Accelerator physics design of the CEPC collider ring

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IHEP

on behalf the CEPC Accelerator Physics Group

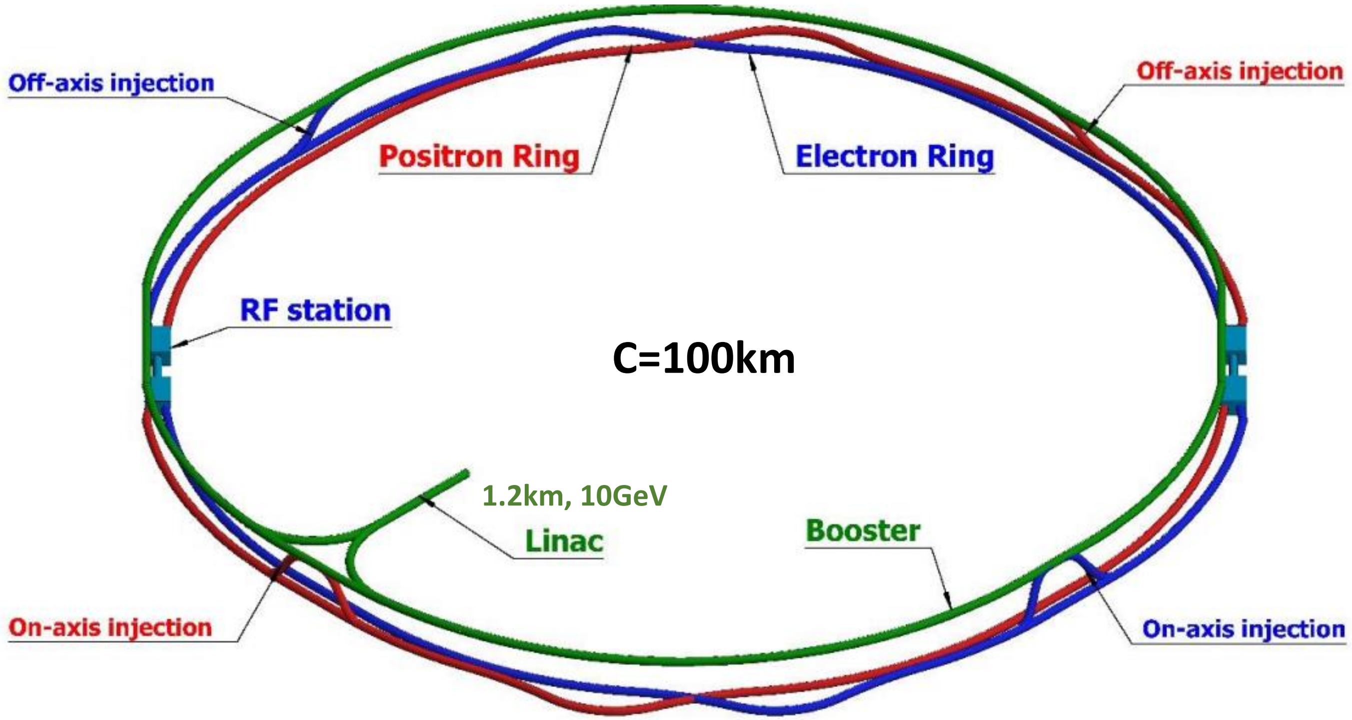
8th annual conference of the CAS Center for Excellence in Particle Physics, 4 Dec. 2020

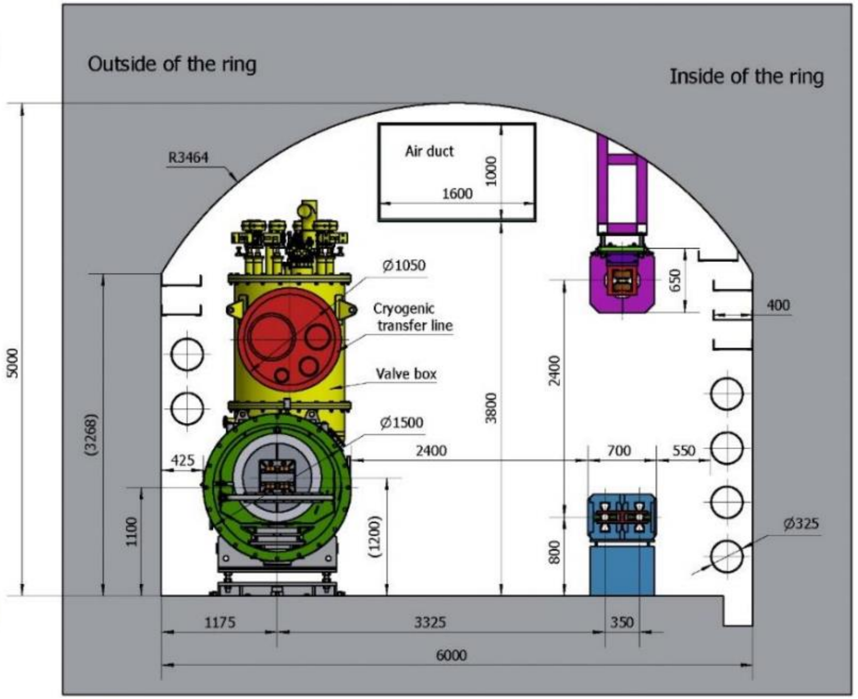
Outline

- Overview of CEPC
- History of collider rings
- Design requirement, key issues of CEPC collide ring
- CDR
- Beyond CDR
- Summary

Overview of the CEPC

- Double ring collider with 2 IPs
- Compatible with the geometry of SPPC





History of e+e- collider rings

- CEPC goal reach both the energy and luminosity frontier of the e+e- collider rings: 120GeV×120GeV, >3×$10^{34}/cm^2/s$

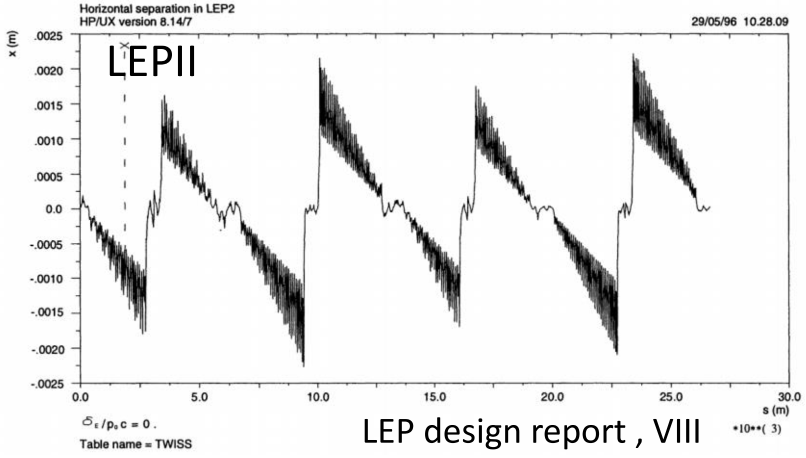
e+e- colliders built and operated since 1991

Location	Accelerator	Energy (GeV × GeV)	Luminosity ($cm^{-2}s^{-1}$)	Operation Period
CERN	LEP	104.5 × 104.5	1×10^{32}	1989-2000
KEK	SuperKEKB	$7\ (e^-) \times 4\ (e^+)$	8×10^{35} (*)	2018-present
	KEKB	$8\ (e^-) \times 3.5\ (e^+)$	2.1×10^{34}	1998-2010
	TRISTAN	32 × 32	3.7×10^{31}	1986-1995
SLAC	PEP-II	$9\ (e^-) \times 3.1\ (e^+)$	1.2×10^{34}	1999-2008
	SLC	46.2 × 46.2	3×10^{30}	1988-1998
DESY	DORIS	5.6 × 5.6	3.3×10^{31}	1974-1992
Cornell	CESR	1.8 × 1.8 to 5.5 × 5.5	1.3×10^{33}	1979-2008
INFN	DAFNE	0.51 × 0.51	2.4×10^{32}	1999-present
IHEP/China	BEPC & BEPC-II	1.5 × 1.5 to 2.5 × 2.5	1×10^{33}	1988-2005, 2008-present
BINP	VEPP-2000	0.2 × 0.2 to 1 × 1	1.2×10^{32}	2010-present
	VEPP-4M	1.5 × 1.5 to 5 × 5	5×10^{30}	1984 -present

