm for Higgs and becomes 1um after tapering the magnet strength with beam energy.

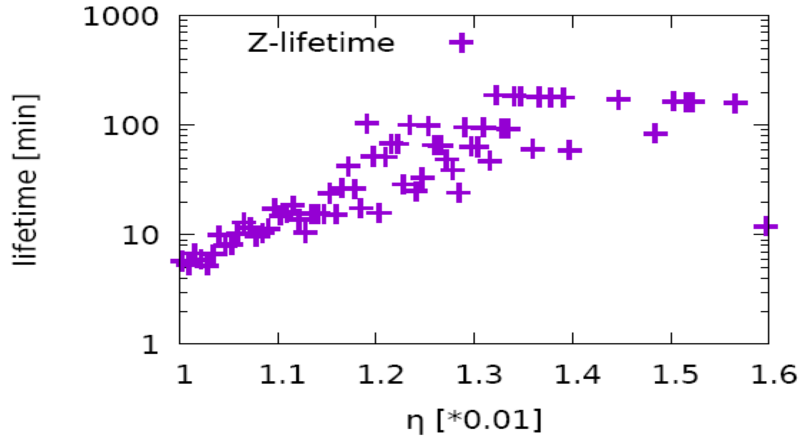


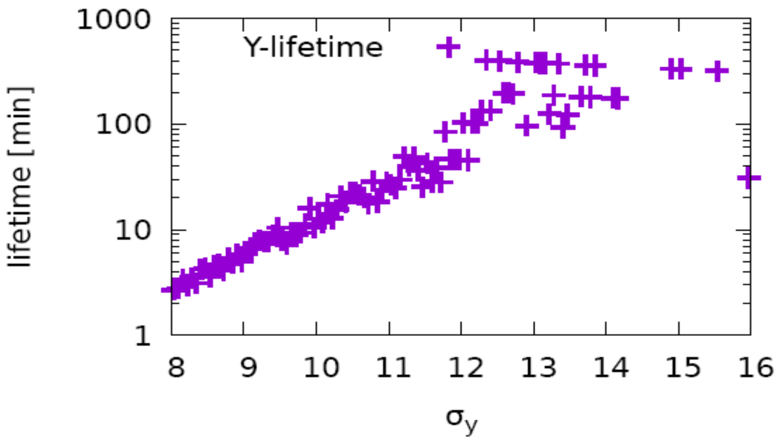


Requirement of the dynamic aperture

- Goal: 13 σx ×12.5 σy × 1.35%
  - Requirement from injection*: **13 σx**
  - Requirement from beam beam (life time 100 min)#: 7.5 σx, **12.5 σy, 1.35 %**







