

Institute of High Energy Physics Chinese Academy of Sciences



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# **CEPC Collider ring lattice**

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### **Machine parameters of CEPC**



by CEPC AP group, 2 June 2022

	Higgs	Z	W	ttbar	
Number of IPs	2				
Circumference [km]	100.0				
SR power per beam [MW]		30			
Half crossing angle at IP [mrad]		16.5			
Bending radius [km]		10.7			
Energy [GeV]	120	45.5	80	180	
Energy loss per turn [GeV]	1.8	0.037	0.357	9.1	
Piwinski angle	5.94	24.68	6.08	1.21	
Bunch number	268	11934	1297	35	
Bunch spacing [ns]	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)	
Bunch population [10^10]	13	14	13.5	20	
Beam current [mA]	16.7	803.5	84.1	3.3	
Momentum compaction [10^-5]	0.71	1.43	1.43	0.71	
Beta functions at IP (bx/by) [m/mm]	0.3/1	0.13/0.9	0.21/1	1.04/2.7	
Emittance (ex/ey) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7	
Beam size at IP (sigx/sigy) [um/nm]	14/36	6/35	13/42	39/113	
Bunch length (natural/total) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9	
Energy spread (natural/total) [%]	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20	
Energy acceptance (DA/RF) [%]	1.6/2.2	1.3/1.7	1.2/2.5	2.3/2.6	
Beam-beam parameters (ksix/ksiy)	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1	
RF voltage [GV]	2.2	0.12	0.7	10	
RF frequency [MHz]	650	650	650	650	
Longitudinal tune Qs	0.049	0.035	0.062	0.078	
Beam lifetime (bhabha/beamstrahlung)[min]	39/40	80/18000	60/700	81/23	
Beam lifetime [min]	20	80	55	18	
Hour glass Factor	0.9	0.97	0.9	0.89	
Luminosity per IP[1e34/cm^2/s]	5.0	115	16	0.5	



# **Optics design of the CEPC collider ring**



- SR power 30MW (50 MW upgradable), 100km, 2 IPs
- Compatible of  $t\bar{t}/H/W/Z$  modes
- Compatible with SPPC
- Correction of sawtooth orbit
- 2 folded symmetry
- 8 arc sections
  - dual aperture dipole and quadrupole magnets
  - non-interleaved sextupoles
- 4 short straight section
  - injection regions for different modes
- 2 interaction regions
  - crab waist collision
  - local chromaticity correction for the interaction region
  - asymmetric interaction region
- 2 RF acceleration regions
  - shared cavities for two beam @ ttbar, Higgs
  - flexible switching between compatible modes



\*ref: CEPC-CDR; CEPC pre-CDR; K. Oide, arXiv:1610.07170; M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010); M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010); A. Milanese, PRAB 19, 112401 (2016);



#### Interaction region for all modes



• Crab waist collision, local chromaticity correction, asymmetric interaction region



	QD	QF
Z	Q1A	Q1B
W/H	Q1A+Q1B	Q2
ttbar	Q1A+Q1B+Q2	add quad Q3A and Q3B

	L [m]	Strength [T/m]			
		ttbar	Higgs	W	Ζ
Q1AIRU	1.21	-141	-141	-94	-110
Q1BIRU	1.21	-59	-85	-56	+65
Q2IRU	1.5	-51	+95	+63	0
Q3AIRU	1.5	+40	0	0	+2
Q3BIRU	1.5	+40	0	0	+2
Q1AIRD	1.21	-142	-142	-95	-110
Q1BIRD	1.21	-64	-85	-57	+65
Q2IRD	1.5	-47	+96	+64	0
Q3AIRD	1.5	+40	0	0	+2
Q3BIRD	1.5	+40	0	0	+2

Strength of other modes doesn't exceeded the one of Higgs mode.



# Interaction region for all modes (cont.)



• Crab waist collision, local chromaticity correction, asymmetric interaction region



	L [m]	Strength [T/m]			
		ttbar	Higgs	W	Z
<b>Q1AIRU</b>	1.21	-141	-141	-94	-110
Q1BIRU	1.21	-59	-85	-56	+65
Q2IRU	1.5	-51	+95	+63	0
Q3AIRU	1.5	+40	0	0	+2
Q3BIRU	1.5	+40	0	0	+2
Q1AIRD	1.21	-142	-142	-95	-110
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Strength of other modes doesn't exceeded the one of Higgs mode.