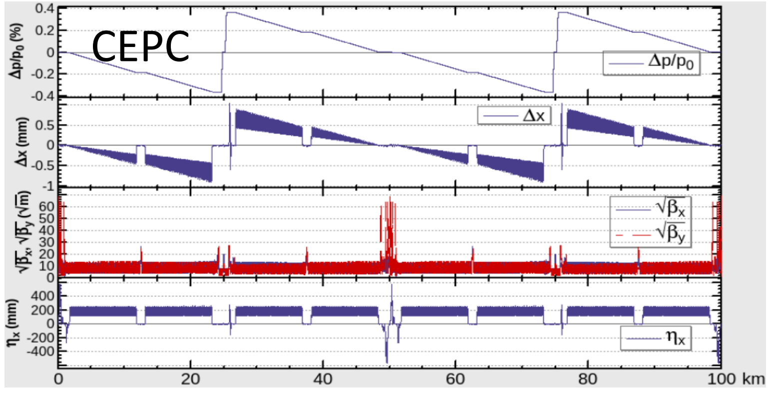
(*) Design goal

Beam effects at energy frontier

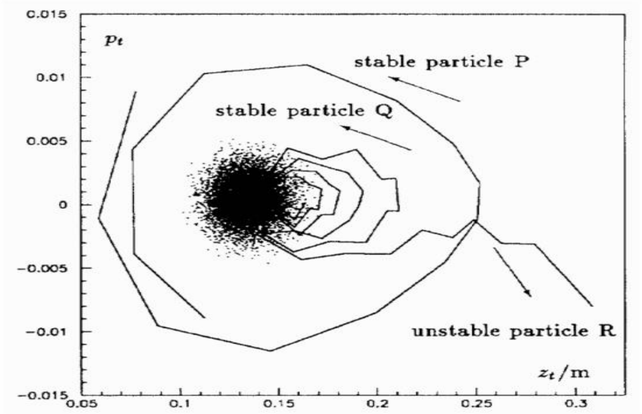
- Sawtooth orbit



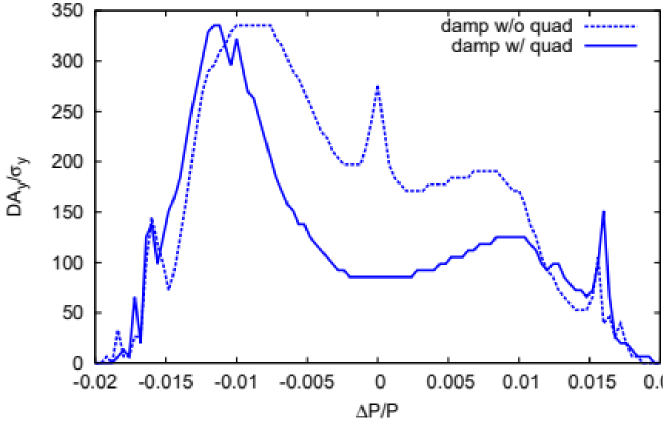
LEP design report , VIII



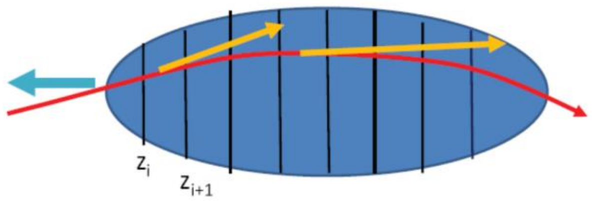
- Radiation due to quadrupole

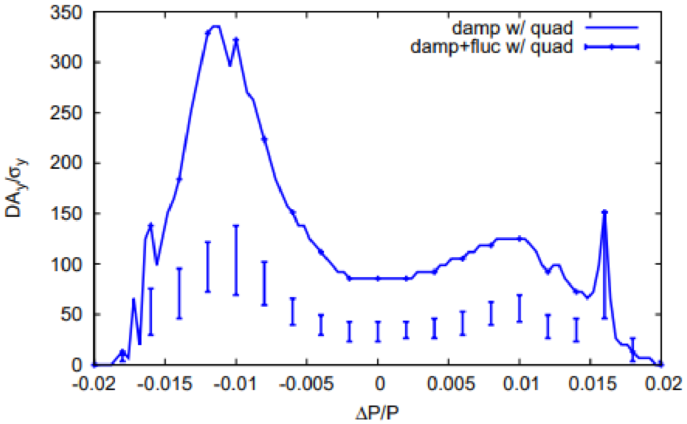


J. Jowett, Conf. Proc. C9401174 (1994) 47-71



- Strong beamstrahlung



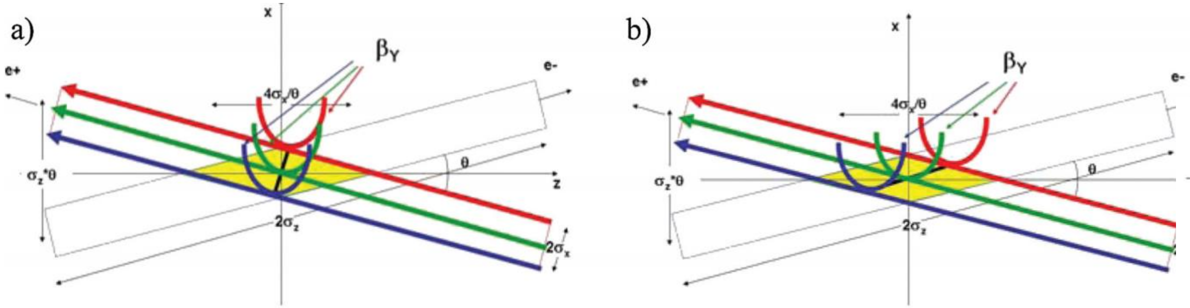


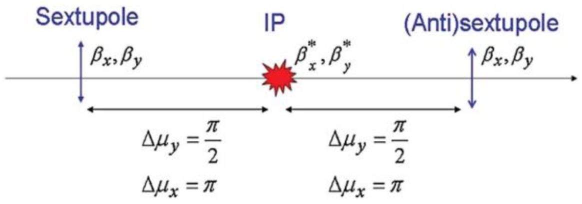
Luminosity frontier

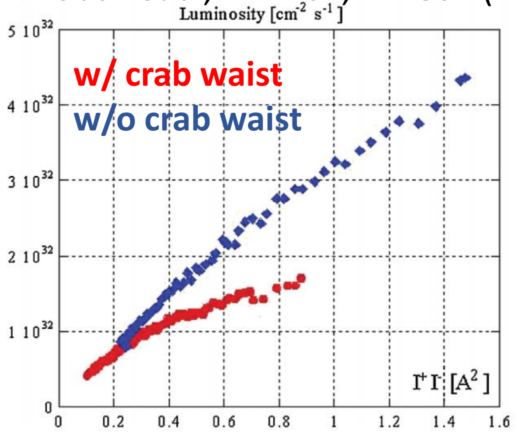
- Crab waist collision: proposed and proved on **DAFNE**

  Flat beam + large Piwinski angle + crab sextupole

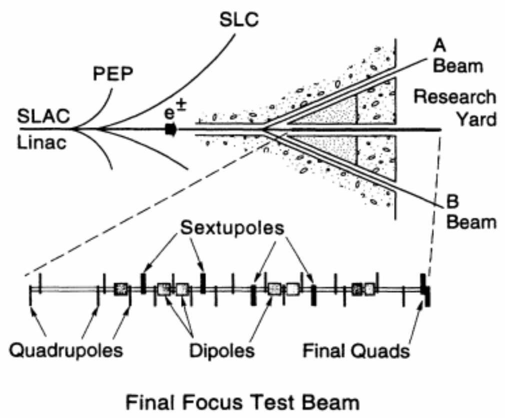
M. Zobov et al, PRL 104, 174801 (2010)

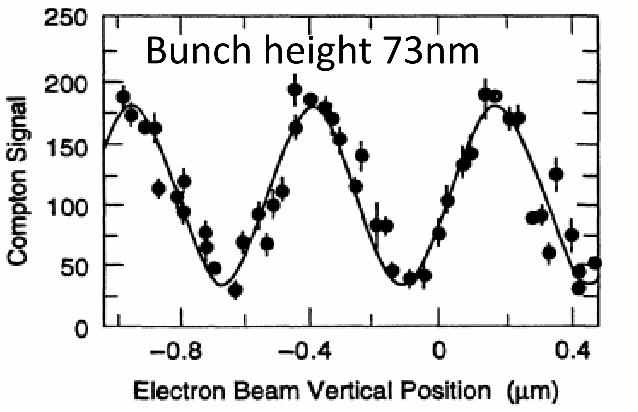


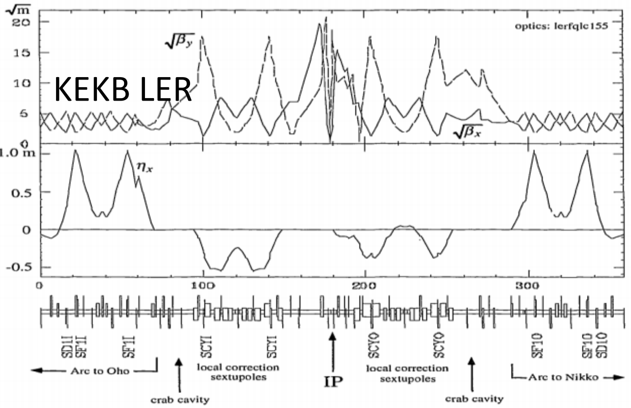




- Local chromaticity correction for the interaction region: **FFTB** proposed for linear collider and 1st applied to circular collider on KEKB





