Beam optics design of the CEPC collider ring with SAD

Yiwei Wang, Yuan Zhang, Chenghui Yu,
Yuanyuan Wei, Sha Bai, Dou Wang
IHEP, CAS

SAD Workshop 2019, 18-19 Nov 2019, KEK, Tsukuba

Thanks for the beneficial discussion with
K. Oide, Y. Cai, D. Zhou, A. Bogomyagkov, K. Ohmi, Y. Ohnishi et al

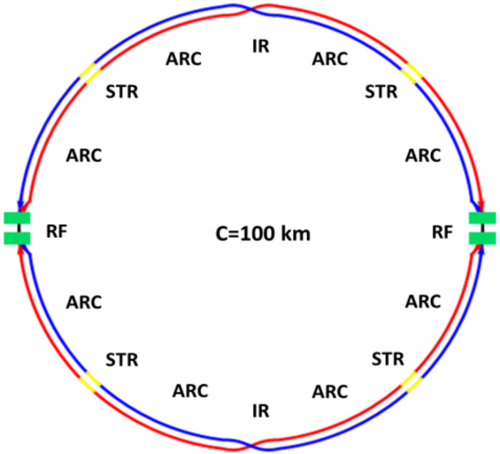
Work supported by National Natural Science Foundation of China (Grant No.: 11605211, 11575218), Key Research Program of Frontier Sciences, CAS (Grant No. QYZDJ-SSW-SLH004)

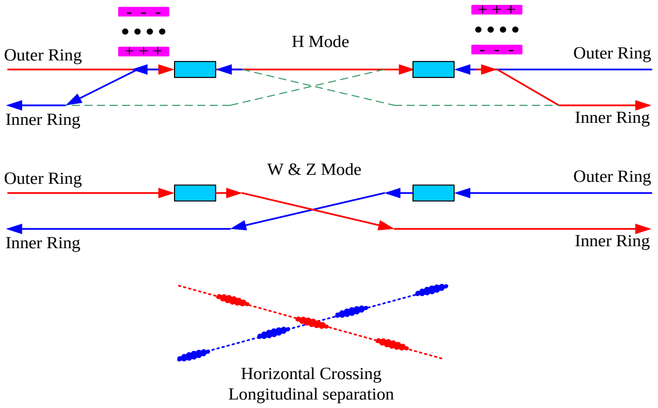
Lattice design of CEPC collider ring

- The SAD has been used for the lattice design and dynamic aperture study.
  - linear lattice and geometry matching
  - Some scripts were developed for the nonlinear optimization
  - A multi-objective optimization by differential evolution algorithm (MODE) was developed for further optimization of the DA.
- The LOCO based on AT is used to make error correction
- The conceptual design was finished by June 2018. We are working on a new lattice aiming at better dynamic aperture, loose error requirements and higher luminosity toward a TDR.

Introduction to CEPC collider ring

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





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

CEPC CDR parameters

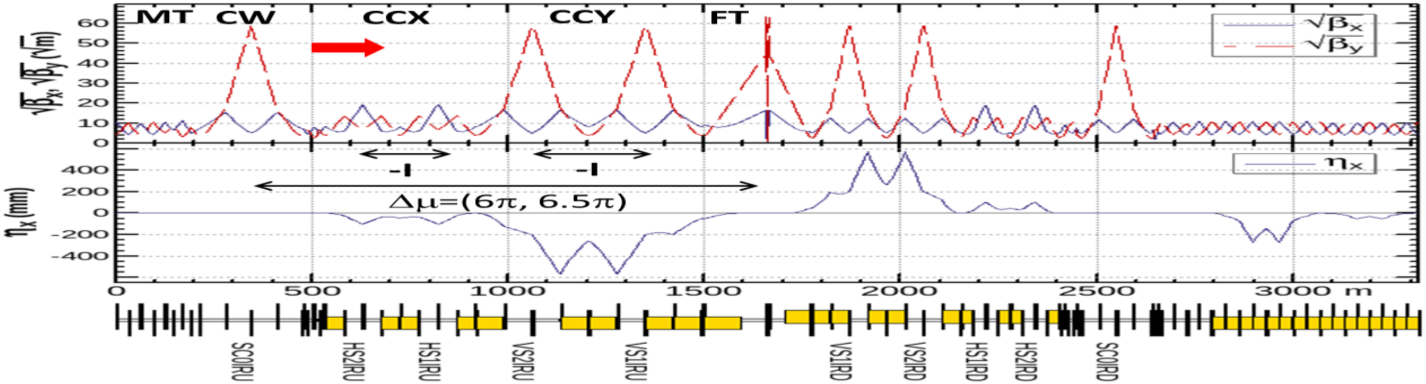
D. Wang
et al

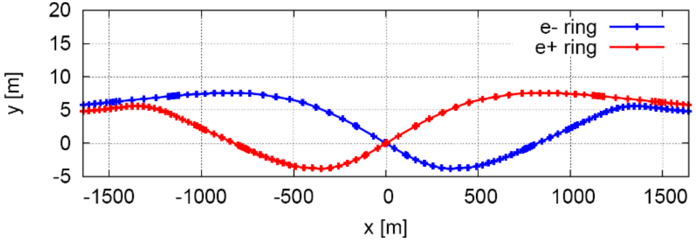
	Higgs	***W***	***Z（3T）***	***Z（2T）***
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	3.48	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
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**

A new luminosity target is 5*10^34 and it need by*=1mm, ex=0.89nm

Optics of Interaction region

- local chromaticity correction of both planes, 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



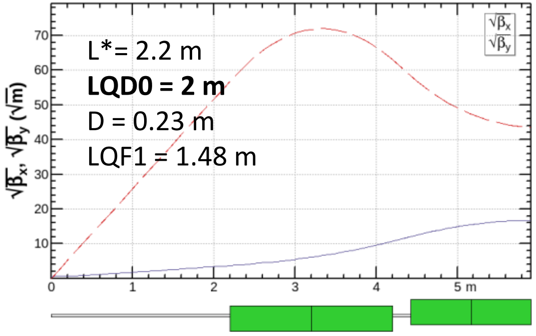


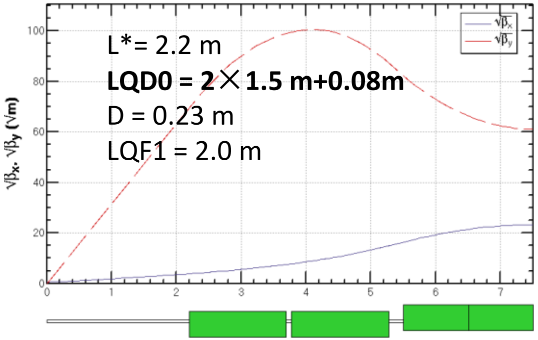
	Higgs	W	Z (3T)	Z(2T)
Vertical emittance [pm·rad]	0.16	0.53	2.9	0.45
Normalized Vertical Emittance Budget	6.7%	33%	71%	28%
Emittance Coupling Budget	0.2%	0.3%	2.2%	0.89%

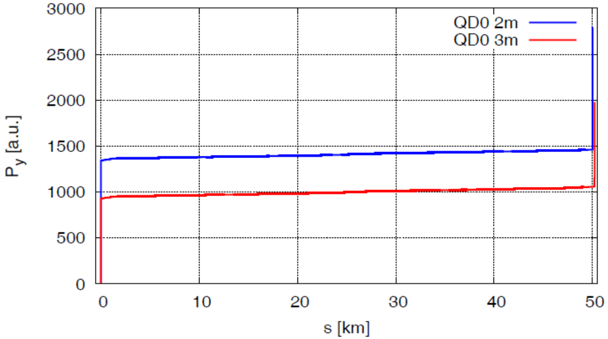
1) K. Oide et al., ICHEP16.
2) M. Zobov et al., Phys. Rev. Lett. 104, 174801(2010).