Simulation of Lattice + Beamstrahlung + SR Fluctuation

x-100min: 7.5 σx

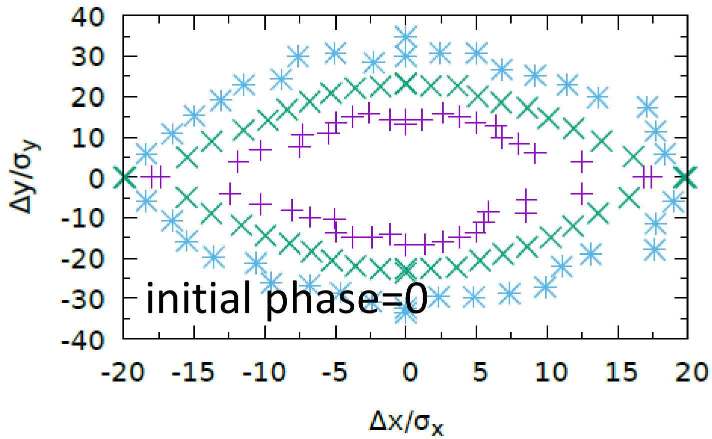
y-100min: **12.5 σy**

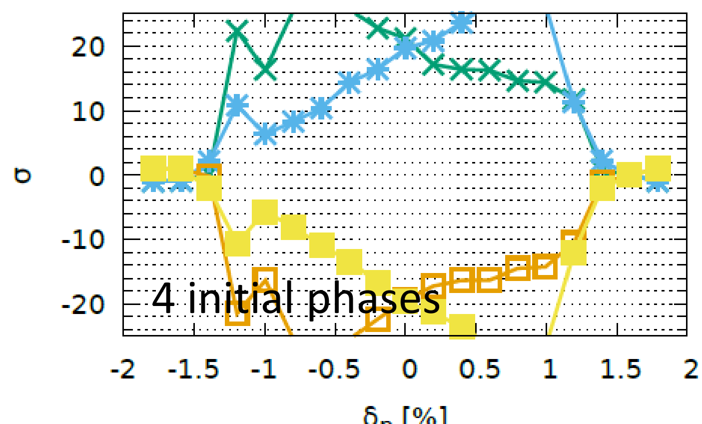
z-100min: **1.35%**

*X. Cui, # Yuan Zhang

Dynamic aperture optimization

- Start point of the optimization
  - 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**
- Tracking in SAD w/ damping, fluctuation(100 samples), energy sawtooth and tapering 200 turns, 4 initial phases





Achieved (without errors)@ Higgs : 15 σx ×15 σy × 1.5%

by Y. Zhang et. al.

Performance with errors

by Yuanyuan Wei

- LOCO based on AT is used to correct distortion of closed orbit, beta, dispersion and coupling
- About **1500 BPMs, horizontal and vertical correctors** are respectively placed in the storage ring (4 per one betatron wave; **IR is perfect**)