\*ref: Y. Cai, IAS2016, HKUST; K. Oide, arXiv:1610.07170;
P. Raimondi, Proc. of the 2nd SuperB Workshop, Frascati, March 2006;
M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010);



### **New RF Scheme\***

\*more details in Jiyuan ZHAI, Cavity and cryomodules developments for CEPC 10:20 - 10:40, 14 Sep 2022, eeFACT22



Stage 1: H/W/LL-Z (and HL-H/W upgrade)

- All-mode seamless switching in whole lifecycle (CEPC, ep ...)
- 1st priority of the Higgs running
- Highest luminosity in each energy
- Maximize the performance and flexibility of future circular electron positron collider

Operation Mode	Collider Ring 650 MHz Cavities / Cryomodules
Higgs	240 2-cell / 40 CMs
HL-Z	100 1-cell / 100 CMs
W	240 2-cell / 40 CMs
ttbar	+240 5-cell / +60 CMs

3146 m 1080 m 160 m 373 m 500 m 1 m Outer Ring

Stage 2: HL-H/W/Z (HL-Z upgrade)







\*quire recent scheme, not implemented in the new lattice yet



# **ARC region for all modes**



- Z and W modes need larger momentum compaction factor  $\alpha p$  and thus larger emittance  $\epsilon x$ , Qs
  - To suppress the impedance induced instability at Z mode
  - To increase stable tune area if considering beam-beam effect and impedance consistently at W and Z modes



Phase advance reduced from 90° to 60° for W and Z modes



**Microwave instability** 



stable tune area with both beam-beam and impedance (Z mode 90/90)

Yuan Zhang





# **ARC region for compatible modes**

- 2<sup>nd</sup> order chromaticity is a main aberration for the optimization of momentum acceptance with one –I sextupole pair scheme.
  - In previous versions, 2<sup>nd</sup> order chromaticity generated in the ARC region are corrected with IR knobs (phase advance or K1).
  - However, the IR knobs will generate distortions at IP (beta, alfa and dispersion) especially for the horizontal plane.
- A lattice with four –I sextupole pairs scheme for Higgs & ttbar modes
  - much less 2<sup>nd</sup> order chromaticity for the horizontal plane
  - The distribution of sextupoles for Higgs & ttbar modes (90 deg cell) allowed to select –I sextupole pairs for W &Z modes (60 deg cell).





# Optimization of the ARC aberration at W and Z modes



- The distribution of sextupoles for Higgs & ttbar mode allowed to select –I sextupole pairs for W &Z mode.
  - 6\*6=36 cases for 23 cells
  - There are much more combinations if choose different cases in each arc section (184 cells)



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# Optimization of the ARC aberration at W and Z modes (cont.)



• Cancellation of main aberration has period of 23\*3 cells.

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#### Lattice of half ring







#### **Dynamic aperture requirement**

X. H. Cui, Y. Zhang, Y. W. Wang

	ttbar	Higgs	W	Z
Horizontal Emittance in collider/booster [nm]	1.4 / 2.83	0.64 / 1.26	0.87 / 0.56	0.27 / 0.19
DA requirement from injection	13.9 $\sigma_x \times 7 \sigma_y$ off axis	14.4 $\sigma_x \times 7 \sigma_y$ off axis 7 $\sigma_x \times 7 \sigma_y$ on axis	10.5 $\sigma_x \times 5 \sigma_y$ off axis	11.8 $\sigma_x \times 5 \sigma_y$ off axis
Beam lifetime (mainly bhabha and beamstrahlung) [min]	18	20	55	80
Energy acceptance requirement from beam lifetime [%]	2.3	1.6	1.2	1.3

\* need beam-beam simulation to check for y





### **Dynamic aperture @ Higgs and ttbar**

- Tracking to get DA without errors, with turns for one transvers damping time, with 4 initial phases
- DA optimized with 84 variables (64 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advance)







#### Dynamic aperture @ Z and W

- Tracking to get DA without errors, with turns for one transvers damping time, with 4 initial phases
- DA optimized with 116 variables (96 arc sextupole families + 8 IR sextupoles + 4 multipoles + 8 phase advance)







# **Correction scheme for magnets errors**

#### by Bin WANG, Yuanyuan WEI, Yiwei WANG

- Correction procedures
  - The closed orbit distortion (COD) correction with sextupoles off
  - Turn on the sextupoles and perform COD correction again.
  - Dispersion correction
  - Beta beating correction
  - Coupling and vertical dispersion correction (Local coupling parameter correction)
- Uniform settings (corrector settings, BPM selection, iteration times, steps and so on) of the batched correction are optimized for all the lattice seeds.
- Individual further correction (additional iteration and adjustment of the corrector settings according to correction result) are performed for those un-converged seeds.