Optimization of the quadrupole radiation effect

- The dynamic aperture reduction due to the damping and fluctuation is significant especially on the vertical plane.
- Radiation power due to quadrupoles: $P \propto \int B^2 ds \propto \int K_1^2 \beta ds \cong \sum (K_1 l)^2 \beta / l$
  - contribution of QD0 dominant
  - longer QD0 will significantly decreased the power on vertical plane and thus help to increase the dynamic aperture: QD0/QF1 2m/1.48m => 3m/2m

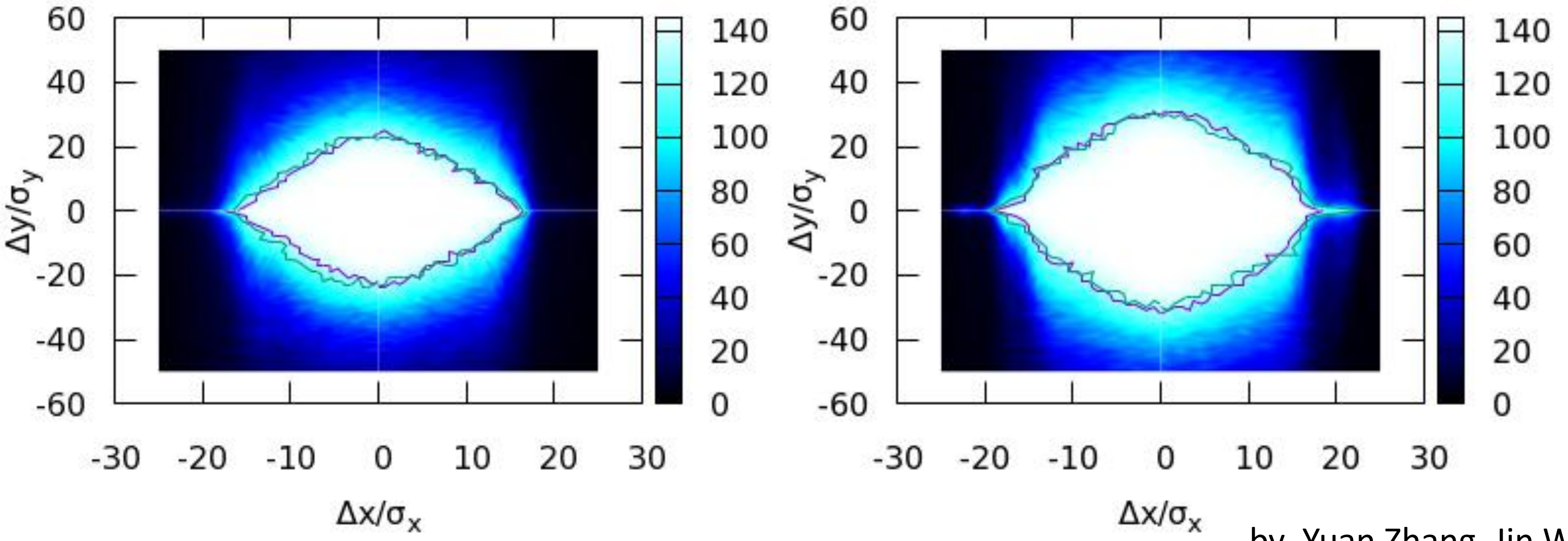






Optimization of the quadrupole radiation effect (cont.)

- Checked with CDR lattice
- With longer QD0, the vertical dynamic aperture increased around 30%.



by Yuan Zhang, Jin Wu

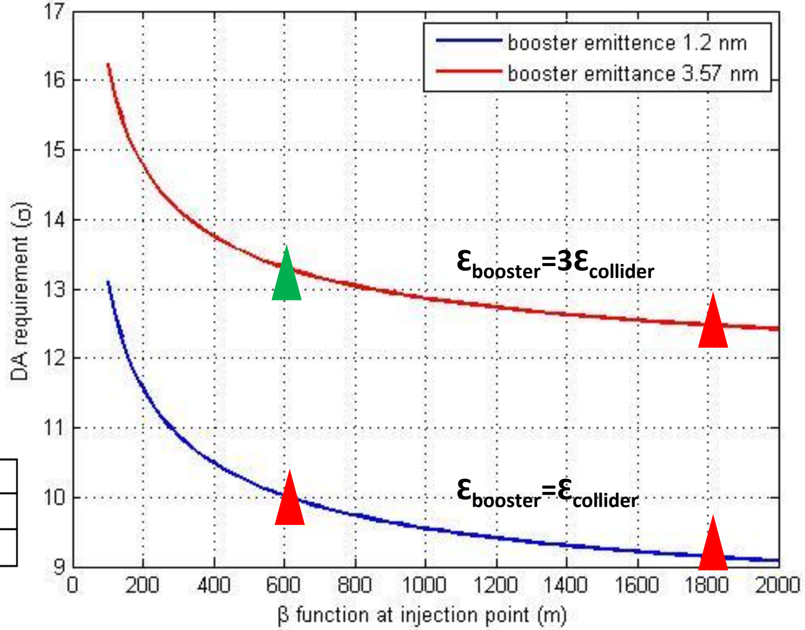
Reduction of dynamic aperture requirement from injection

- Trying to relax the dynamic aperture requirement of the off-axis injection scheme
  - Larger βx at injection point
  - Smaller injected emittance from booster

DA requirement for the CDR parameters

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

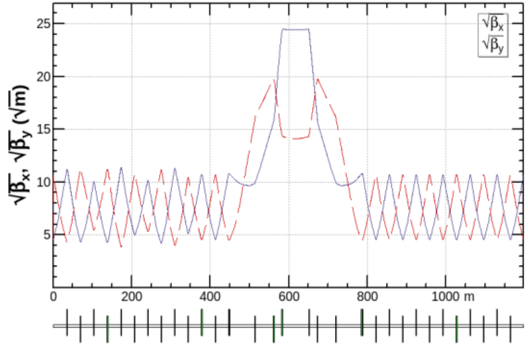
Horizontal DA requirement with off-axis injection

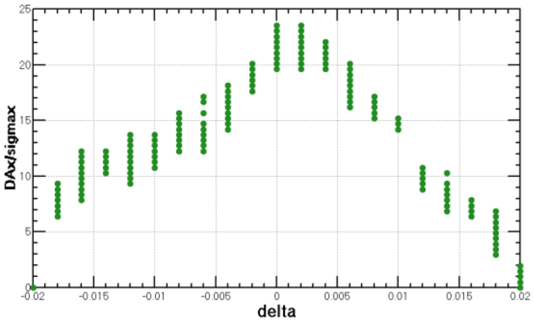


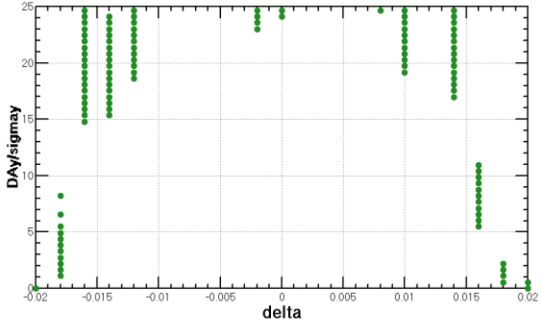
by Xiaohao CUI

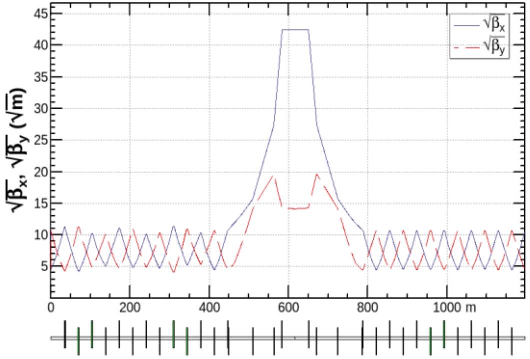
Reduction of dynamic aperture requirement from injection (cont.)

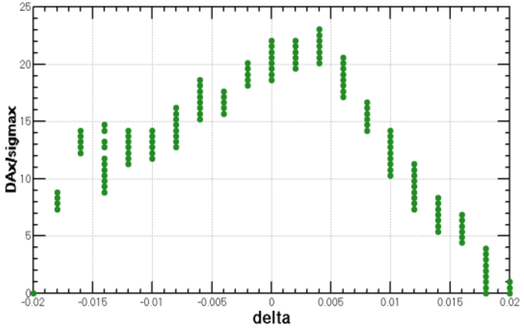
- Larger βx at injection point
  - βx increased from 600m to 1800m
  - Increased horizontal chromaticity is small and the results of DA are almost the same.