  1. correct COD w/o sextupoles

  2. correct the beta and dispersion w/ sextupoles

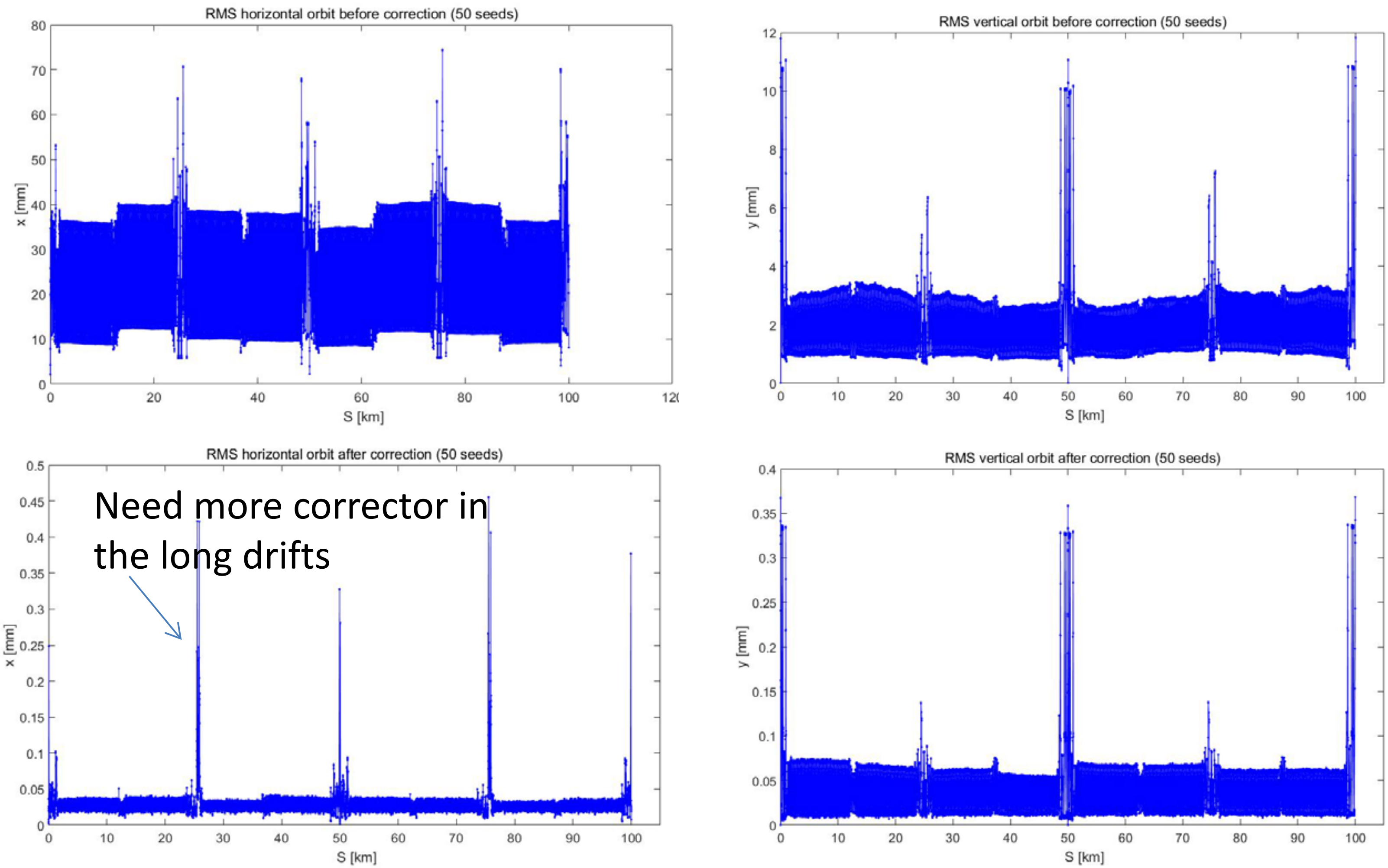
  3. correct coupling

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)
Dipole	0.05	0.05	0.1
Quadrupole	0.03	0.03	0.2
Sextupole	0.03	0.03	0.2

