Beam Optics design for CEPC collider ring

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IHEP, Beijing

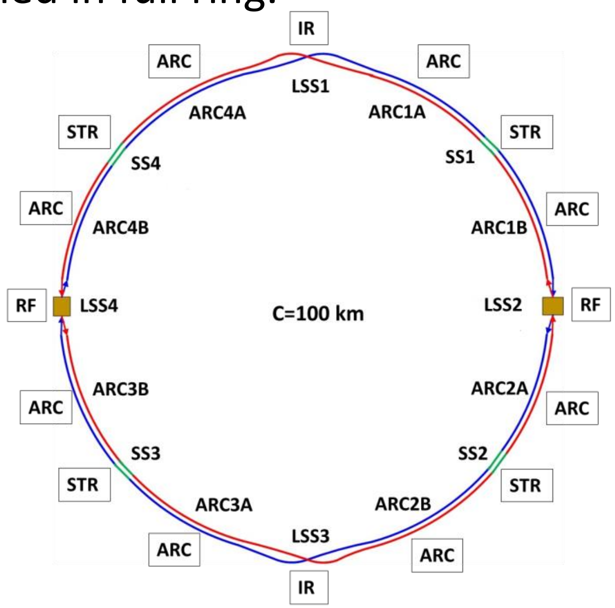
1st workshop on applications of high energy Circular Electron-Positron Collider （CEPC） synchrotron radiation source
6-8 Dec 2017

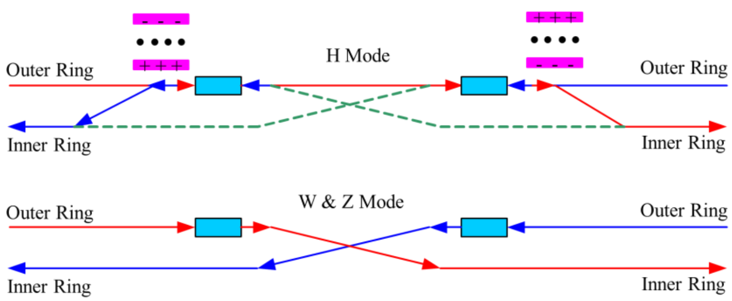
Outline

- Introduction
- Optics of Collider ring (linear optics, nonlinearity correction)
  - Interaction region
  - Arc region
  - RF region
  - Straight section region
  - Whole ring
- Summary

Introduction

- The circumference of CEPC collider ring is **100 km**.
- In the RF region, the **RF cavities are shared by two ring 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, half number of cavities will be used** and bunches can be filled in full ring.





Parameters of CEPC collider ring

D. Wang

	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	**120**	**80**	**45.5**
Circumference (km)	100		
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)	16.5		
Piwinski angle	2.75	4.39	10.8
N_e/bunch (10^{10})	12.9	3.6	1.6
Bunch number	286	5220	10900
Beam current (mA)	17.7	90.3	83.8
SR power /beam (MW)	30	30	2.9
Bending radius (km)	10.9		
Momentum compaction (10^{-5})	1.14		
β_{IP} x/y (m)	0.36/0.002		
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/IP	0.024/0.094	0.009/0.055	0.005/0.0165
RF Phase (degree)	128	134.4	138.6
V_{RF} (GV)	2.14	0.465	0.053
f_{RF} (MHz) (harmonic)	650		
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.48	3.7	5.18
HOM power/cavity (kw)	0.46 (2cell)	0.32(2cell)	0.11(2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance requirement (%)	1.21		
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
Lifetime due to beamstrahlung (hour)	1.0		
F (hour glass)	0.93	0.96	0.986
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.0	4.1	1.0

Parameters of CEPC collider ring

D. Wang
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	Higgs	W	Z	
Number of IPs	2			
Energy (GeV)	120	80	45.5	
Circumference (km)	100			
SR loss/turn (GeV)	1.68	0.33	0.035	
Half crossing angle (mrad)	16.5			
Piwinski angle	2.58	4.39	12.8	9.03
N_e/bunch (10^{10})	15	3.6	4.8	
Bunch number	248	5220	8334	
Beam current (mA)	17.9	90.3	192.3	
SR power /beam (MW)	30	30	6.7	
Bending radius (km)	10.9			
Momentum compaction (10^{-5})	1.14			
β_{IP} x/y (m)	0.36/0.002			
Emittance x/y (nm)	1.21/0.0037	0.54/0.0018	0.17/0.0029	
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076	
ξ_x/ξ_y/IP	0.031/0.116	0.009/0.055	0.0084/0.062	0.017/0.088
V_{RF} (GV)	2.14	0.465	0.053	0.1
f_{RF} (MHz) (harmonic)	650 (217500)			
Nature bunch length σ_z (mm)	2.72	2.98	3.67	2.38
Bunch length σ_z (mm)	3.26	3.7	6.16	4.33
HOM power/cavity (kw)	0.56 (2cell)	0.32(2cell)	0.7(2cell)	
Energy spread (%)	0.098	0.066	0.037	
Energy acceptance requirement (%)	1.52			
Energy acceptance by RF (%)	2.06	1.48	0.75	1.7
Photon number due to beamstrahlung	0.29	0.11	0.25	
Lifetime due to beamstrahlung (hour)	1.0			
Lifetime (hour)	0.33 (20 min)	3.5	7.4	
F (hour glass)	0.93	0.96	0.986	
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.49	4.1	5.83	8.26