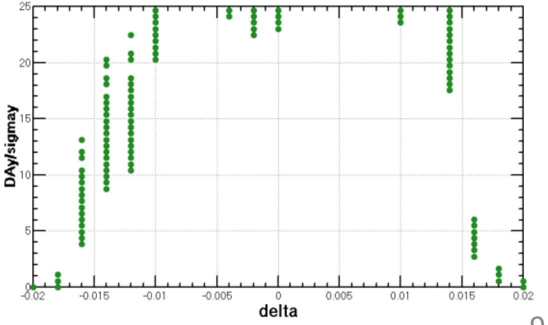












*based on CDR lattice

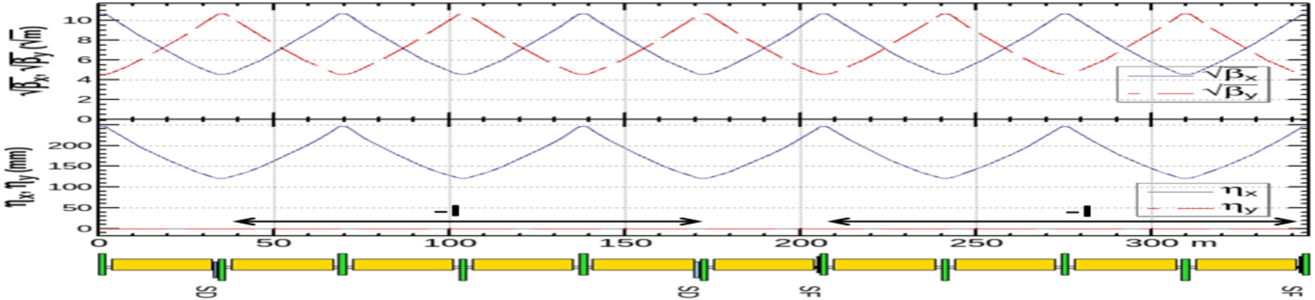
Optics choice of ARC region

For the Arc region, the FODO cell structure is chosen to provide a large filling factor.

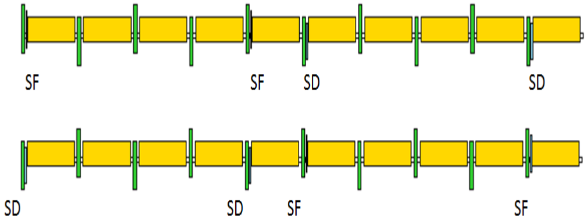
	Interleave sextupoles	**Non-interleaved sextupoles**
60 ° /60°	n=6 lowest 2 orders of RDT except 2Qx-2Qy due to sextupoles cancelled **dQ(Jx,Jy): accumalte to be large** dQ(δ): small even with 2 families **DA on momentum: limited by tune shift dQ(Jx,Jy)** DA off momentum: easy to optim.	-
90 ° /60 °	n=12 lowest 2 orders of RDT except 4Qx due to sextupoles cancelled **dQ(Jx,Jy): accumalte to be large** dQ(δ): small even with 2 families **DA on momentum: limited by tune shift dQ(Jx,Jy)** DA off momentum: easy to optim.	-
90 ° /90 °	n=4 lowest 2 orders of except 4Qx, 2Qx+2Qy, 4Qy, 2Qx-2Qy due to sextupoles cancelled **dQ(Jx,Jy): accumalte to be large** dQ(δ): small even with 2 families **DA on momentum: limited by tune shift dQ(Jx,Jy)** DA off momentum: easy to optim.	n=5 lowest 2 orders of except small 4Qx, 2Qx+2Qy, 4Qy, 2Qx-2Qy due to sextupoles cancelled **dQ(Jx,Jy): small** dQ(δ): correct with many families **DA on momentum: large as small tune shift dQ(Jx,Jy)** **DA off momentum: with many families to correct dQ(δ) and –I break down**

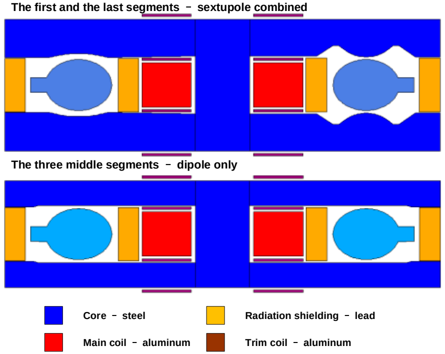
Optics design of ARC region

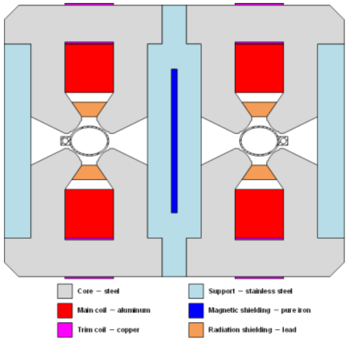
- FODO cell, 90°/90°, non-interleaved sextupole scheme, period =5cells



- **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.



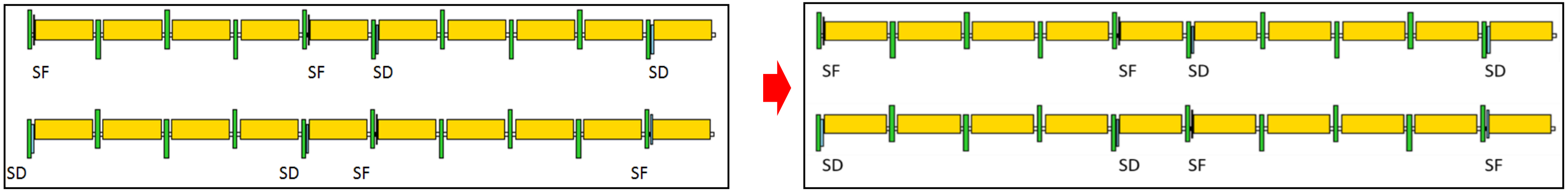


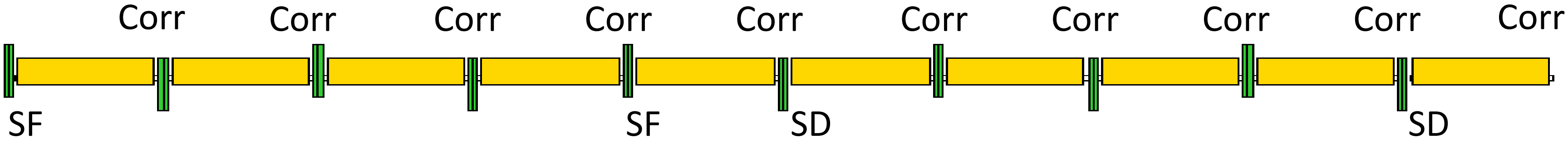


*Ref: A. Milanese,
PRAB 19, 112401 (2016)

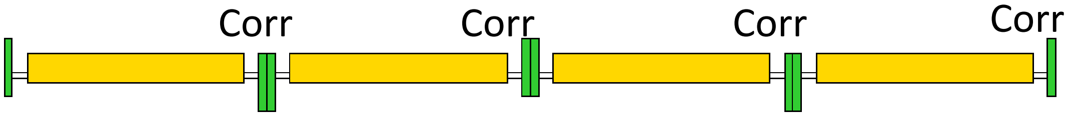
magnets designed by
F. Chen, M. Yang, X. Sun et al.