Component	Field error
Dipole	0.03%
Quadrupole	0.02%

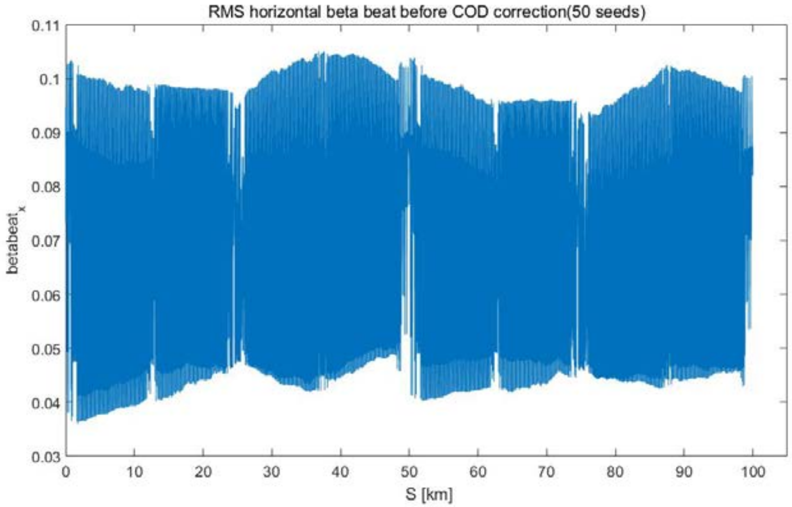
Basically same with HEPS

1. correct COD w/o sextupoles
Closed orbit distortion

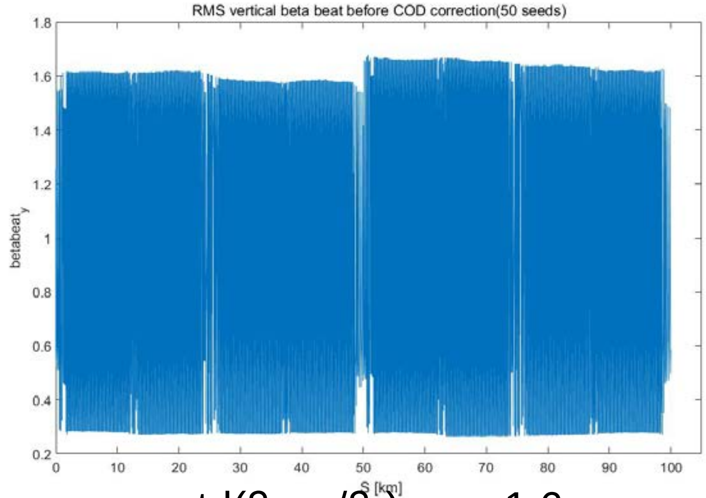


residue $\sigma_{COD} \approx$ 40/75 um (x/y) after orbit correction
50 seeds

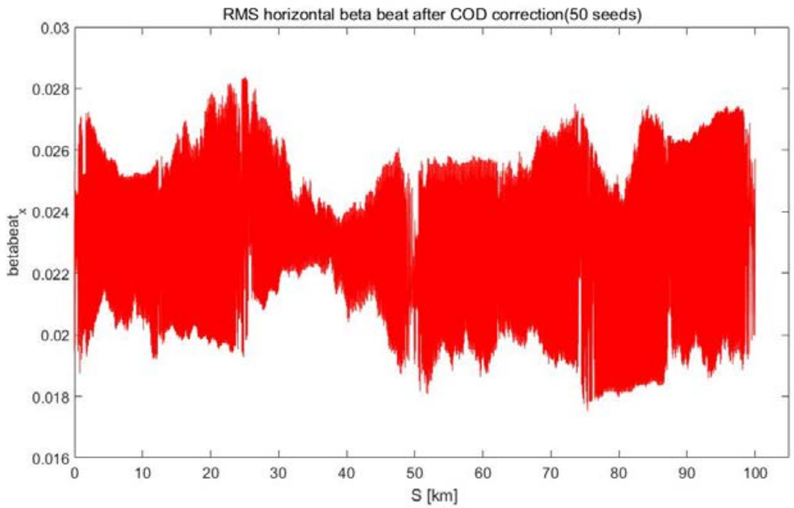
1. correct COD w/o sextupoles
Beta functions distortion



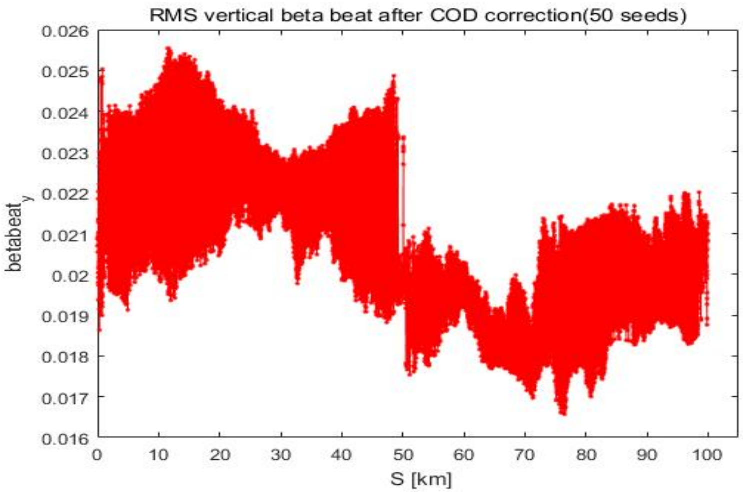
$std(\beta_{x\_err}/\beta_x)_{max} = 0.1$



$std(\beta_{y\_err}/\beta_y)_{max} = 1.6$



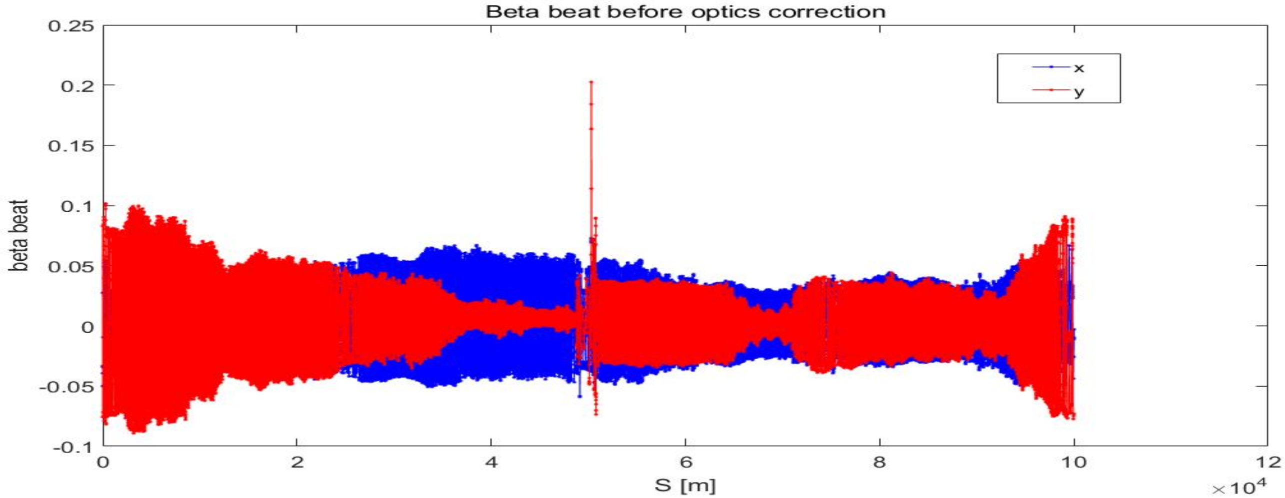
$std(\beta_{x\_err}/\beta_x)_{max} = 0.028$