Time structure

X. Cui, T. Bian

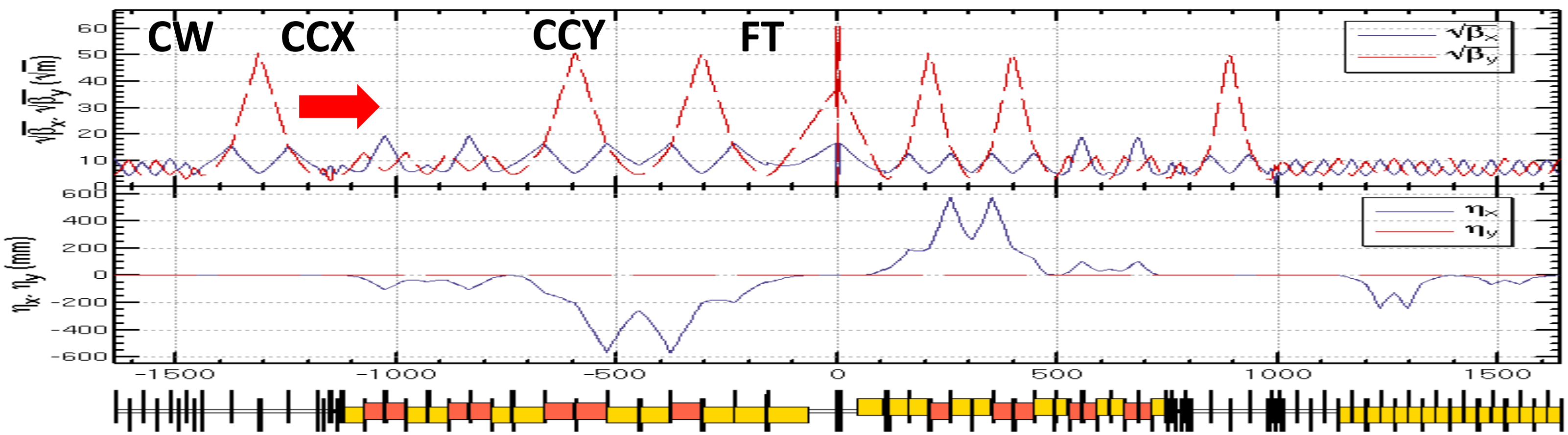
Top-up injection

	Higgs	W	Z
Injection Energy (GeV)	120	80	45.5
Bunch number	286	5220	8334
Bunch distance (ns)	583	64	31
Ne/bunch (10^10)	12.9	3.6	1.6
Beam current (mA)	17.7	90.3	83.8
Number of Injection Cycles	1	5	5
Current decay	3%	3%	3%
Ramping Cycle (sec)	10	6	2
Filling time (sec)	27	160	272
Collider Lifetime (hour)	0.33	3.5	7.4
Injection frequency (sec)	37	383	811

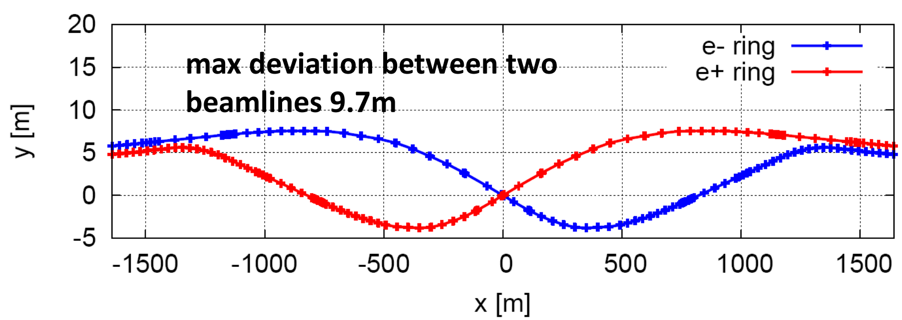
Transfer efficiency is 92% if the emmitance of LINAC is 300nm while beam lifetime is 14min.

Linear optics of Interaction region

- Provide local chromaticity correction of both plane
- **L*=2.2m, θc=33mrad, GQD0=151T/m, GQF1=102T/m**
- IP upstream of IR: **Ec < 100 keV within 400m, last bend Ec = 47 keV**
- IP downstream of IR: Ec < 300 keV within 250m, last bend Ec = 95 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**.



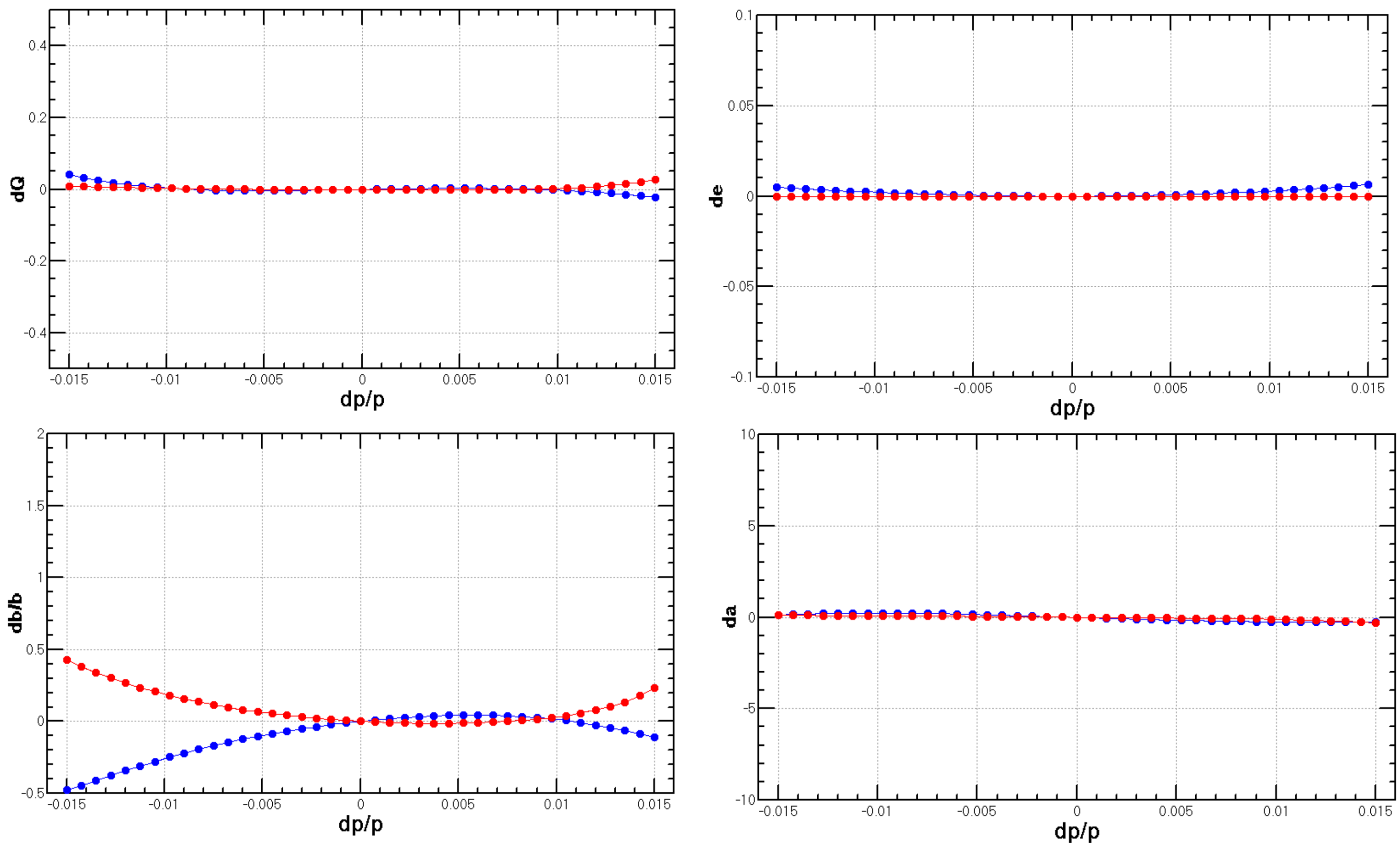
L*= 2.2m
βx*= 0.36mm
βy*= 2mm
GQD0≅-151T/m
GQF1≅102T/m
LQD0=1.73m
LQF1=1.48m