Maximization of the bend filling factor in the ARC





L+0.7m 1.1m+L+0.7m 1.1m+L+0.7m 1.1m+L+0.7m L+0.7m L+0.7m 1.1m+L+0.7m 1.1m+L+0.7m 1.1m+L+0.7m L+0.7m

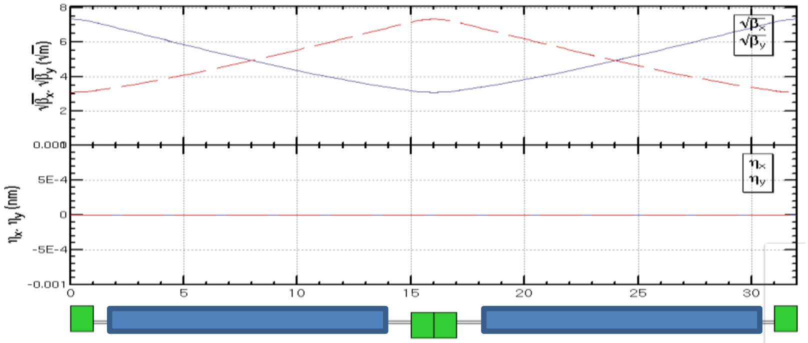


1.1m+L+0.7m 1.1m+L+0.7m 1.1m+L+0.7m 1.1m+L+0.7m

Bend: L -> L+0.7m, L+1.8m
Quad: 2m -> 3m
SF: 0.7m
SD: 1.4m
Corr: 0.3m (drift 0.15m)
Drift: 0.2m

FODO cell for cryo-module

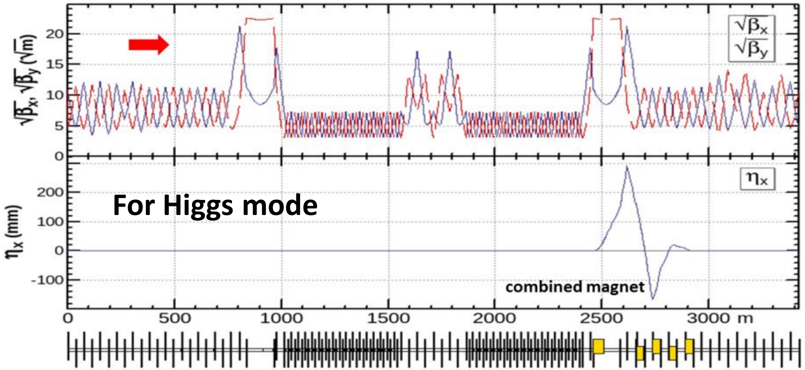
- Get a smallest average beta function to reduce the multi-bunch instability caused by RF cavities especially for the Z mode
  - 90/90 degree phase advance
  - The distance between quadrupoles is 13.7 m which allow a cryo-module with length of 12m.
  - average beta function 30 m
- 336 / 6 / 2RF stations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