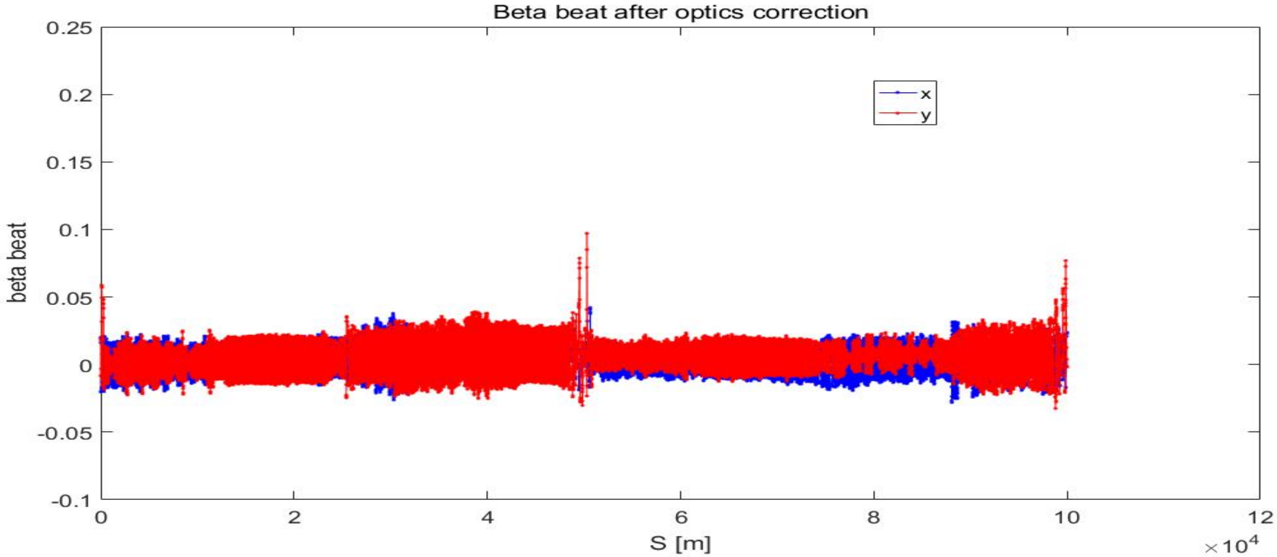
$std(\beta_{y\_err}/\beta_y)_{max} = 0.025$

2. correct the beta and dispersion w/ sextupoles

1/5 quadrupole (~600 out of 3000 quadrupoels) strengths are changed to restore beta functions



one sample



3. correct the coupling

with one sample

- Quadrupoles rotation and feed-down effects in the quadrupoles will cause vertical dispersion and generates betatron coupling
- Skew-Quads are installed in the sextupoles. Totally about 200 Skew-quads (1/5 sextupoles) are used in the coupling correction
- Before correction

  emitx=1.25nm, emity=5.11e-3nm, emity/emitx=0.4%
- After correction

  emitx=1.26nm, emity=9.64e-4nm, emity/emitx=0.08%

Summary

- Linear optics of the CEPC collider ring designed fulfilling requirements of the parameters list, geometry, photon background and key hardware.
- Nonlinearity correction made to give a good start point of dynamic aperture optimization.
- Further optimization of dynamic aperture is made with MODE and downhill simplex method.
- Study of errors and correction made and the study of effects on dynamic aperture is under going.

Thanks

- Thanks for the beneficial discussion with
  Y. Cai, K. Oide, A. Bogomyagkov
- IAS HEP program

Thank you!