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

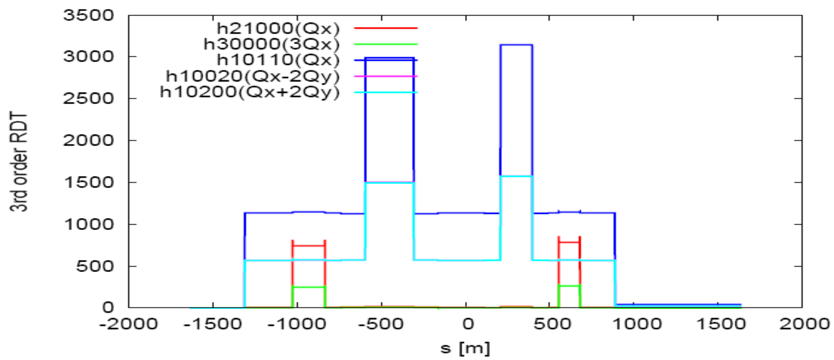


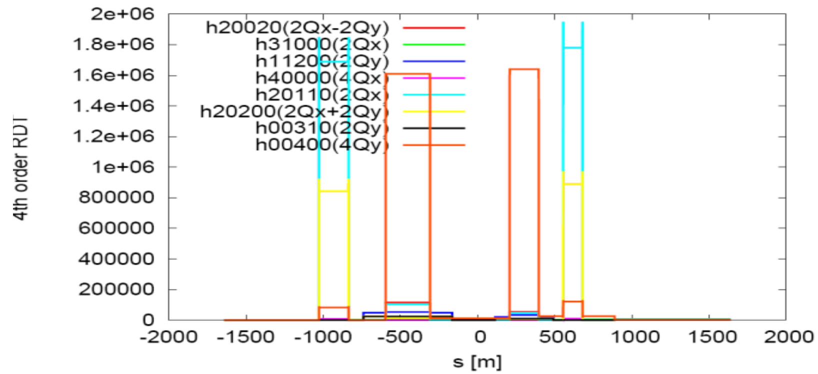
Nonlinearity correction of Interaction region

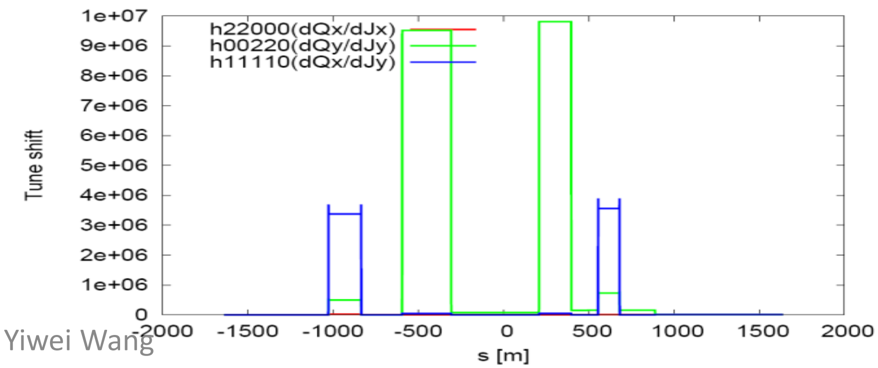
- **Local chromaticity correction** with sextupoles pairs separated by –I transportation
  - all **3rd and 4th RDT** due to sextupoles almost cancelled 1)
  - **tune shift dQ(Jx, Jy)** due to finite length of main sextupoles corrected with additional weak sextupoles 3,4)
  - **Break down of -I due to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

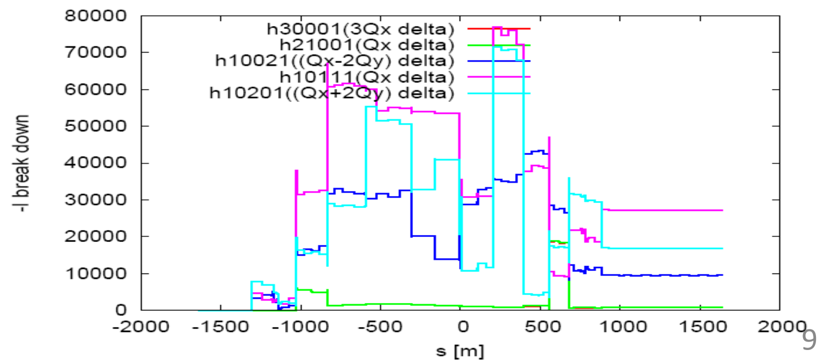
    Brinkmann sextupoles 2) or pair of decapoles 3)