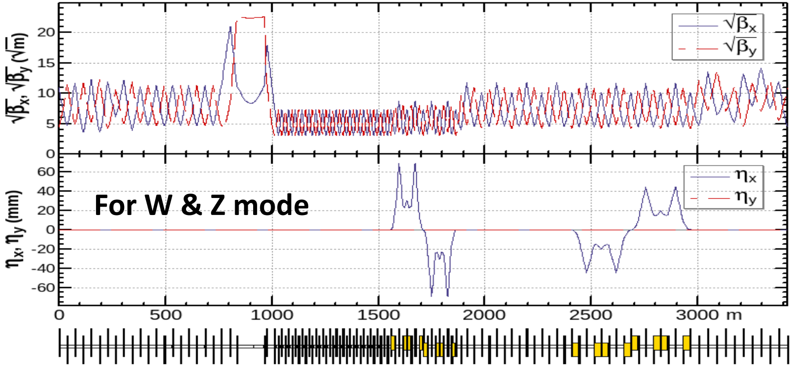


90/90 deg
Half cell: 13.7m+2.3m
βmax: 53.8 m
βmin: 9.5 m

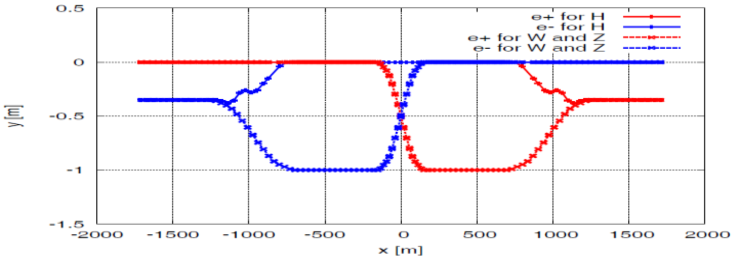
Optics design of RF region

- **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**



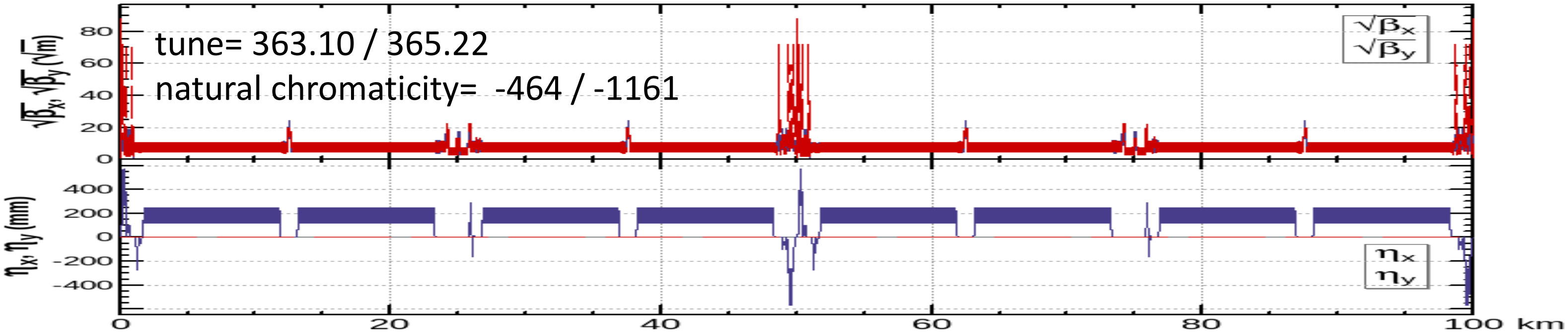


Esep= 2.0 MV/m
Bdip=66.7 G
L= 4 m×10
Δx= 13.3 cm at the entrance of quad

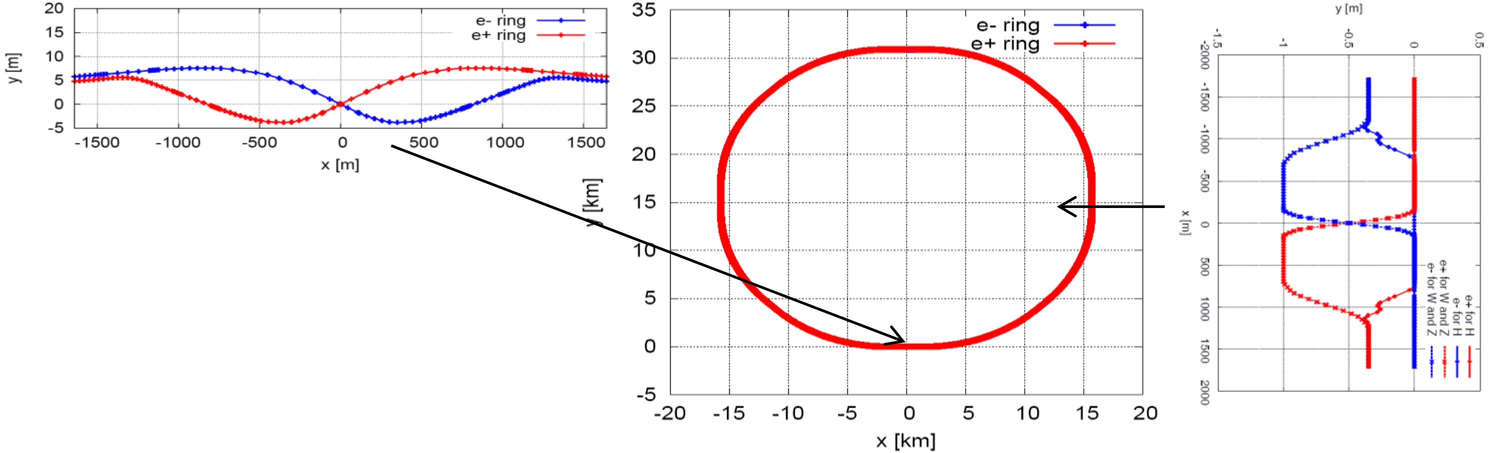


Optics of the collider ring

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

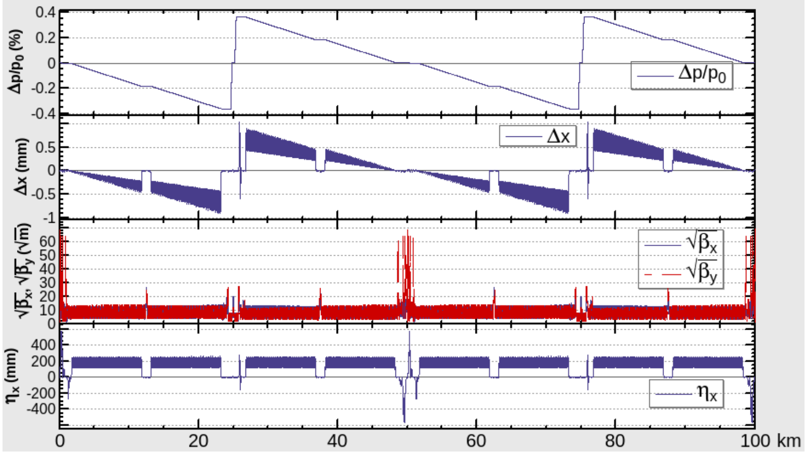

tune= 363.10 / 365.22

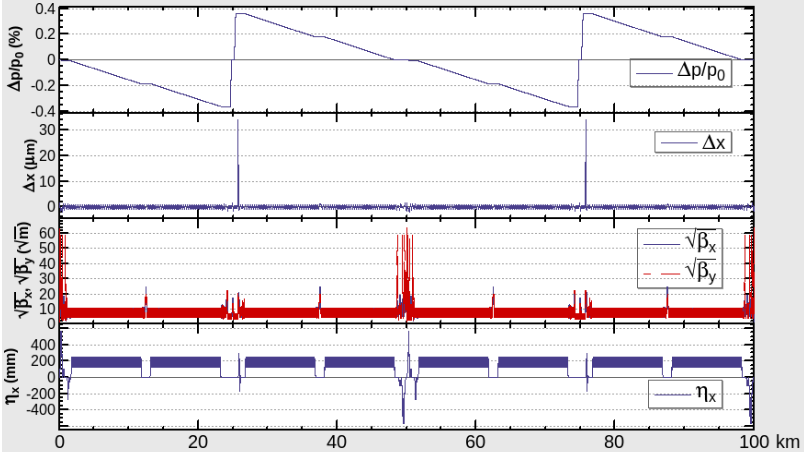
natural chromaticity= -464 / -1161



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%





Nonlinearity optimization

- SAD provided flexible optimization method of the beta, dispersion distortion and tune shift due to energy deviation.
- Other nonlinearity such as tune shift due to amplitude, resonance-driving-terms analysis are not implemented in SAD thus some scripts were developed.

Analysis of the resonance-driving-terms

- Analysis of the resonance-driving-terms with one-turn map
  - The value of whole ring is important as well as the transportation along the beam line
  - The latter analysis show how the RDTs generated, transported, canceled or enhanced.
- J. Bengttson and C. Wang's explicit formulas for the lowest 2 orders of RDTs used

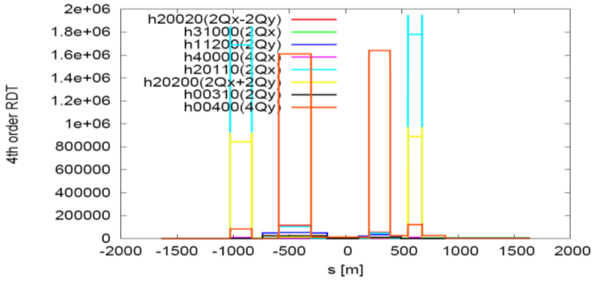
$$h_{00310} = h^*_{00130} = \sum \frac{i}{32} \bar{b}_{3i}\bar{b}_{3j}\sqrt{\beta_{xi}\beta_{xj}}\beta_{yi}\beta_{yj}\left[e^{i(\psi_{xi}-\psi_{xj}+2\psi_{yi})} - e^{-i(\psi_{xi}-\psi_{xj}-2\psi_{yi})}\right],$$

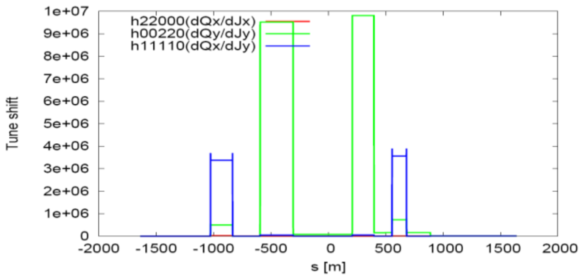
$$h_{00400} = h^*_{00040} = \sum \frac{i}{64} \bar{b}_{3i}\bar{b}_{3j}\sqrt{\beta_{xi}\beta_{xj}}\beta_{yi}\beta_{yj}e^{i(\psi_{xi}-\psi_{xj}+2\psi_{yi}+2\psi_{yj})},$$

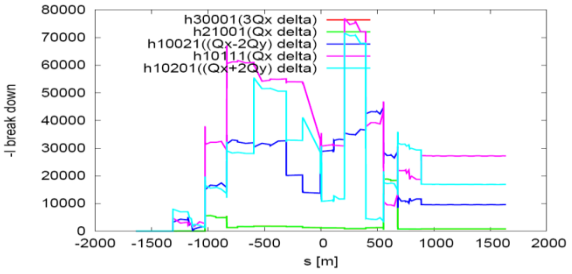
Nonlinearity correction of Interaction region

- **Local chromaticity correction** with sextupoles pairs separated by –I transportation
  - lowest 2 orders of resonance driving terms (RDT) due to sextupoles cancelled1)
  - **up to 3rd order chromaticity** corrected with main sextupoles, phase tuning, additional sextupole pair 2,3)
  - **tune shift dQ(Jx, Jy)** due to finite length of main sextupoles corrected with additional weak sextupoles 3,4)
  - **Break down of –I** could be 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

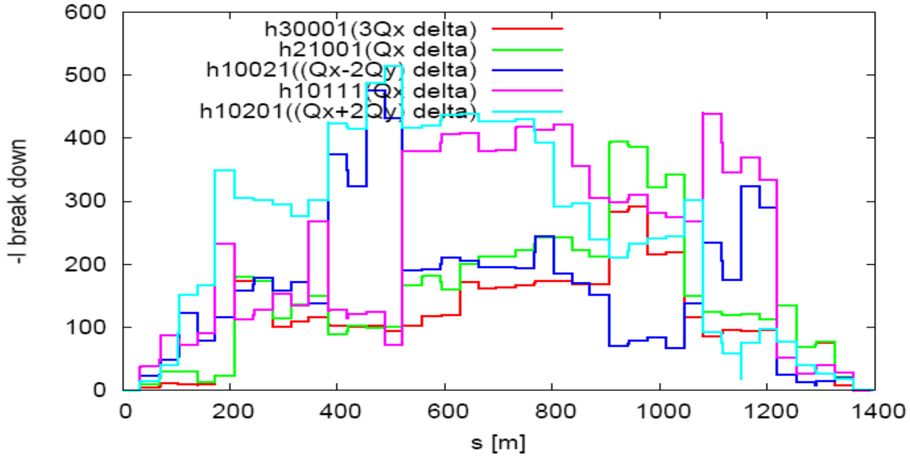






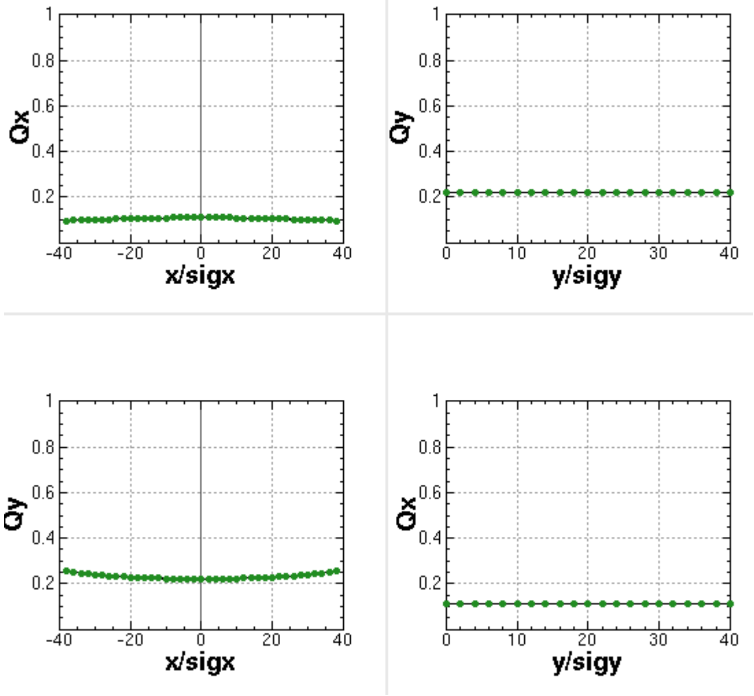
Nonlinearity correction of ARC region

- FODO cell, 90°/90°, non-interleaved sextupole scheme, period =5 cells
- With 2 families of sextupoles in each 4 periods, i.e. 20 cells
  - lowest 2 orders of 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