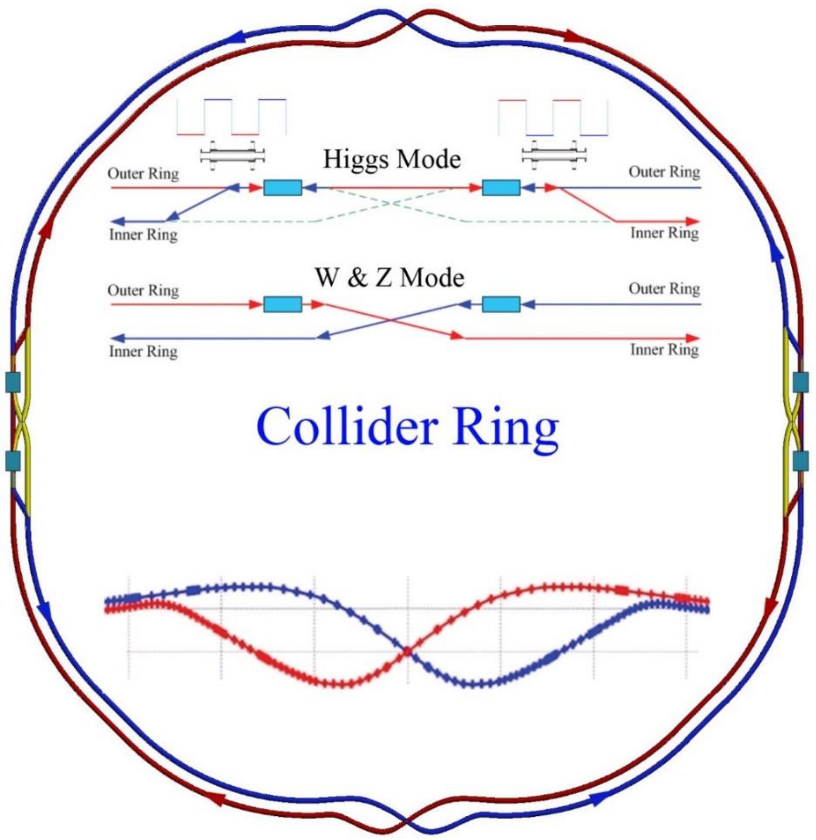


V. Balakin et al, Vol 74, Num 13 PRL, 1995

KEKB DR

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 and W
- 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



Key issues of accelerator physics design for the CEPC collider ring

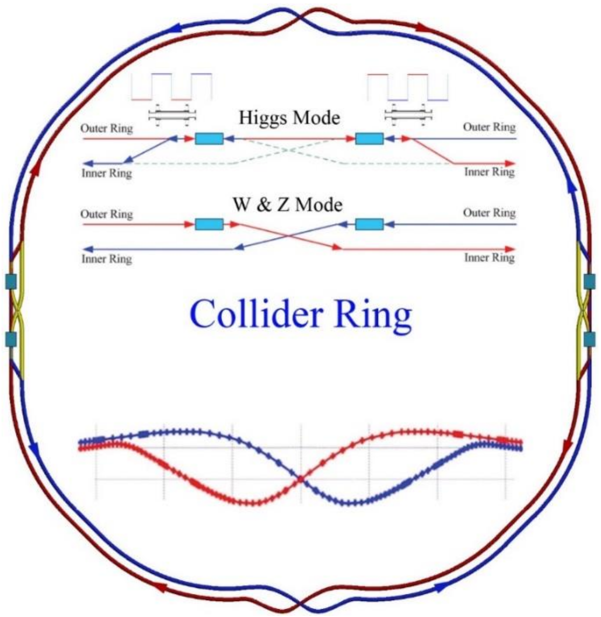
- Large enough dynamic aperture of lattice
- Low emittance tuning
- Machine detector interface
- On axis injection
- Beam collective instability

CDR parameter

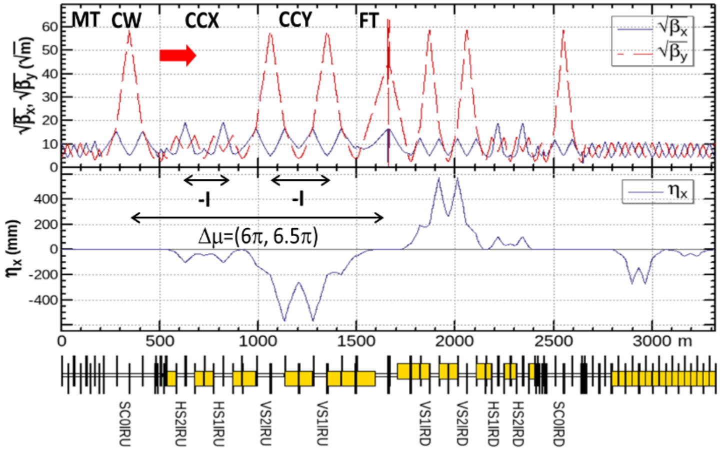
by D. Wang et al

	Higgs	*W*	*Z*
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	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0024	0.54/0.0016	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	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	2.5
F (hour glass)	0.89	0.94	0.99
Luminosity/IP *L* (10^{34}cm^{-2}s^{-1})	**3**	**10**	**32**