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



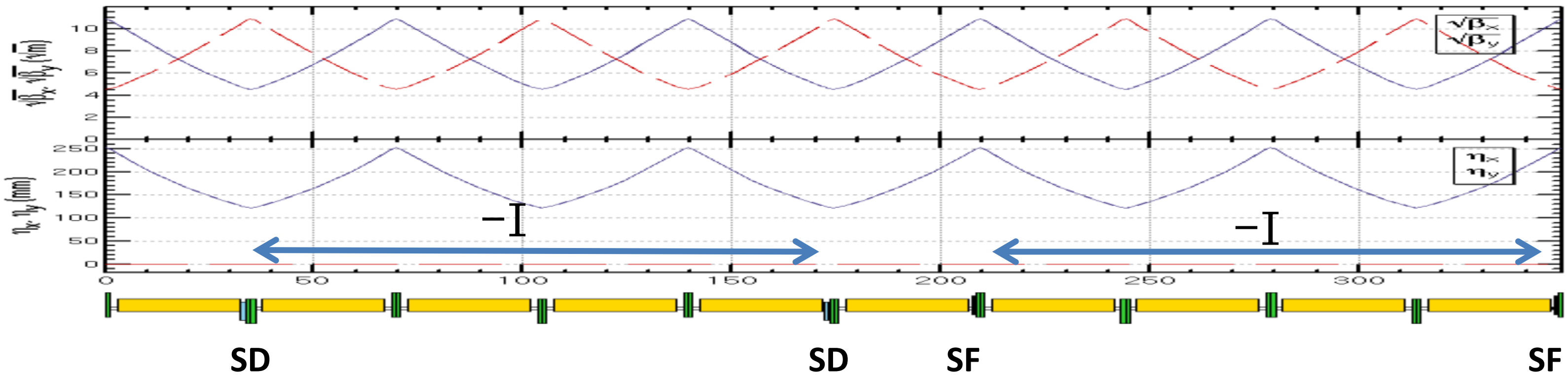




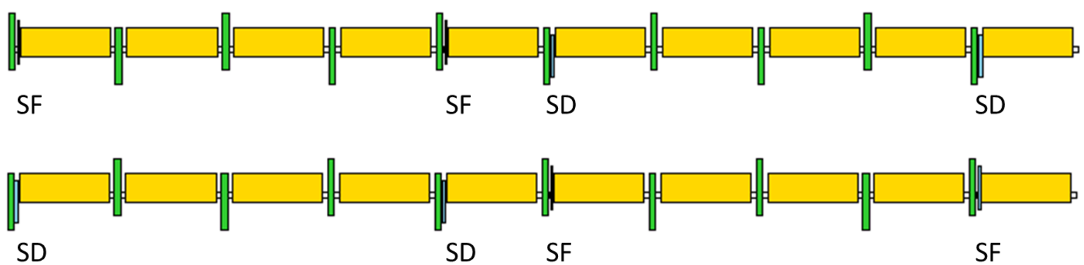


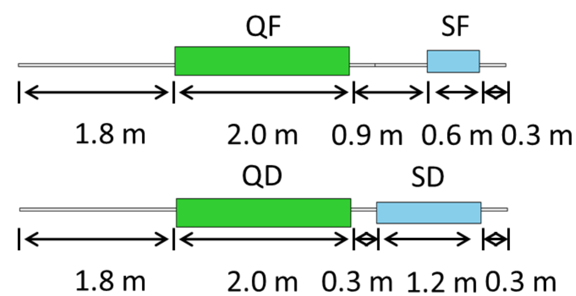
Linear optics design of ARC region

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

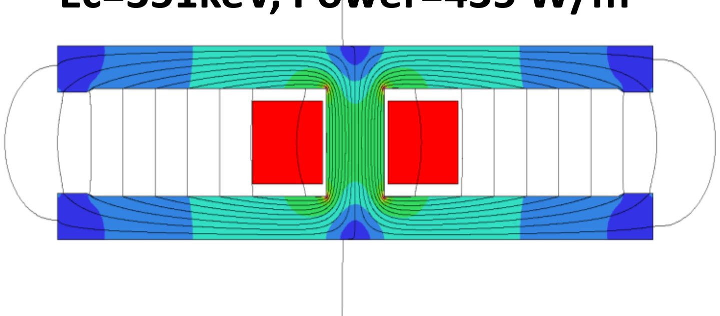


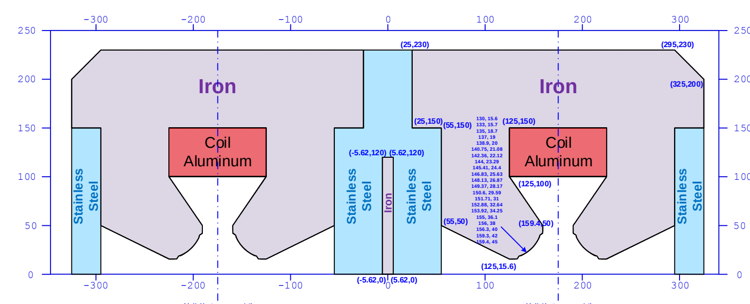
- **Twin-aperture of dipoles and quadrupoles is adopt in the arc region** to reduce the their power. The distance between two beams is 0.35m.