Tune shift of the whole ring

- A package of FMA scripts translated from the AT was implemented.
- Tune shift due to the amplitude of the whole ring



Dynamic Aperture Tracking & Optimization

Y. Zhang

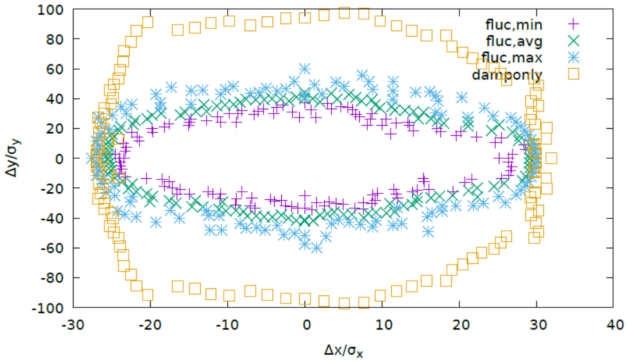
SAD (http://acc-physics.kek.jp/SAD/):
Synchrotron motion, synchrotron radiation in dipoles, quads and sextupoles, tapering, Maxwellian fringes, kinematical terms, crab waist are considered.

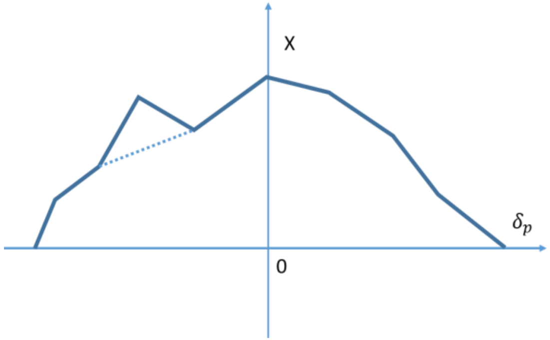
Suppress noise of DA with SR fluctuation

- 10 more times survey for on-momentum particle is tracked, and the minimum value is treated as the on-momentum DA
- Tracked DA result will be clipped to ensure DA at large momentum deviation will be less than that at small deviation

Two algorithms are used in the optimization

- **MODE**: **M**ulti-**O**bjective optimization by **D**ifferential **E**volution (Y. Zhang and D. Zhou, IPAC'16; J. Qiang, IPAC'13)
- **Downhill Simplex** implemented in SAD by K. Oide





Dynamic Aperture Tracking & Optimization

- SAD(http://acc-physics.kek.jp/sad/) is used for the DA determination. It is a parallel code, but the scalability is not very good. A MPI-based parallel code to call SAD will be much more efficient for the **MODE.**

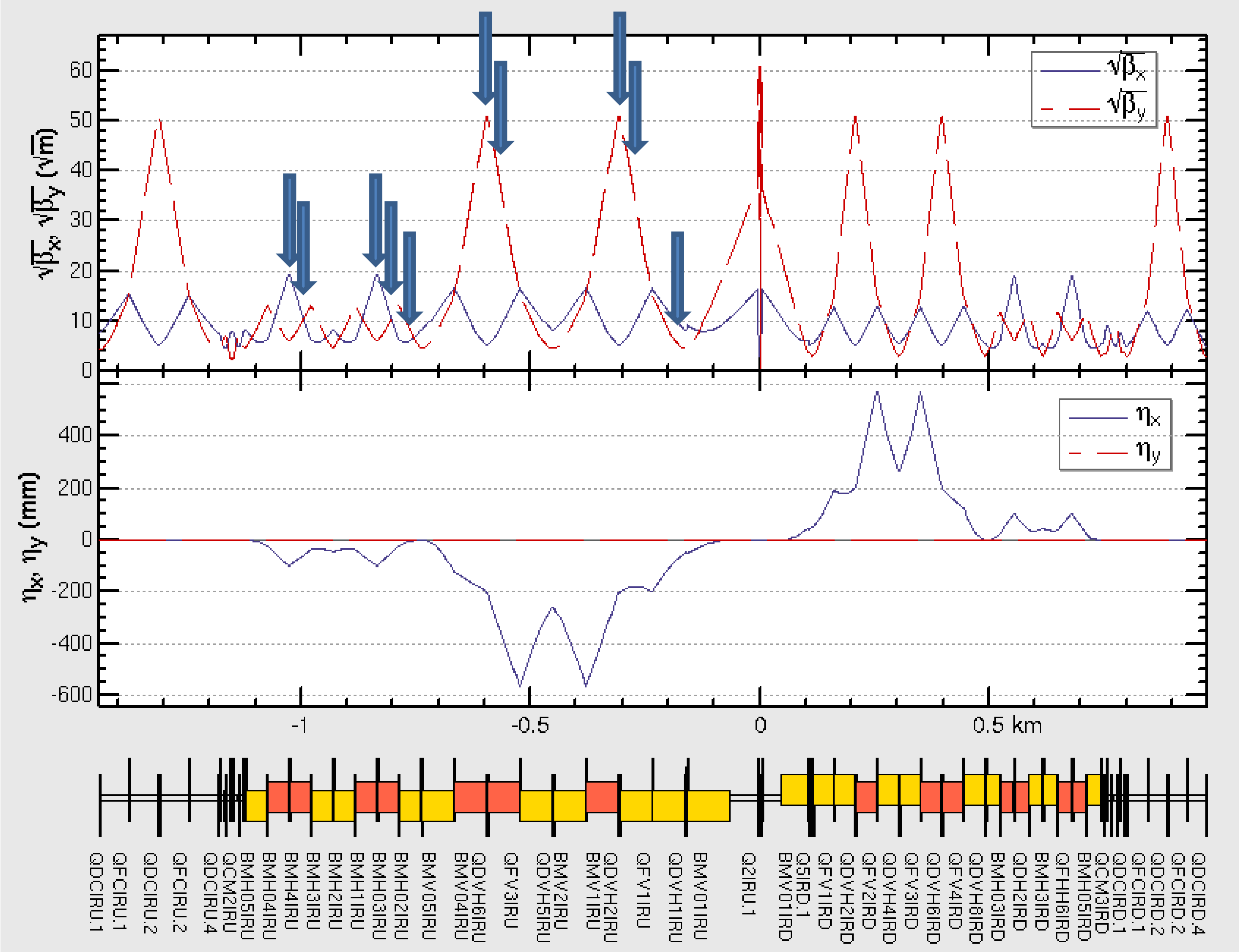
Dynamic aperture optimization

- 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
  - Nonlinearity optimized term by term with 10 families of sextupoles in the IR and 4 families of sextupoles in the ARC.
- **Directly optimize dynamic aperture** with MODE
  - With **10 families of sextupoles in the IR, 32 families of sextupoles in ARC and 8 phase advances**

IR knobs



- Main Chromaticity Sextupoles (2)
- Neighbor weaker sextupole to correct finite length effect (2)