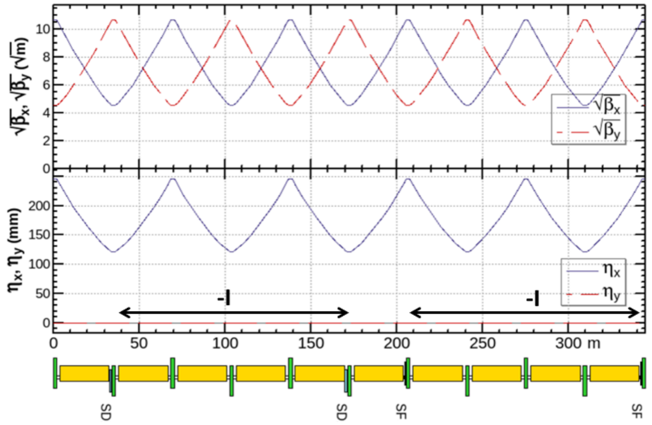
CDR lattice of CEPC collider ring



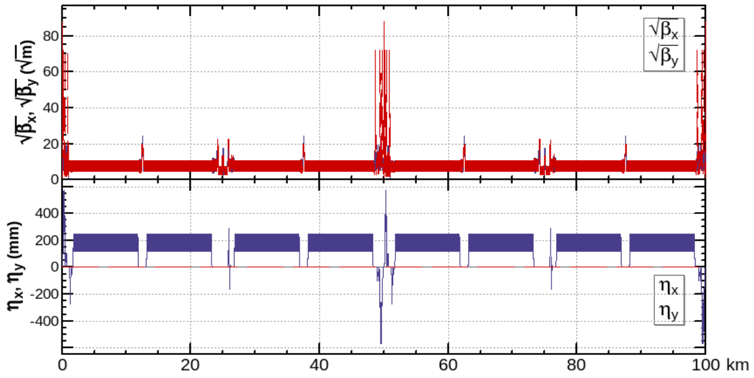
Interaction region



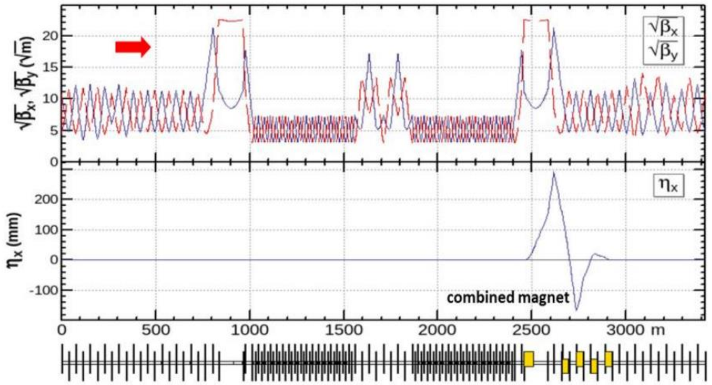
ARC region



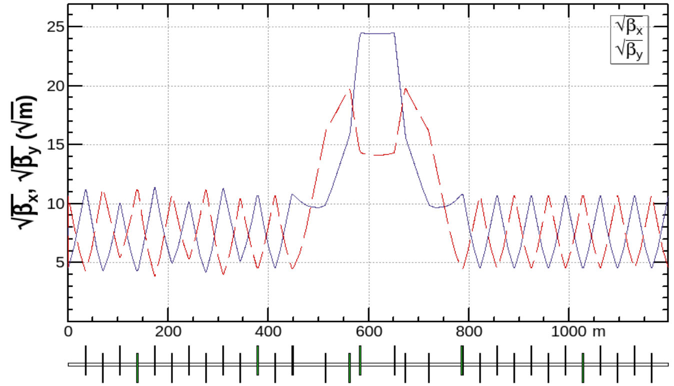
Collider ring



RF region



Injection region



Dynamic aperture with errors

Robust correction of error effects

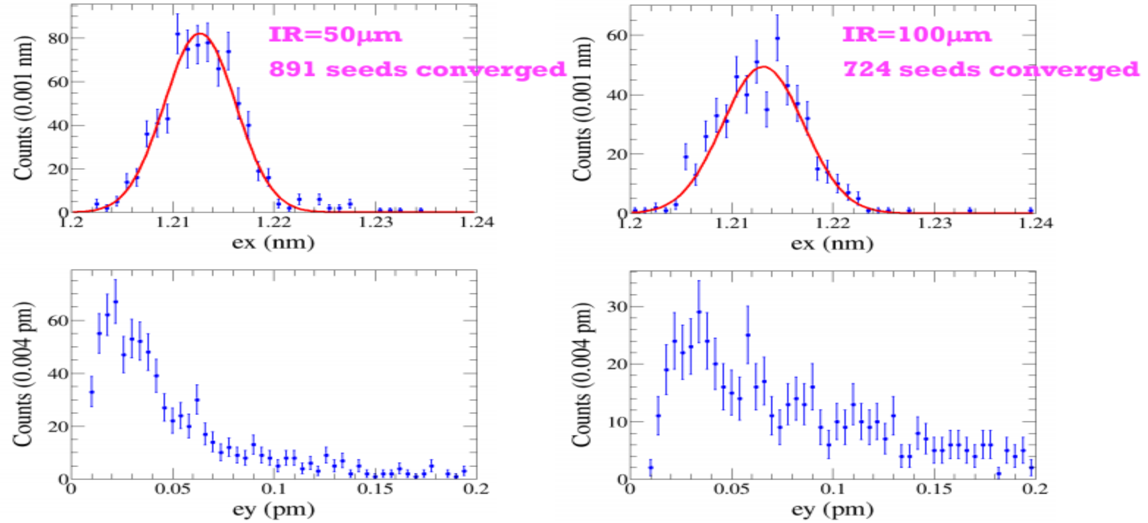
by B. Wang, Y. Wei

IR=50μm

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	

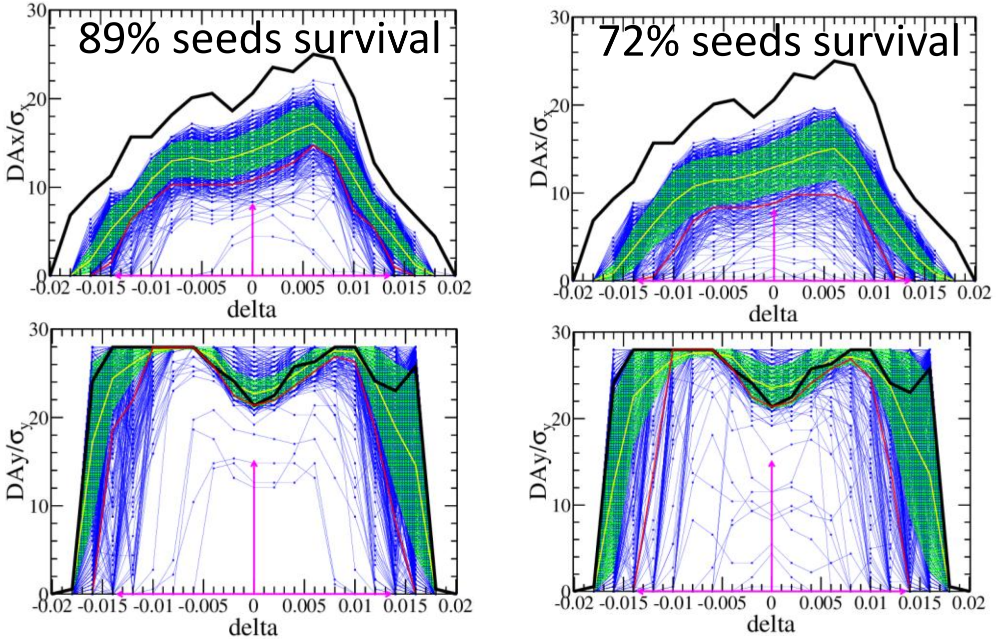
IR=100μm

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	**0.10**	**0.10**	**0.10**	
Sextupole	0.10	0.10	0.1	



ex = 1.2127±0.0035 nm
ey = 0.050± 0.0015 pm
ey/ex = (0.0041± 0.0001)%

ex = 1.2131±0.0040 nm
ey = 0.0777± 0.0023 pm
ey/ex = (0.0064± 0.0002)%



High luminosity scheme at Higgs energy

by C. Yu, Y. Wang, S. Bai, Y. Zhu, D. Wang et al

Key parameters of CDR scheme

- **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

- **L*=1.9m, θc=33mrad, βx*=0.33m, βy*=1.0mm, Emittance=0.68nm**
  - Strength requirements of anti-solenoids B_z~7.2T
  - Two-in-one type SC quadrupole coils (Peak field 3.8T & 141T/m) with room temperature vacuum chamber & Iron yoke

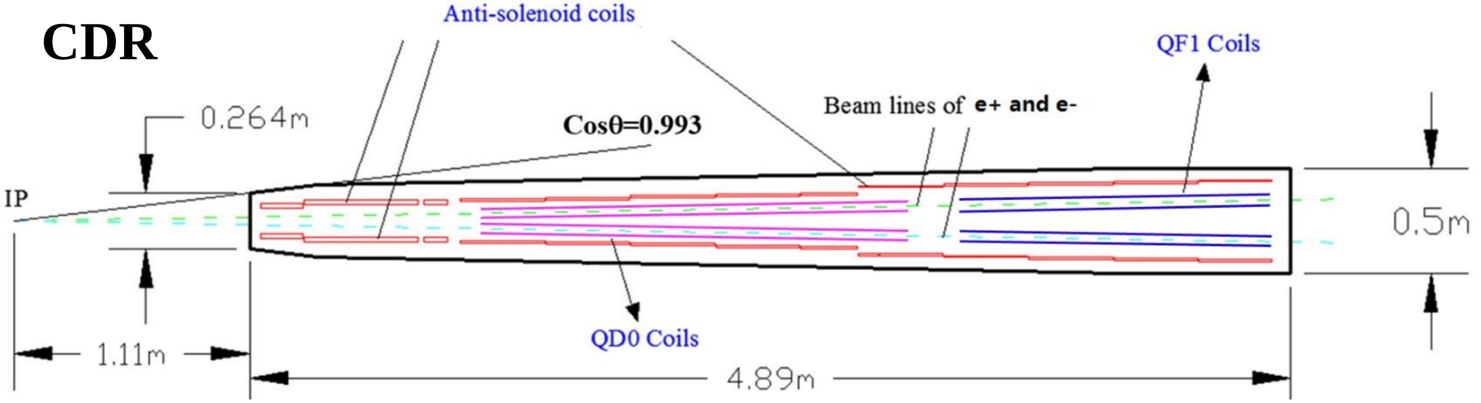
Lower emittance and smaller beam pipe aperture within the region of SCQ