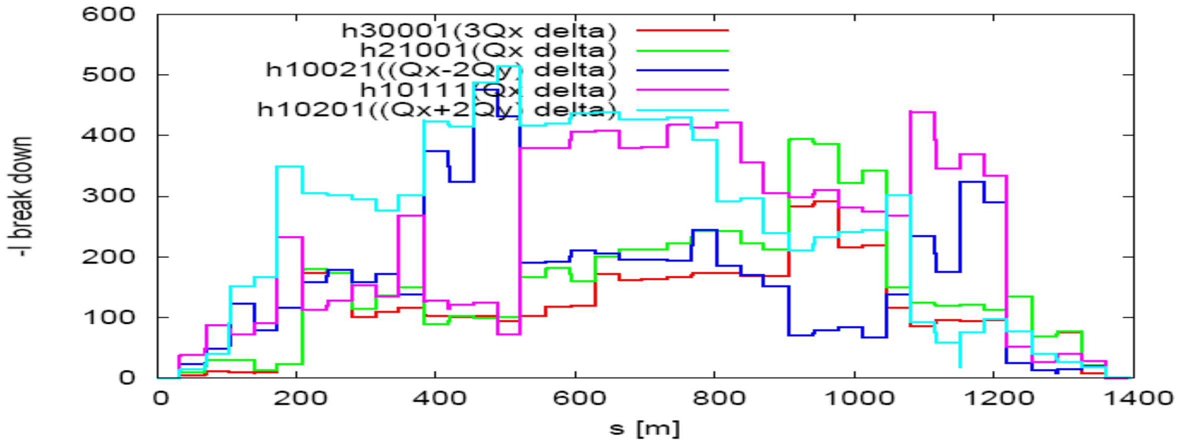
Ec=351keV, Power=435 W/m





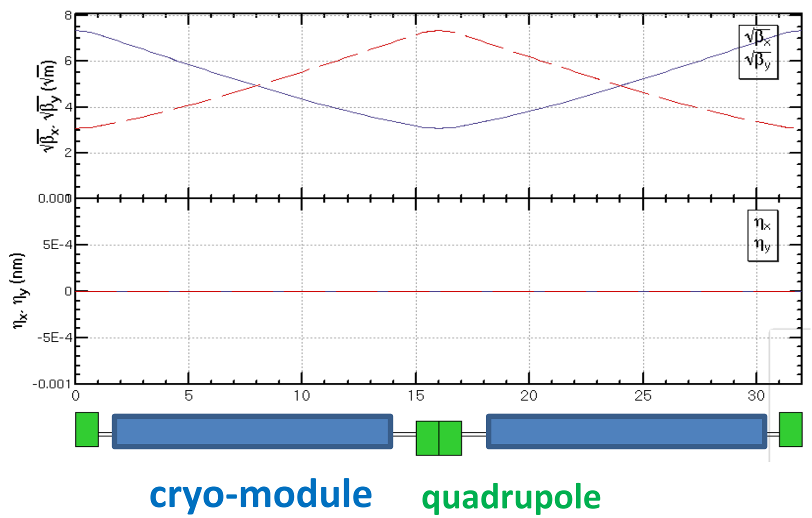
Nonlinearity correction of ARC region

- **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

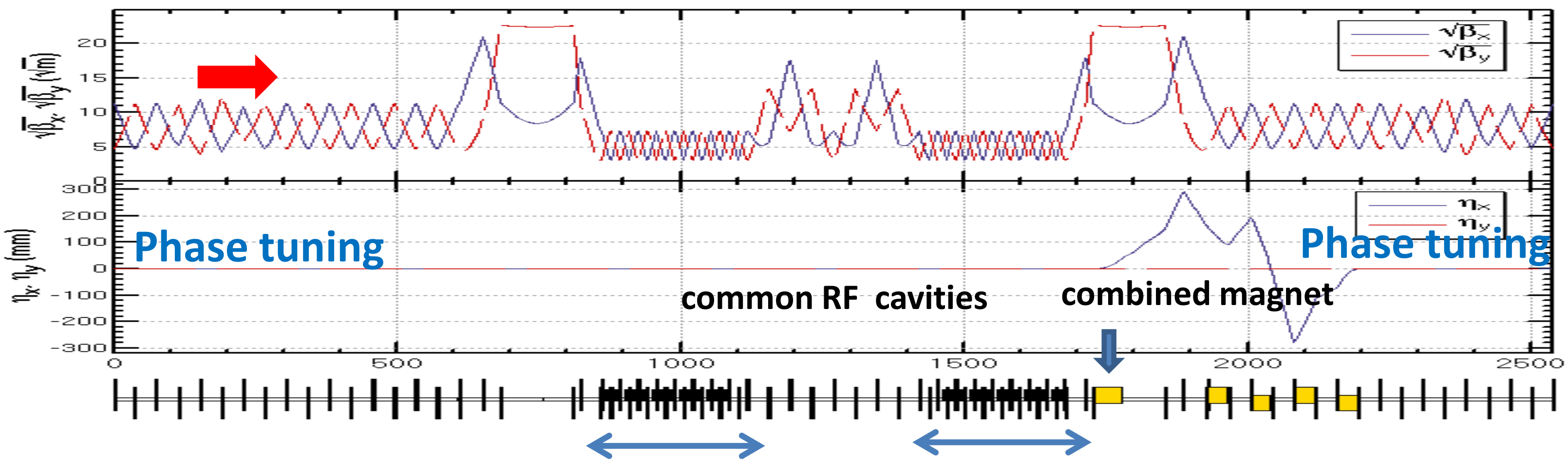
- 336 / 6 / 2RF stations / 2 sections / 2= 7 cells in each section
- **get a smallest average beta function to reduce the multi-bunch instability caused by RF cavities**
  - 90/90 degree phase advance
  - as short as possible distance between quadrupoles, but should be larger than a module length (12m)



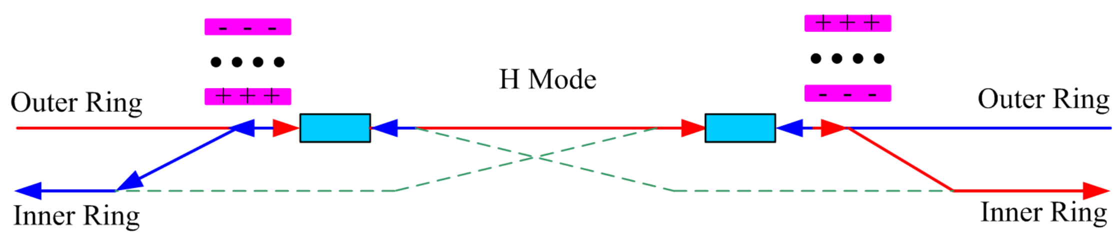
90/90 deg
Half cell: 14m+2m
βmax: 53.8 m
βmin: 9.5 m

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**

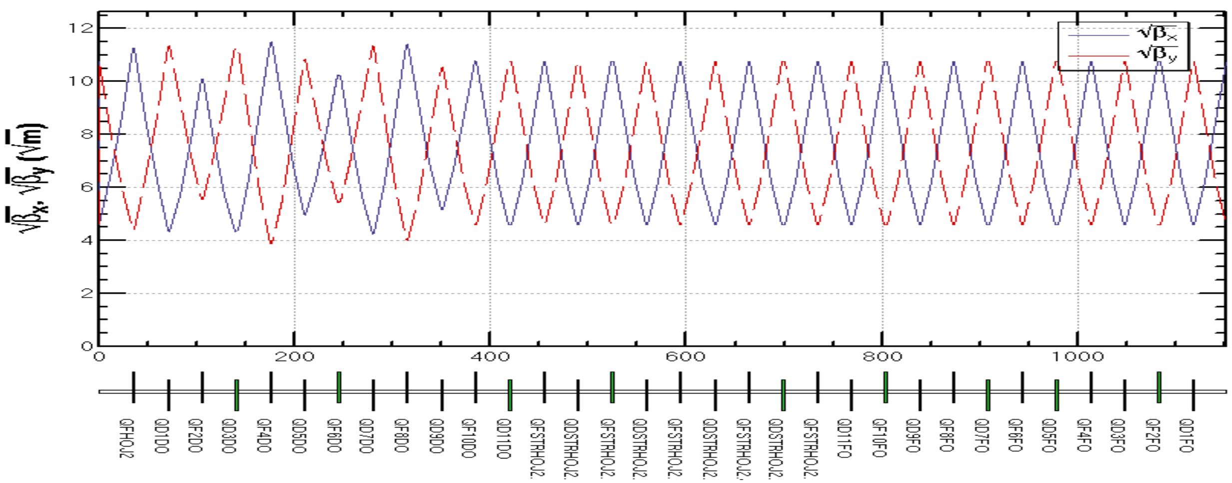


Esep=1.8 MV/m
Lsep=50m
Ldrift=75m
Δx=10cm at entrance of quad



Optics design of Straight section region

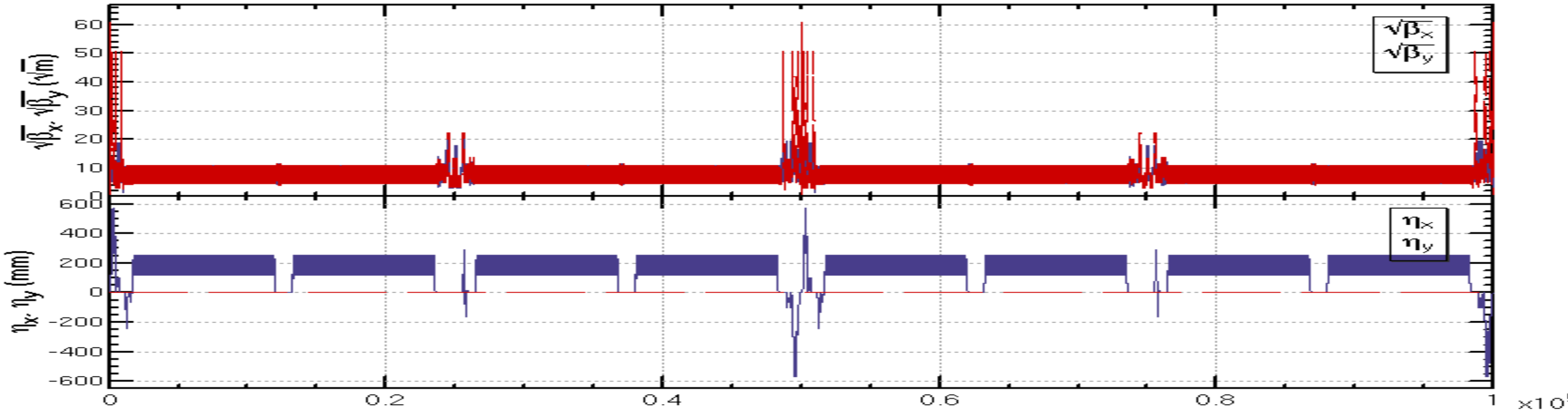
- The function of the straight section is phase advance tuning and injection.
  - Independent magnets for two rings
  - 0.3m between two quadrupoles of two rings allows a larger size of quadrupoles