# **Correction of the closed orbit distortion**



- Correction of the closed orbit distortion (COD) with sextupoles off is made firstly.
- Turn on the sextupoles and perform COD correction again.
- Mover used to get fine alignment of sextupole
- Orbit correction is applied using orbit **response matrix and SVD method.**



### **Dispersion correction**



• With dispersion free steering (DFS): orbit manipulation by knob correctors.

$$\vec{d} = \begin{pmatrix} (1-\alpha)\vec{u} \\ \alpha \vec{D}_u \end{pmatrix} \qquad M = \begin{pmatrix} (1-\alpha)A \\ \alpha B \end{pmatrix}$$
$$\vec{d} + M\vec{\theta} = 0$$

- $\vec{u}$  orbit vector
- $\vec{D}_u$  dispersion vector
- $\vec{\theta}$  Corrector strengths vector
- $\alpha$  Weight factor
- *A* Orbit response matrix
- *B* Dispersion response matrix



# **Beta-beating correction**



- Correct the beta functions with sextupoles on.
- **Based on AT LOCO**: model based correction
  - Establish lattice model  $M_{mod}$ , multi-parameter fit to the orbit response matrix  $M_{meas}$  to obtain calibrated model:

$$\chi^{2} = \sum_{i,j} \frac{\left(M_{\text{mod},ij} - M_{\text{meas},ij}\right)^{2}}{\sigma_{i}^{2}} \equiv \sum_{i,j} V_{ij}^{2}$$

- Parameters fitted: K, KS ...
- Use calibrated model to perform correction and apply to machine.
- Application to correct beta-beating, dispersion and coupled response matrix.



# **Coupling correction**



• Neglecting beam-beam effects

$$\varepsilon_y \simeq \varepsilon_{y0} + \kappa \varepsilon_x + r E^2 (D_y^{\rm rms})^2$$

- Both coupling and vertical dispersion are controlled.
- Using the trim coils of the sextupoles, which providing skew-quadrupole field, to perform emittance tuning for CEPC.
- The vertical orbit distortion due to a horizontal deflection at a BPM is:

$$\frac{\Delta y_{cod}}{\Delta x_{cod}} = \bar{c}_{b,22}k_1 + \bar{c}_{b,12}k_2 + \bar{c}_{c,11}k_3 + \bar{c}_{c,12}k_4$$

 $k_1, k_2, k_3, k_4$ : only related to the decoupled linear optics

 $\bar{c}_{b,22}, \bar{c}_{b,12}, \bar{c}_{c,11}, \bar{c}_{c,12}$ : local coupling parameters

$$\bar{c}_{b,12} = M_c \overrightarrow{ks}$$

- $M_c$ :  $\bar{c}_{b,12}$  response matrix
- $\overrightarrow{ks}$ : skew-quadrupole vector





## **Correction for the compatible lattices**

- With assumption of 100 um transverse misalignments
- The Higgs and ttbar lattices are similar, the Z and W lattices are similar.
  - The error corrections have been performed for the Higgs and Z lattices.
  - 1000 seeds used for the Higgs, 500 lattice seeds used for the Z

Component	Δx (mm)	Δy (mm)	$\Delta \theta_{z} (mrad)$	Field error
Dipole	0.10	0.10	0.10	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.02%
IR Quadrupole	0.10	0.10	0.10	
Sextupole	0.10*	0.10*	0.10	

\* reduced to 0.01 mm with movers



# **Correction of the closed orbit distortion @ Higgs**



- BPMs placed at each quadrupoles
- H/V correctors placed beside focusing/defocusing quadrupoles
- The converged seeds is increased from 678 to **799** after additional iteration and manual optimization.
  - The rest 201 seeds are not manual optimized yet due to time being.







#### **Dispersion correction @ Higgs**



- The dispersion correction is performed for the 799 lattice seeds.
- 541 seed converged after batched dispersion correction
- The converged seeds is increased from 541 to 649 with manual optimization.





#### **Beta-beating correction @ Higgs**



- For the beta beating correction, the manual adjustment is necessary for almost all lattice seeds
- only 541 lattice seeds are performed for beta beating correction





- The emittance coupling fulfill the requirement (<0.2%)
- With batched correction for Higgs mode, 404 out of 1000 seeds satisfy the DA.
- For the remaining 596 error seeds, 97 seeds out of randomly-selected 108 seeds satisfy the DA requirements after individual further correction. In the near future we will finish the study of all the 1000 seeds.

#### Emittance and dynamic aperture with error @ Z



- The dedicated correction code for Z mode is still under development. 96 seeds out of randomly-selected 102 seeds satisfy the DA requirements after individual further correction.
- In the near future we will finish the study of all the 500 seeds by both batched and individual further correction.
- The emittance coupling fulfill the requirement (<0.5%)







- The optics of CEPC collider ring was designed with luminosity goal 5e34/cm^2/s/IP @ Higgs with 30 MW/beam.
  - RF region: 1st priority of the Higgs running and flexible switching
  - ARC: New aberration correction scheme in ARC region. The distribution of sextupoles for Higgs & ttbar modes (90 deg cell) allowed to select –I sextupole pairs for W &Z modes (60 deg cell).
  - IR: Crab waist collision, local chromaticity correction, asymmetric interaction region
- Dynamic aperture w/o error for four modes achieve the requirement of energy acceptance.
- The lattice w/ error for Higgs and Z modes are corrected
  - The emittance coupling fulfill the requirement
  - For both Higgs and Z lattice, the pass rate of random seeds is high enough to fully satisfy the DA requirements with both batched correction and individual further correction .
  - Further correction study with girder misalignment, main field errors of the sextupole and IR quadruple are under going.