High luminosity scheme at Higgs energy

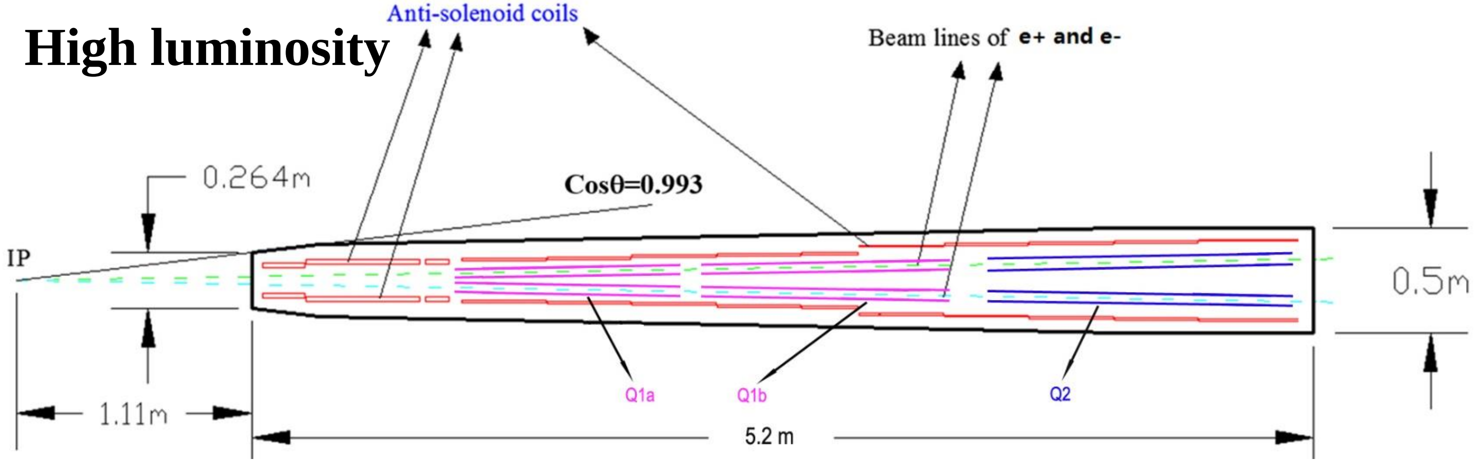
Change of final doublet cryostat

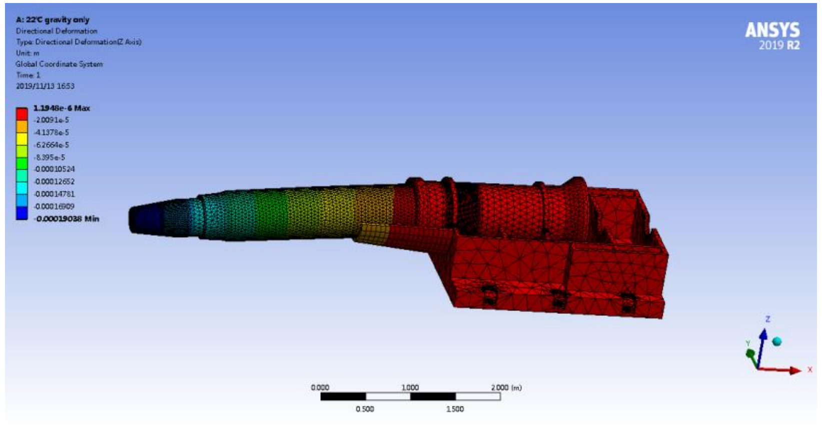
by S. Bai, Y. Zhu, H. Wang et al

CDR



High luminosity





- With gravity, deformation=190μm
- Installation
- Vacuum situation at the IP

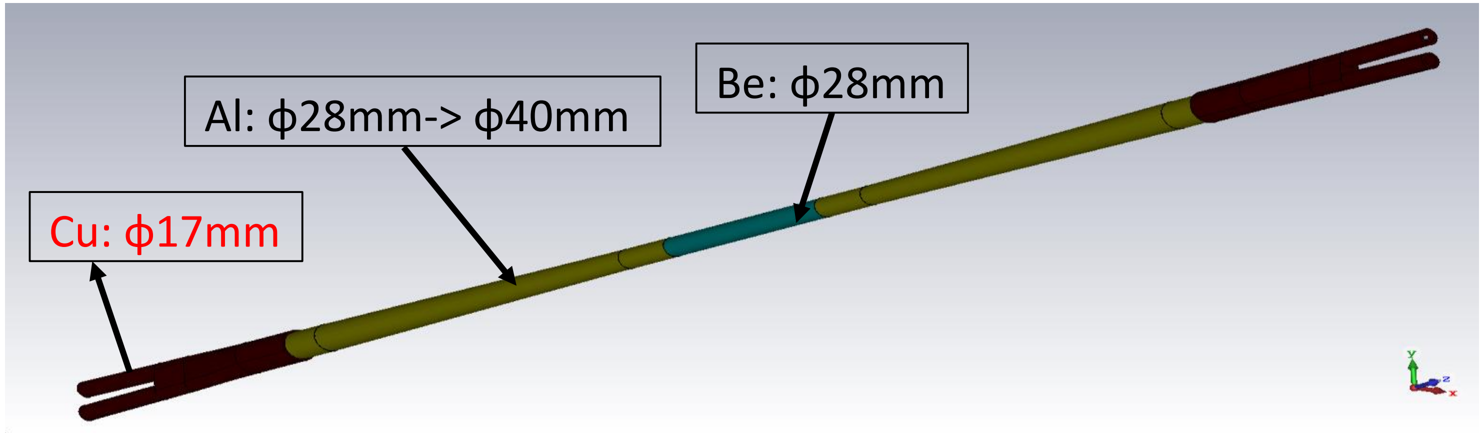
We hope the length of cryostat to be as shorter as possible and as

For the part of cryostat inside the detector, the shape and size stay the same as CDR. The detector design won't be affected.

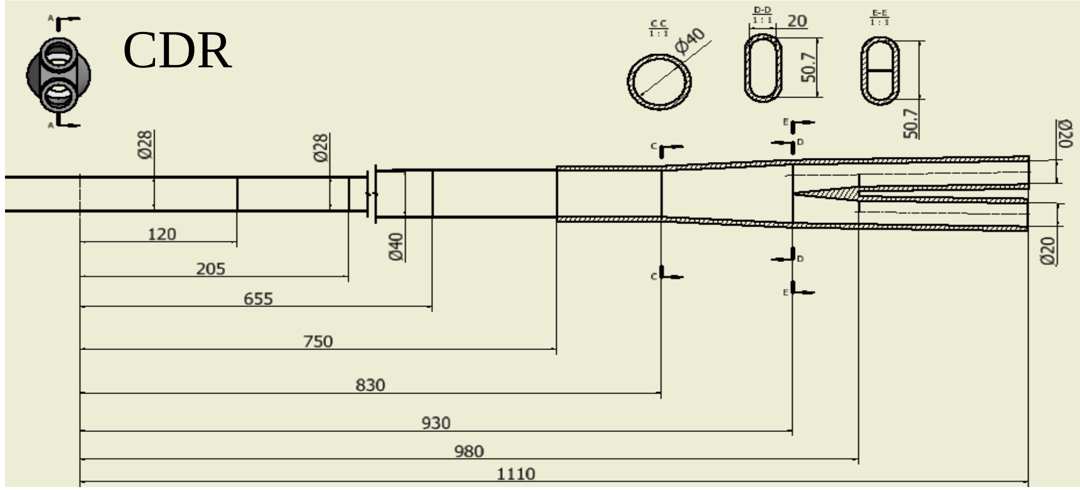
High luminosity scheme at Higgs energy

Change of IP chamber

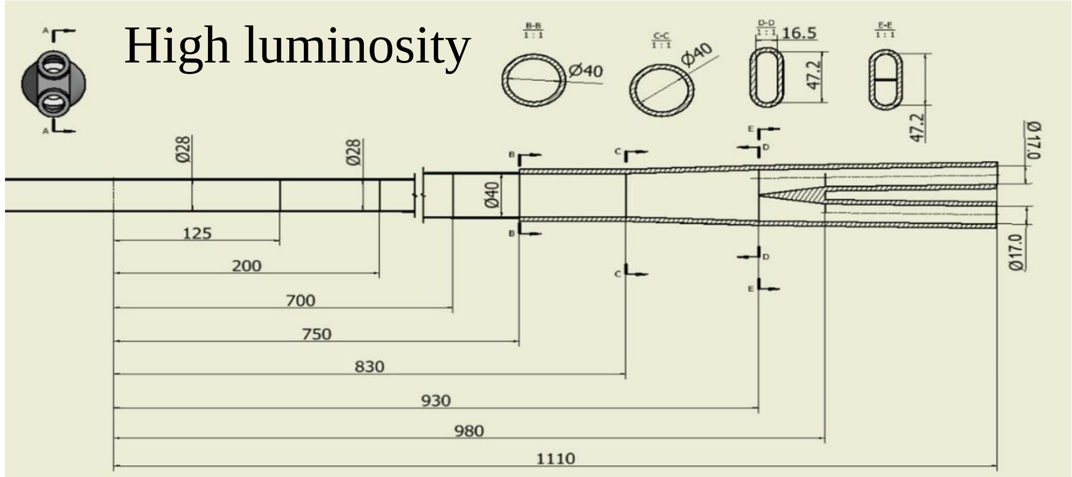
by H. Wang, Y. Liu et al



Be pipe: 28mm, SCQ Beam pipe:20mm



Be pipe: 28mm, Beam pipe:17mm



High luminosity scheme at Higgs energy

Change of HOM deposition nearby the IP

by Y. Liu et al

HOM Power distribution	**CDR** **Be pipe: 28mm SCQ Pipe:20mm**		**High luminosity** **Be pipe: 28mm SCQ Pipe:17mm**	
	Higgs	Z	Higgs	Z
Be pipe	2.66w	40.74 w	3.46w	52.1w
Al	21.32w	317.2w	22.62w	335.4w
Y-shape crotch	12.9w	191.5w	13.4w	199w
Total power	36.88w	549.5w	39.48w	586.5w

Shrinking the SCQ pipe aperture from 20mm to 17mm, the power deposition will increase 10% which is acceptable.

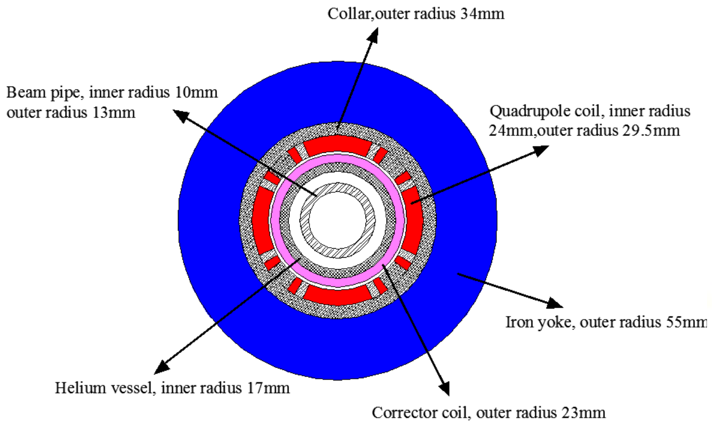
High luminosity scheme at Higgs energy

Change of final focusing quadrupole coils

by S. Bai, Y. Zhu et al

Coil	Central field gradient (T/m)	Magnetic length (m)	Width of GFR (mm)	Minimal distance between two aperture beam lines (mm)
Q1a	141	1.21	15.21	62.71
Q1b	84.7	1.21	17.92	105.28
Q2	94.8	1.5	24.14	155.11

- Q1a is the most challenging.
- The design of quadrupoles and anti-solenoid is similar to that in CDR.
- Iron yoke is adopted to eliminate the field crosstalk between the two apertures.