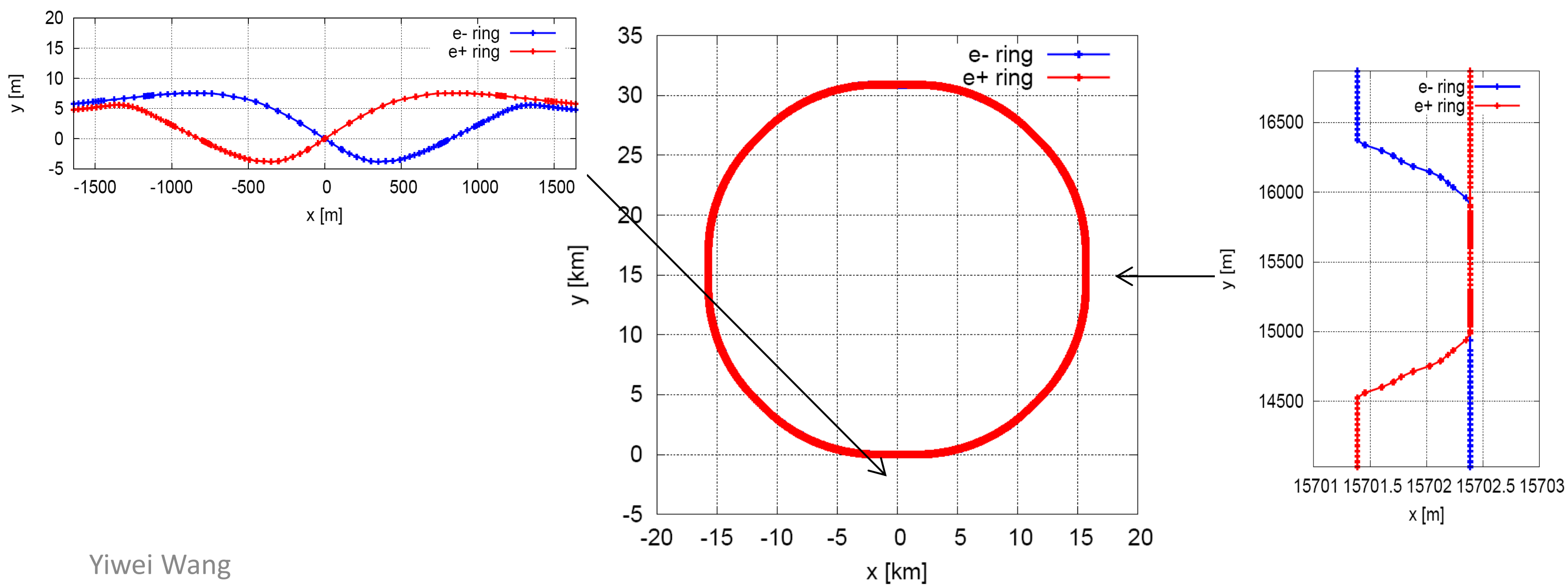


Phase tuning **Injection** **Phase tuning**

Linear optics of the collider ring

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

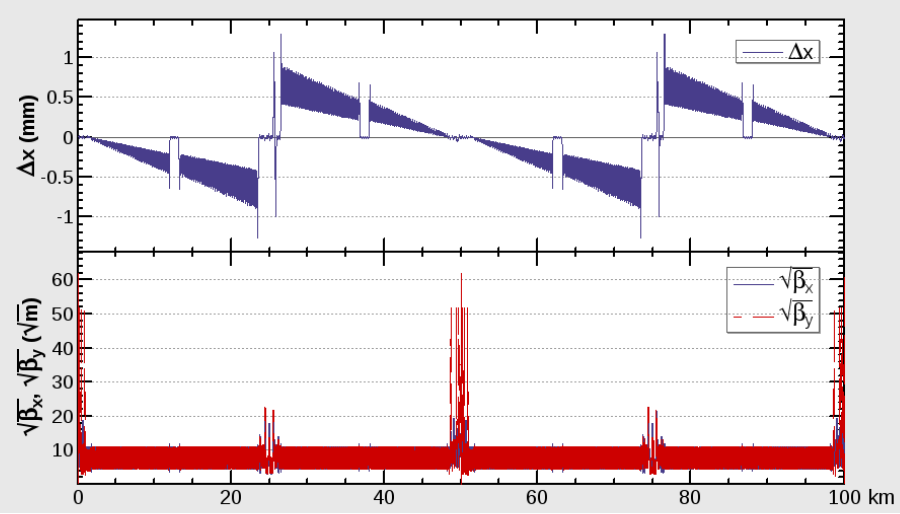


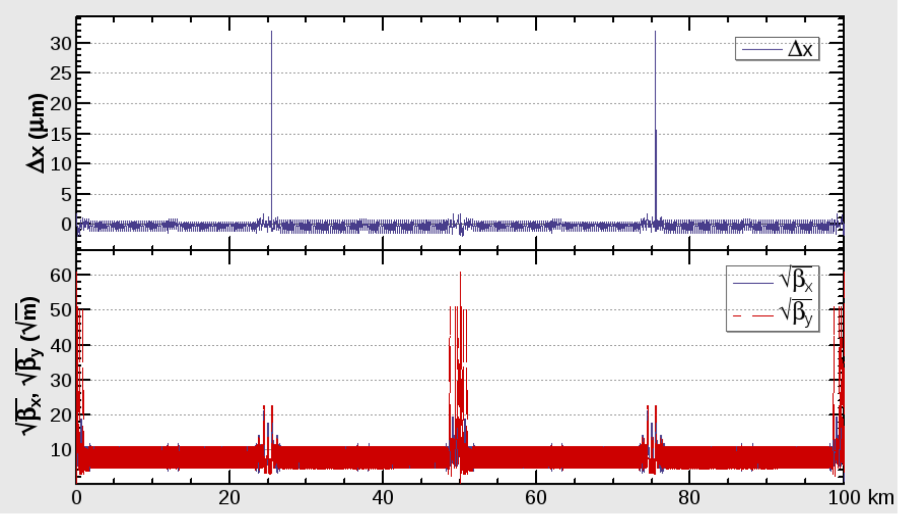


Sawtooth orbit correction

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

$$\delta_E = \frac{U_0}{2N_{RF}E} = 0.35\%$$





Dynamic aperture optimization

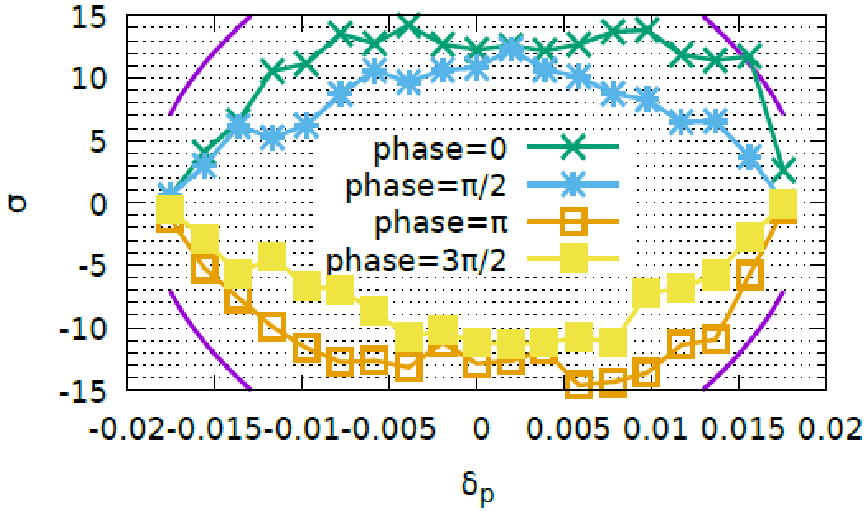
Y. Zhang

- SAD is used
- 200 turns tracked
- 100 samples
- IR sextupoles + 32 arc sextupoles

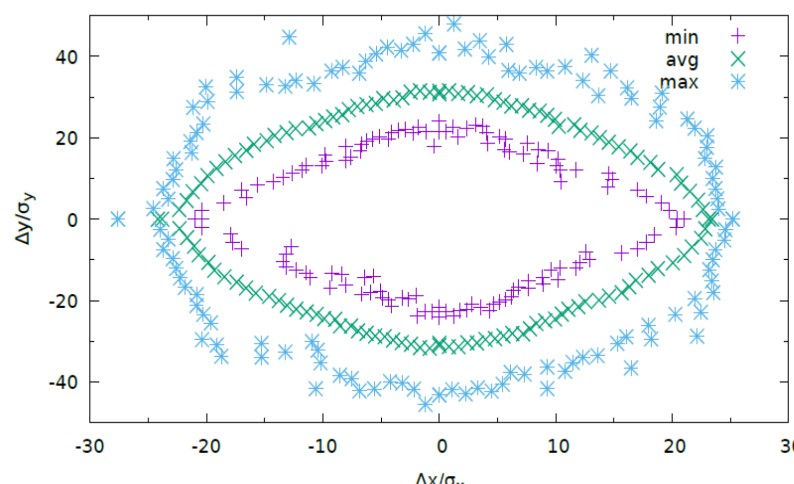
  (Max. free various=254)
- Damping at each element
- RF ON
- Radiation fluctuation ON