A. Bogomyagkov, ArXiv:0909.4872

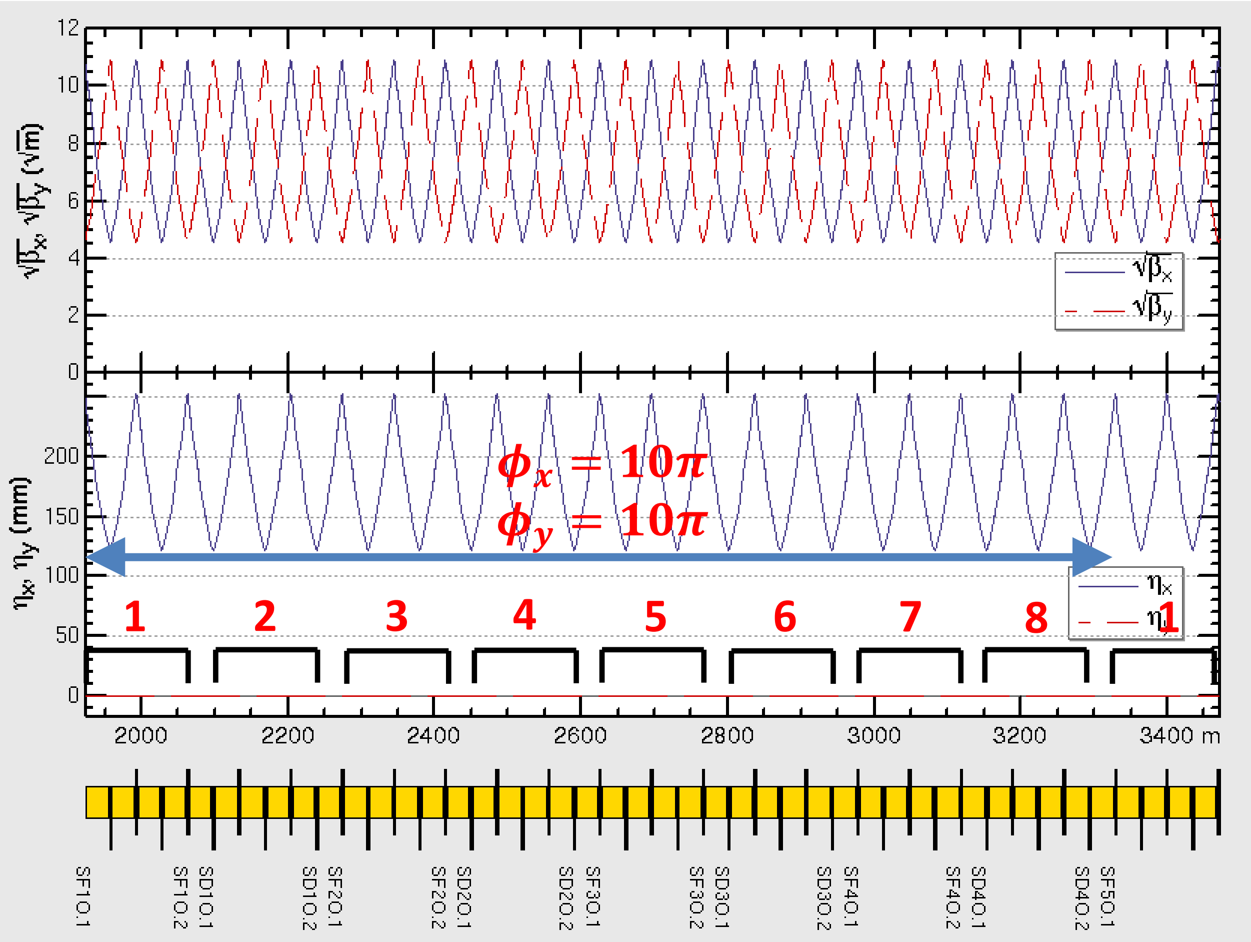
- Sextupole to correct higher order chromaticity in vertical direction (1)

Y. Cai, PRAB.19.111006

Different strength between Upstream and Downstream of IP.

10 knobs in IR.

Arc sextupole

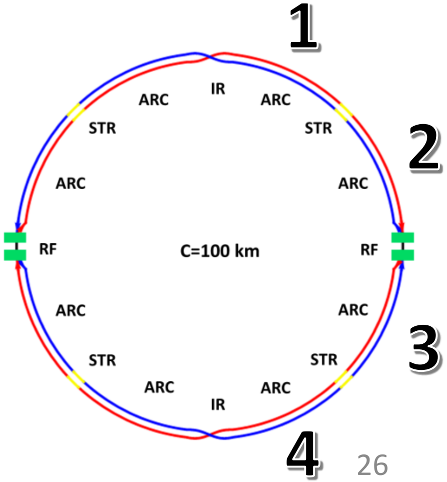


$\phi_x = 10\pi$

$\phi_y = 10\pi$

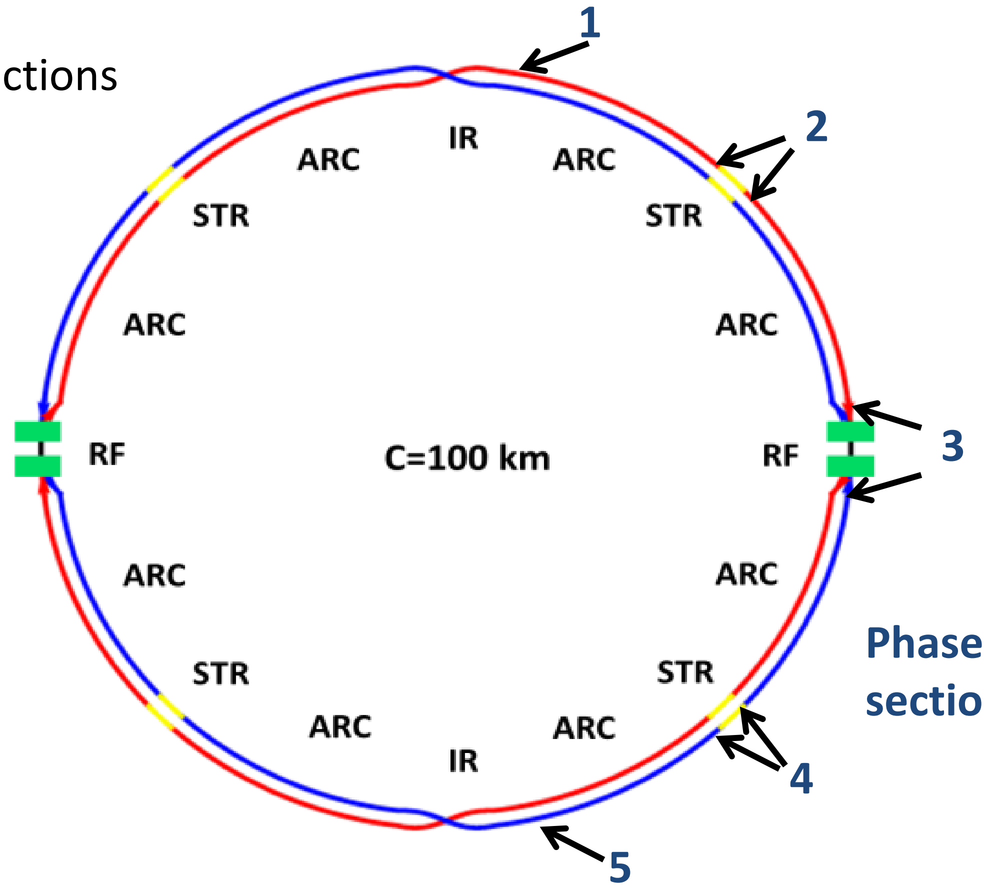
- 90/90 FODO
- Non-interleave sextupole scheme
- 4 SF + 4 SD sextupole configurations in one arc section
- 7 sub-period in in one arc section
- 4 arc section in half ring

Total knobs: 32 (or 56*4=224)



Phase advance tuning knobs

- 10 knobs in x and y directions
- Keep tune fixed
- Only 8 free knobs

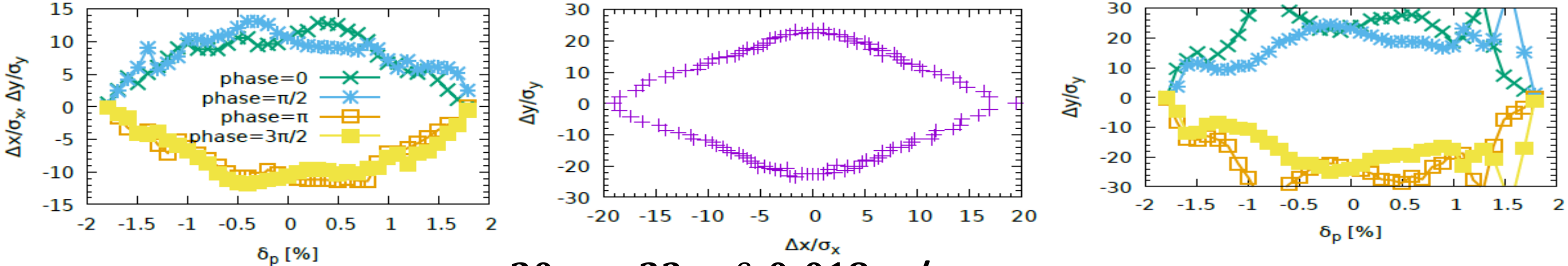


Phase tuning section

Dynamic aperture result (w/o errors)