High luminosity scheme at Higgs energy

Change of ARC region

- Shorter cell length to squeeze the emittance from CDR 1.2nm to 0.68nm
- Optimization of the quadrupole radiation effect
  - Interaction region: longer Q1a quadrupoles, from 2m to 2.5m
  - ARC region: longer quadrupoles, from 2m to 3m
- Reduction of dynamic aperture requirement from injection
  - Straight section region: larger βx at injection point
- Optimization of high order chromaticity for arc region
- Better correction of energy dependent aberration

High luminosity scheme at Higgs energy

by D. Wang et al

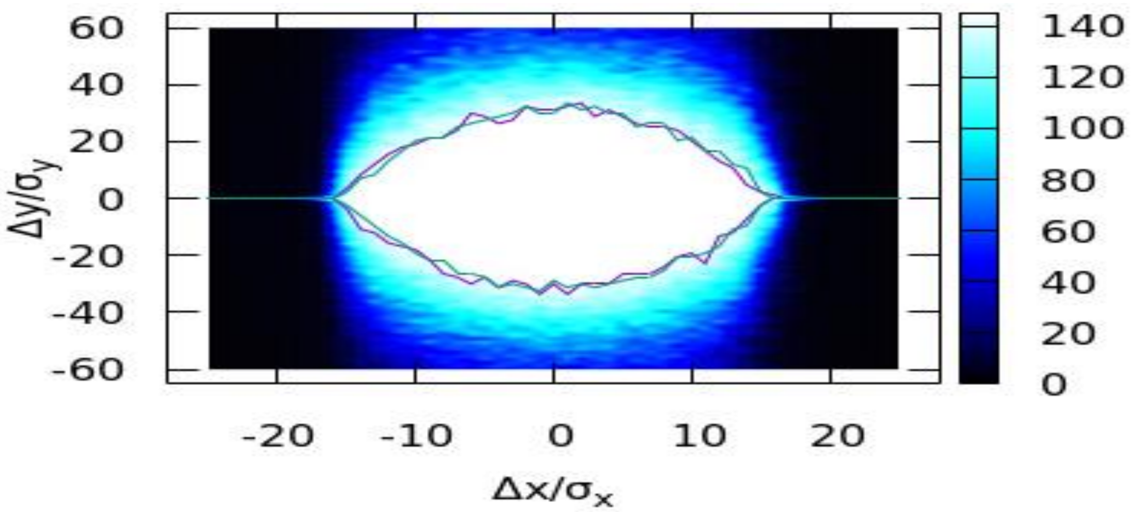
	Higgs (CDR)	*Higgs (high luminosity)*
Number of IPs	2	2
Beam energy (GeV)	120	120
Circumference (km)	100	100
Synchrotron radiation loss/turn (GeV)	1.73	1.8
Crossing angle at IP (mrad)	16.5×2	16.5
Piwinski angle	3.48	4.87
Number of particles/bunch N_e (10^{10})	15.0	16.3
Bunch number (bunch spacing)	242 (0.68μs)	214
Beam current (mA)	17.4	16.8
Synchrotron radiation power /beam (MW)	30	30
Bending radius (km)	10.7	10.2
Momentum compact (10^{-5})	1.11	7.34
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.33/0.001
Emittance e_x/e_y (nm)	1.21/0.0024	0.68/0.0014
Beam size at IP s_x/s_y (μm)	20.9/0.06	15.0/0.037
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.018/0.115
RF voltage V_{RF} (GV)	2.17	2.27
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)	650 (217500)
Natural bunch length σ_z (mm)	2.72	2.25
Bunch length σ_z (mm)	4.4	4.42
HOM power/cavity (2 cell) (kw)	0.46	0.48
Energy spread (%)	0.134	0.19
Energy acceptance requirement (%)	1.35	1.7
Energy acceptance by RF (%)	2.06	2.5
Beamstruhlung lifetime /quantum lifetime* (min)	80/80	41
Lifetime (hour)	0.43	21
F (hour glass)	0.89	0.88
Luminosity/IP L (10^{34}cm^{-2}s^{-1})	**2.93**	**5.0**

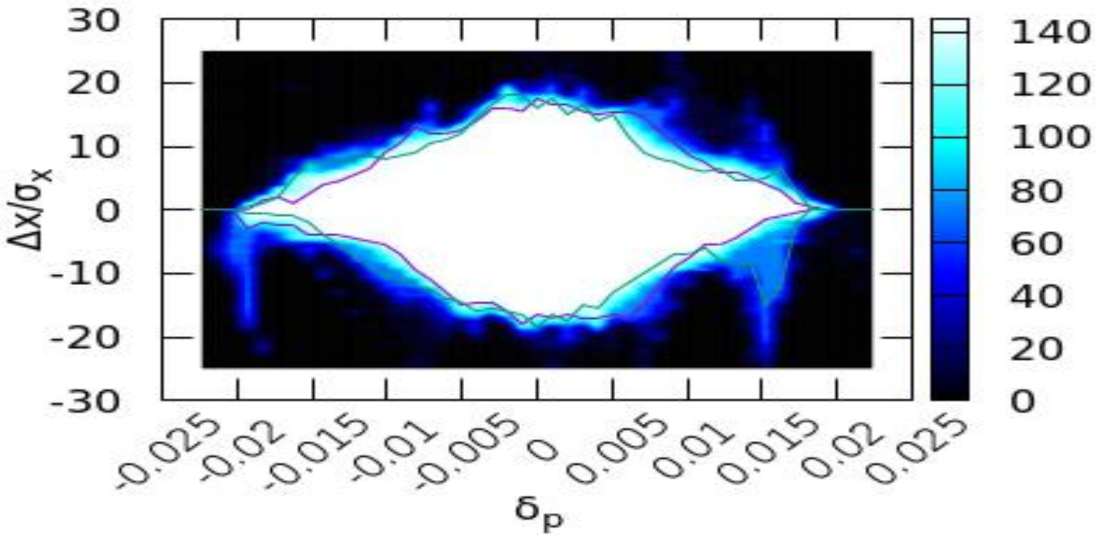
High luminosity scheme at Higgs energy

Dynamic aperture

by J. Wu, Y. Zhang, Y. Wang

Dynamic aperture optimization with diffusion map analysis at CEPC using differential evolution algorithm





Achieved (without errors): $16\sigma_x \times 32\sigma_y \times 1.9\%$

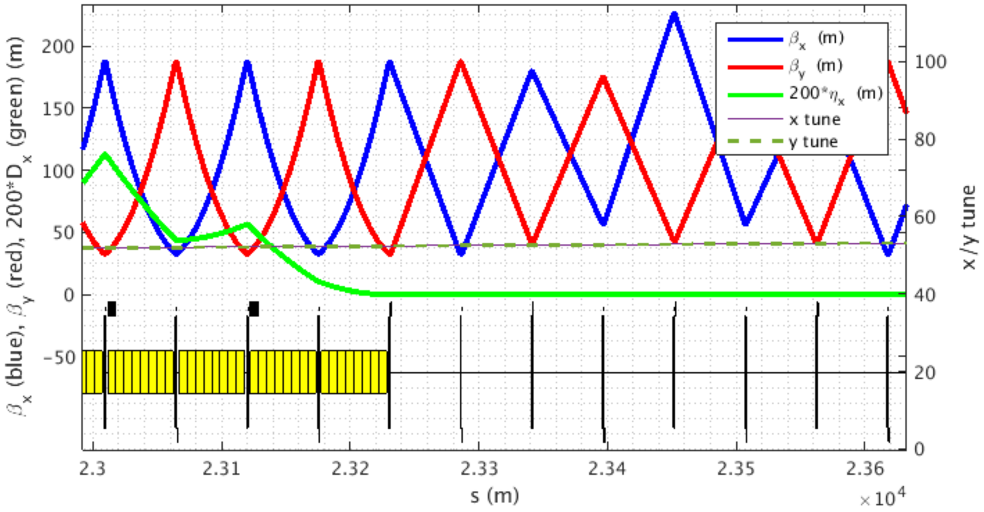
Goal (with errors): $8\sigma_x \times 15\sigma_y \times 1.7\%$

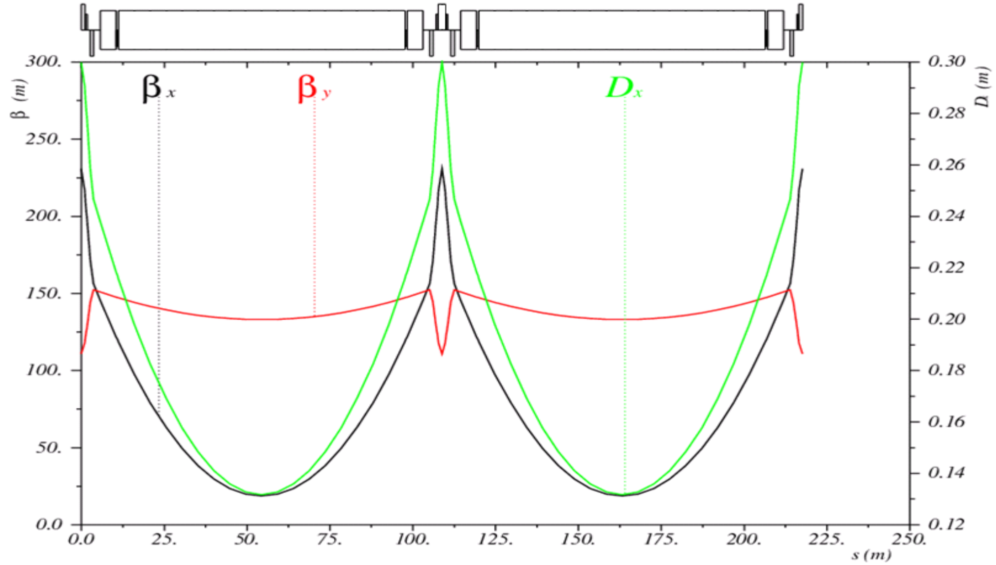
Enough margin to start error correction study