- Sawtooth on with tapering
- The requirements

$16\sigma_x \times 16\sigma_y$ & 0.015

$20\sigma_x \times 20\sigma_y$ & 0.017@ Higgs without errors



Minimum DA of 100 samples.
0.3% coupling. 200 turns.



Dynamic Aperture of on-momentum particles

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.
- Optimized DA fulfill requirement from beam-beam and injection.
- Study with errors and correction is undergoing.

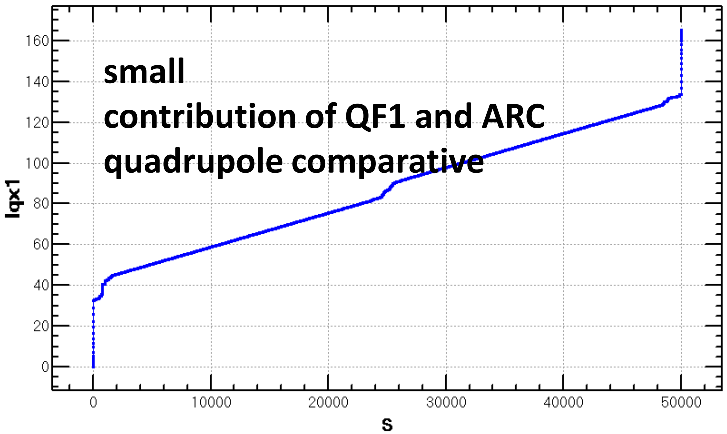
Backup

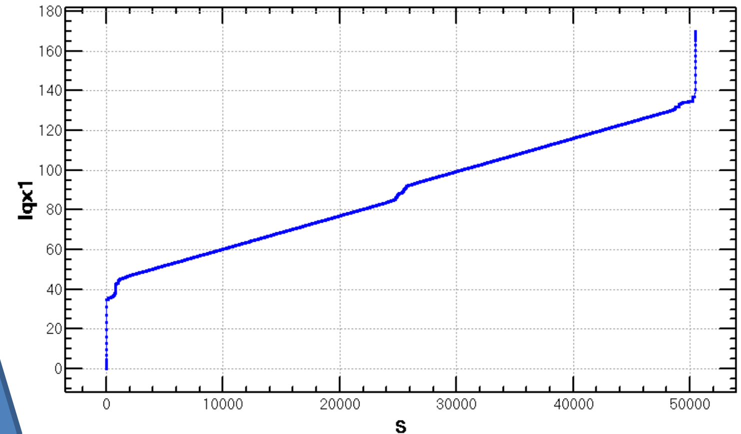
Damping vs damping+fluctuation

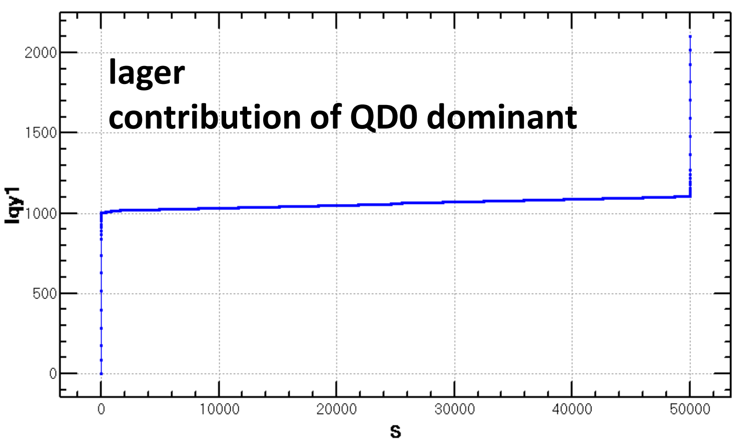
Radiation power due to quadrupoles: $P \propto \int B^2 ds \propto \int {K_1}^2 \beta ds \cong \sum (K_1 l)^2 \beta / l$