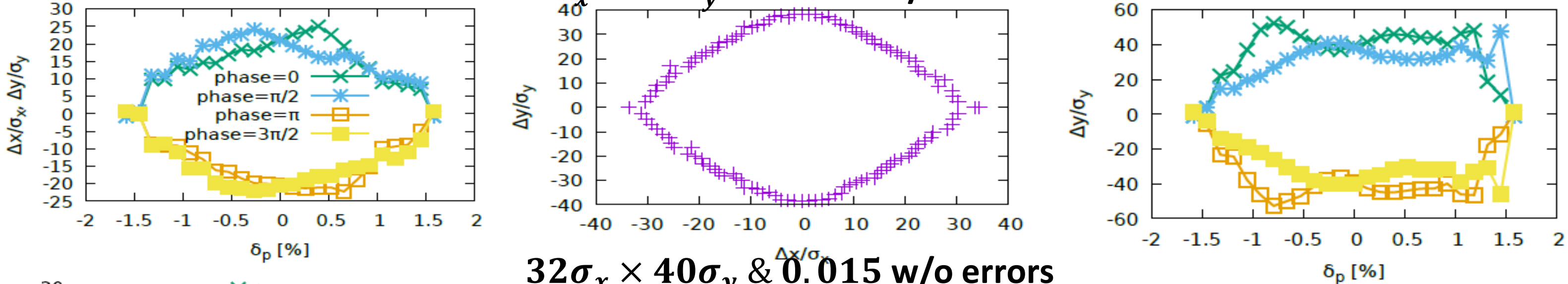
Tracking in SAD w/ synchrotron radiation damping, fluctuation(100 samples), energy sawtooth and tapering, 145/475/2600 turns(H/W/Z, 2 damping times), 4 initial phases

Higgs



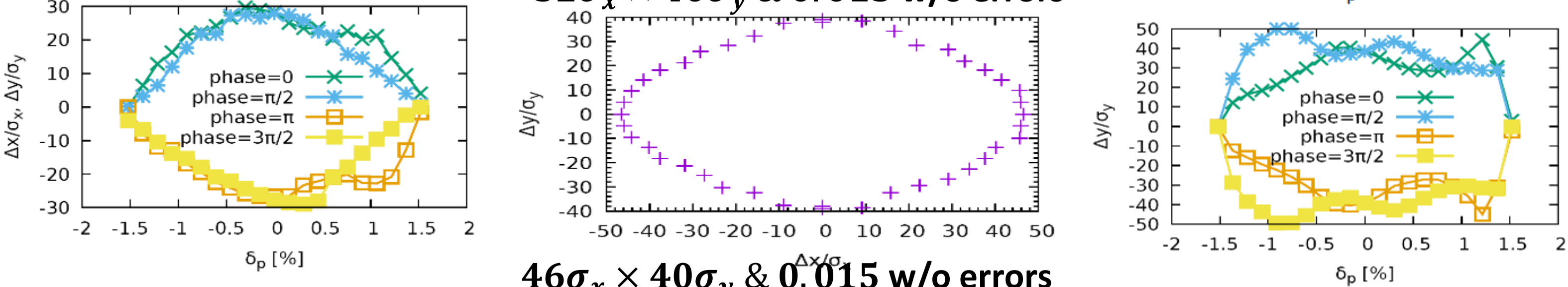
$20\sigma_x \times 23\sigma_y$ & 0.018 w/o errors

W



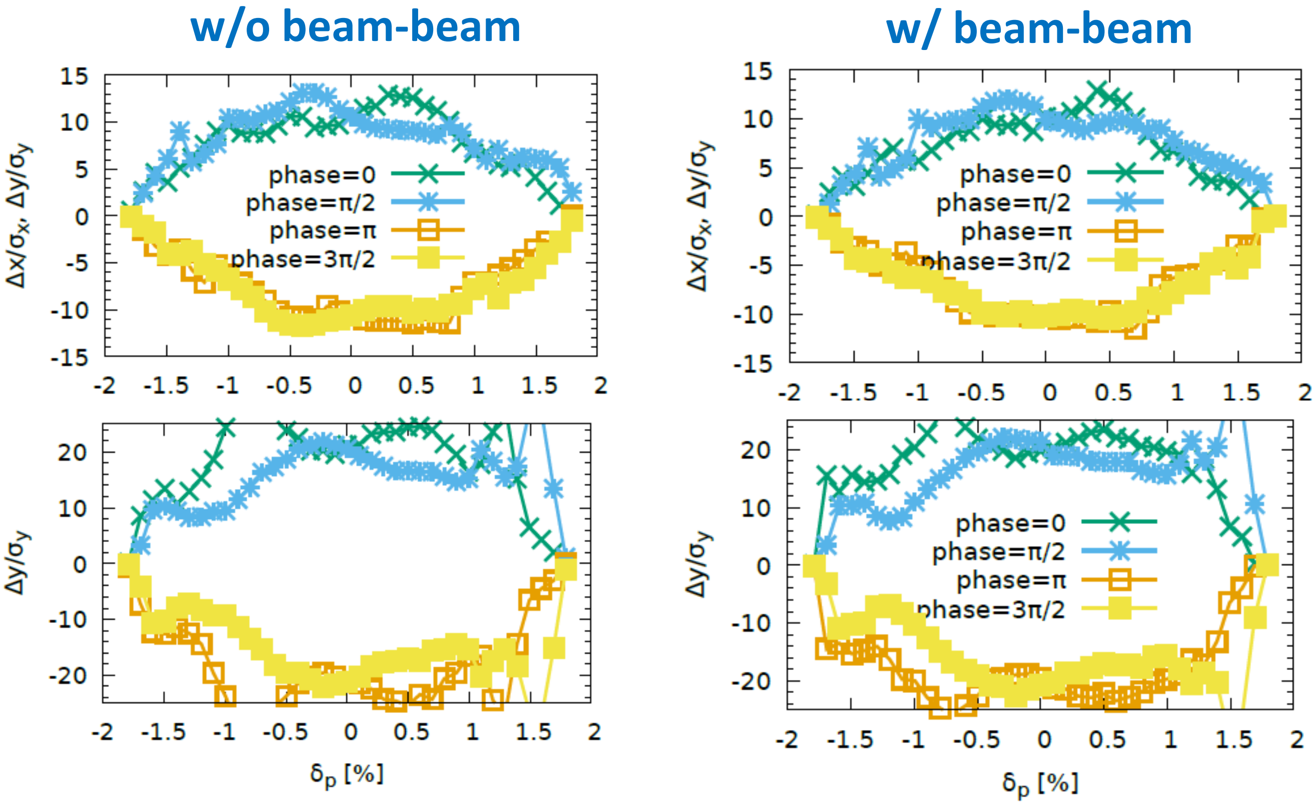
$32\sigma_x \times 40\sigma_y$ & 0.015 w/o errors

Z



$46\sigma_x \times 40\sigma_y$ & 0.015 w/o errors

Dynamic aperture: w/o and w/ beam-beam interaction


w/o beam-beam

w/ beam-beam

Higgs

The DA are almost the same as the beam-beam interaction are weak for the particles with large amplitude.

Speed-up Method

- Brute-force dynamic aperture tracking is very time consuming
- The objective is first eased, for example only track 100 turns instead of 1000 turns.
- Some constraints must be satisfied and may be much faster. Referencing to Ehrilichman's work[arXiv: 1603.02459], the multi-objectives are classified into two kinds. The time consuming cost function be calculated only when the necessary constraints (or objective) be satisfied.

Summary

- The SAD has been used for the lattice design and dynamic aperture study of CEPC collider ring. It’s friendly programmable and provides flexible functions for lattice design and optimization.
  - linear lattice and geometry matching
  - Nonlinearity optimized term by term to give a good start point of DA optimization
  - A multi-objective optimization by differential evolution algorithm (MODE) was developed for further optimization of the DA. To be scalable, it is a MPI-based parallel code to call SAD.