High luminosity scheme at Higgs energy

Booster ring

by D. Wang



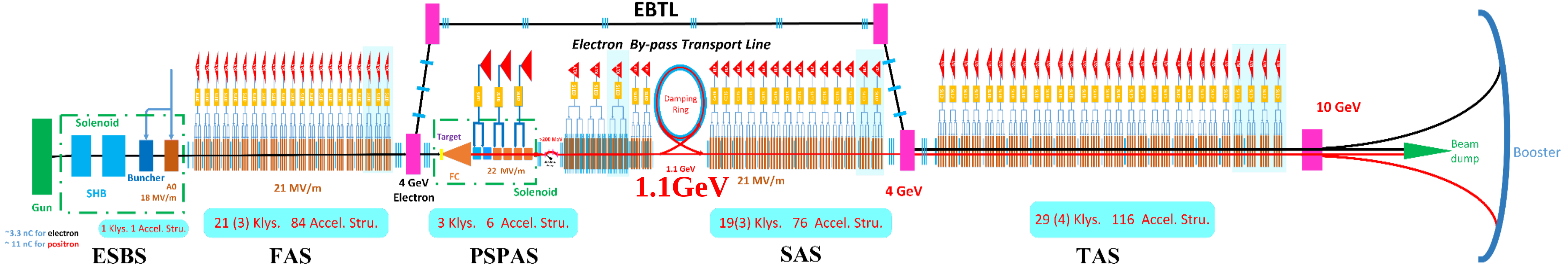


- Standard TME cells are chosen for lower booster emittance to relax the DA requirement of collider ring.
- **1.4nm** is expected (CDR: 3.6nm)

High luminosity scheme at Higgs energy

LINAC

by C. Meng

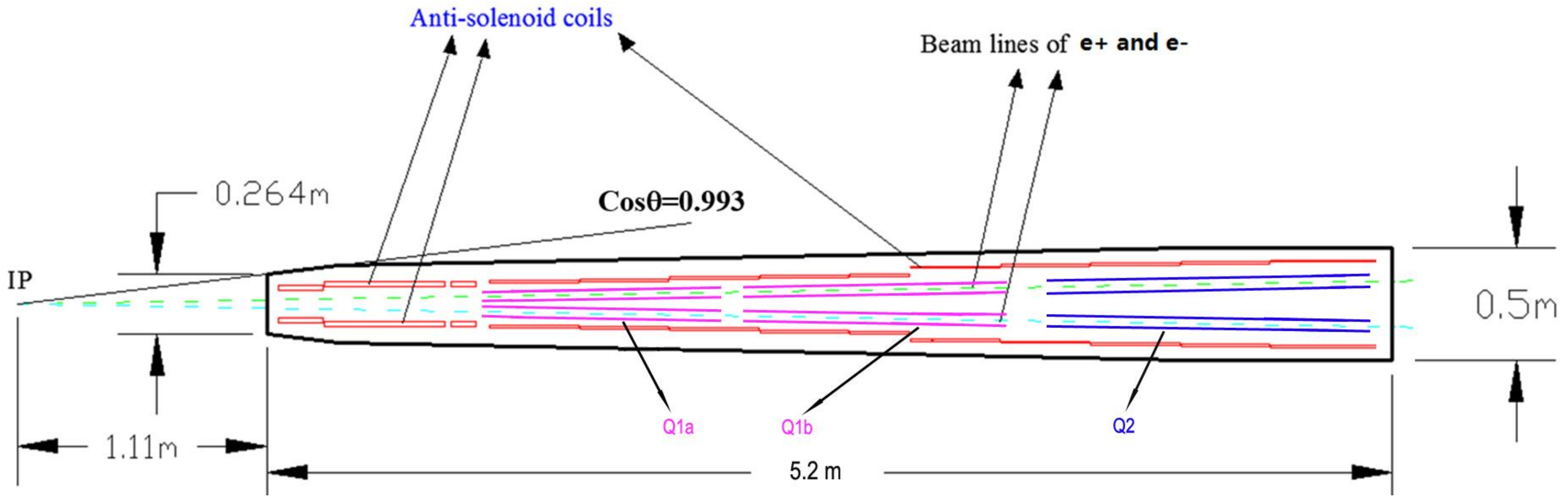


In order to relax the DA requirement of booster the beam emittance of Linac should be controlled as **10 nm** with the damping ring of energy 1.1GeV. (CDR: 40nm)

Parameter	Symbol	Unit	Designed
e^- /e^+ beam energy	E_{e-}/E_{e+}	GeV	**10**
Repetition rate	f_{rep}	Hz	**100**
e^- /e^+ bunch population	N_{e-}/N_{e+}		**> 9.4×10^9 / >9.4×10^9**
		nC	**> 1.5**
Energy spread (e^- /e^+)	Σ_e		**< 2×10^-3 / < 2×10^-3**
Emittance (e^- /e^+)	ε_r	nm· rad	**10**
Bunch length (e^- /e^+)	Σ_l	mm	**1 / 1**
e^- beam energy on Target		GeV	**4**
e^- bunch charge on Target		nC	**10**

Compatible schemes base on high luminosity higgs scheme

by C. Yu



Z mode: Q1a=Vertical focusing quadrupole, Q1b+Q2=Horizontal focusing quadrupole

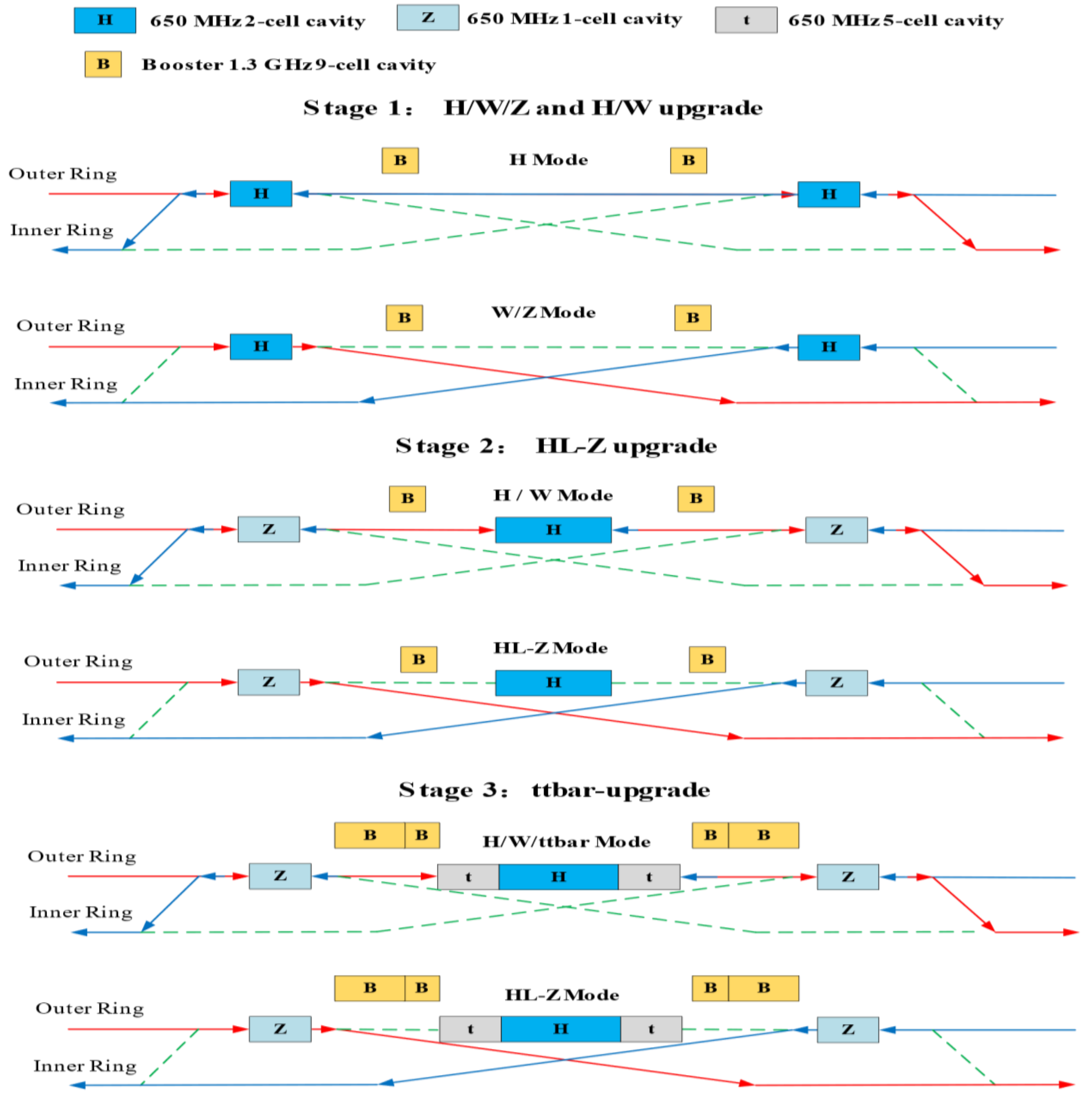
W & H mode: Q1a+Q1b=Vertical focusing quadrupole, Q2=Horizontal focusing quadrupole

$t\bar{t}$ mode: Q1a+Q1b+Q2=Vertical focusing quadrupole

High luminosity Z: HOM at SCQ Pipe will be one of the dominant constraint. Replacing the whole cryostat is the best option. The shape and size of cryostat stay the same and the inner aperture of SCQ beam pipe can be made large enough since Z beam energy is low enough.