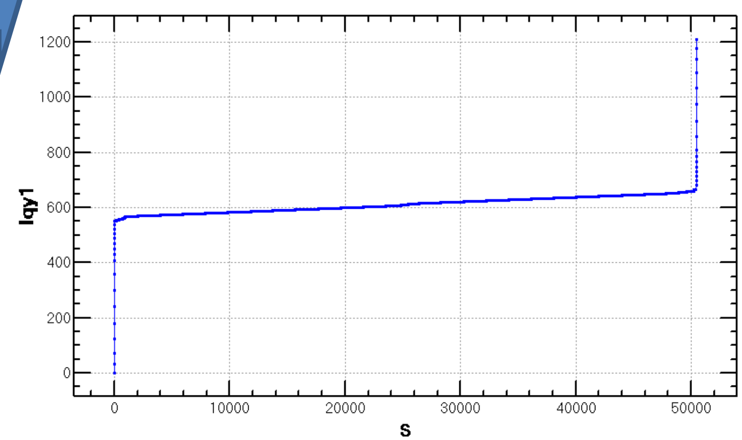
LQF=LQD=2.0 m
LQD0=1.73 m, LQF1=1.48m

LQF=LQD=2.0 m
LQD0=1.73 m × **2.0**, LQF1=1.48m







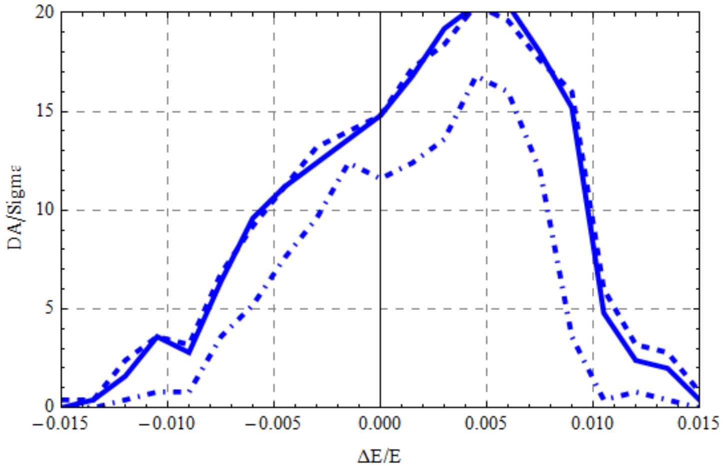


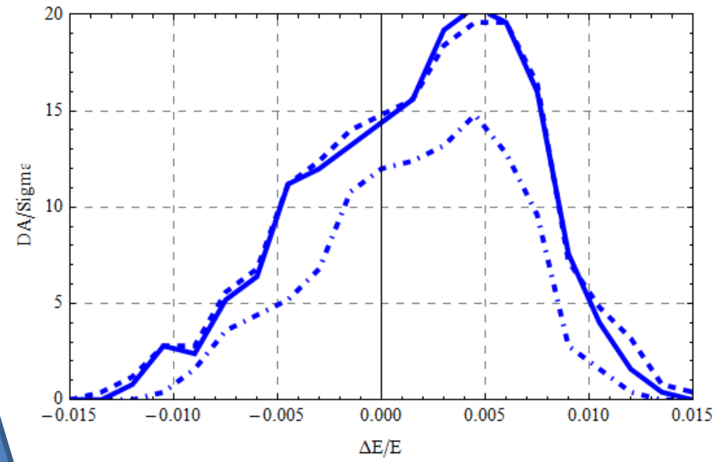
Damping vs damping+fluctuation

LQF=LQD=2.0 m
LQD0=1.73 m, LQF1=1.48m

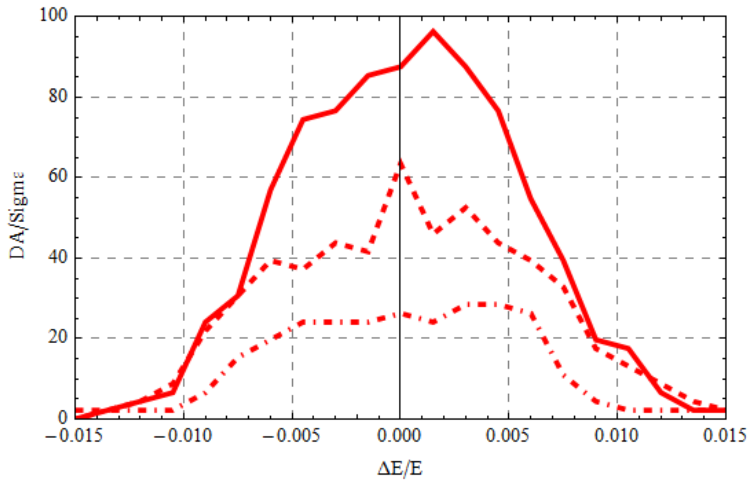
LQF=LQD=2.0 m
LQD0=1.73 m × 2.0, LQF1=1.48m

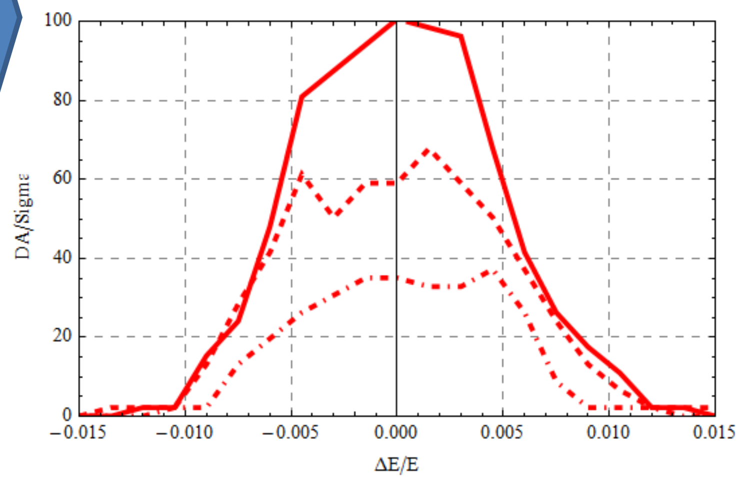
x





y





Hard line: w/ damping only
Dashed line: w/ damping and fluctuation (20 samples, maximum)
Dot-dashed line: w/ damping and fluctuation (20 samples, minimum)

Further optimization with longer QD0 by MODE is undergoing.

Injection time structure

X. Cui, T. Bian

Top-up injection