Compatible schemes base on high luminosity higgs scheme

by J. Zhai, Y. Wang



高频腔 bypass 升级方案

Stage 1：Higgs优先运行，中低亮度Z。高频布局和参数与CDR相同，加长中段。

Stage 2：高亮度Z升级。安装强流超导腔模组。Bypass Higgs腔（方案关键点）。

Stage 3：ttbar升级。安装铌三锡超导腔模组，显著降低低温造价和功耗。

解决CEPC亮度提升的瓶颈，设计理念和方案与FCC高频系统不同

- 确保Higgs优先运行，降低初期造价，逐步增加技术难度。
- 实现各能量最高亮度、释放机器潜力的同时，模式可切换、灵活运行。

Spin Polarization

by W. Xia, Z. Duan, Y. Wang

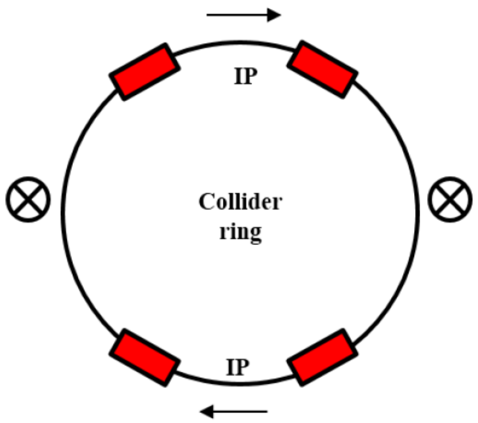
- 基于螺线管的自旋旋转器的设计

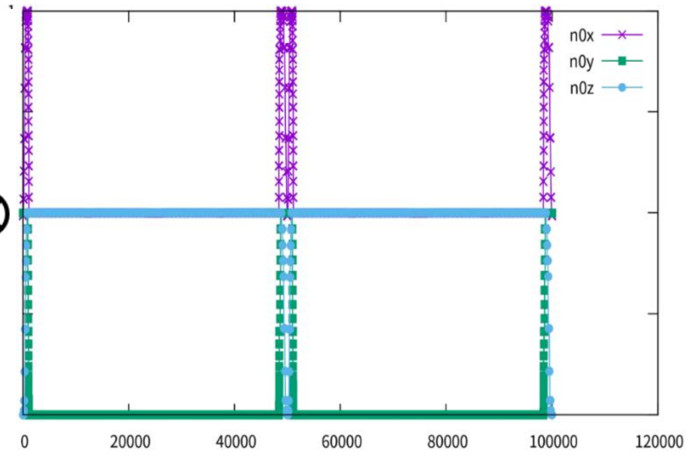
螺线管解耦合结构

Solenoids		Quadrupoles		Drifts	
Length (m)	Field strength (T)	$\frac{\partial B_y/\partial x}{B\rho}$ (m^{-2})	Length (m)	Length (m)	Total Length (m)
1.48895	8	Q1: -0.83 Q2: 1.35 Q3: -0.90 Q4: -0.82	0.8	D1: 0.2 D2: 0.2 D3: 0.2 D4: 0.1	9.97796

- 自旋旋转器在储存环中的分布

横向极化束流在进入对撞点之前需要在自旋旋转器的作用下偏转为纵向，经过对撞点之后，在另一个自旋旋转器的作用下偏转回横向。

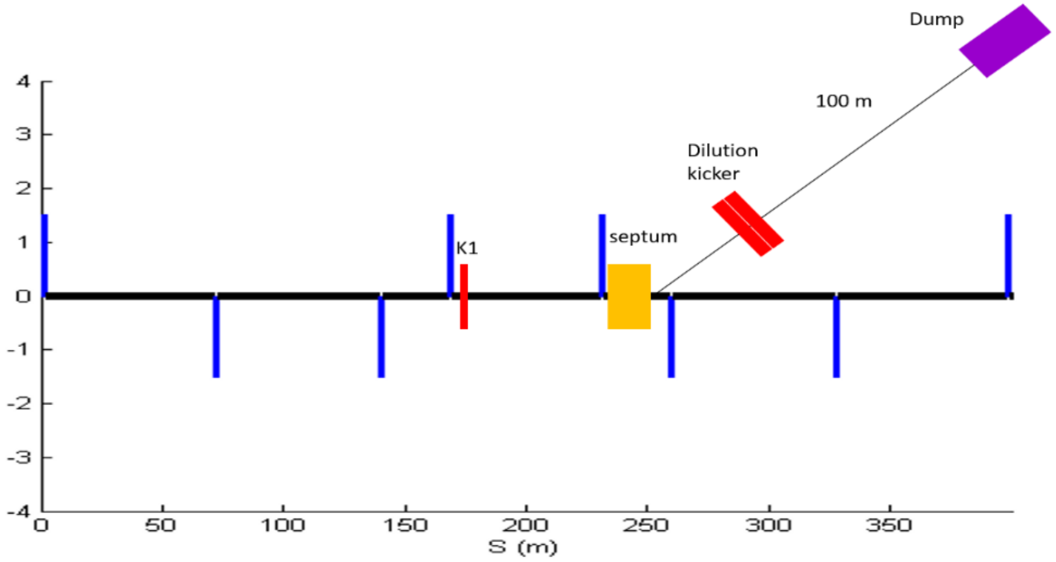




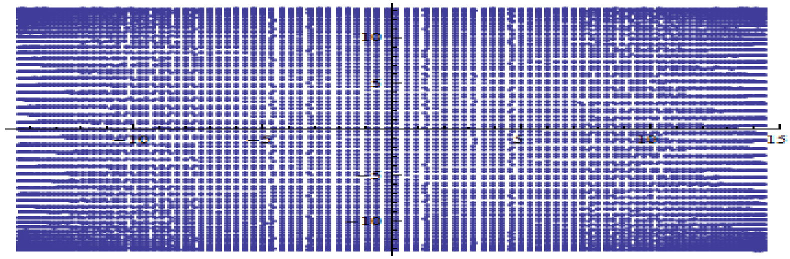
Beam dump

by X. H. Cui, Z. J. Ma et al

- 通过调节冲击磁铁的强度和频率可以使得正负电子束流在垃圾桶截面尽量分布均匀，从而降低垃圾桶截面上的粒子密度和温度。



CEPC垃圾桶输运线

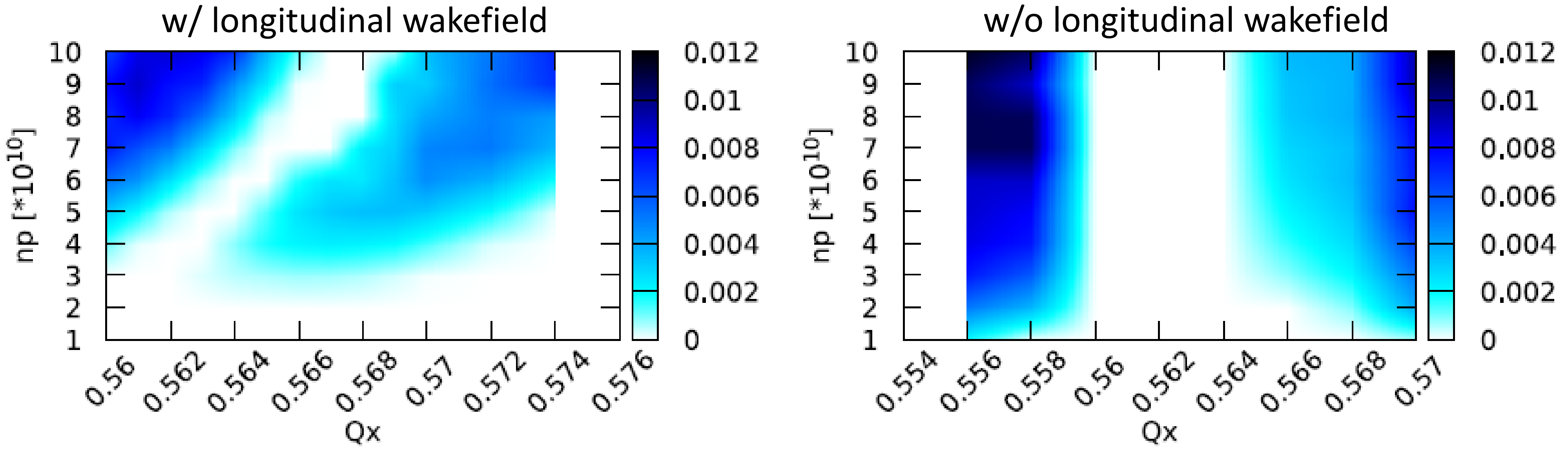


CEPC垃圾桶横截面上的粒子分布

Beam-beam effects

by Y. Zhang, N. Wang et al

- 系统地模拟研究了对撞中的韧致辐射对 X-Z 不稳定性的影响，独立的纵向尾场对 X-Z 不稳定性的影响，以及完全**自洽的模拟研究**（即同时考虑韧致辐射、纵向尾场）
- 模拟研究了bootstrapping注入过程中的X-Z 不稳定性情况，对比了考虑和不考虑纵向尾场效应的差别。结果提示在**注入过程中可能需要对水平工作点进行调制**。



Bootstrapping 注入过程中的水平尺寸增长速度随工作点的变化。

Summary

- The high luminosity scheme of CEPC collider ring with $5\times10^{34}cm^{-2}s^{-1}$ & 30MW has been designed. It doesn't meet strong limitation and also won't affect the current mechanical design of detector.
- More detailed studies will be done. DA optimization with errors, detector background evaluation, etc.