Status of optics tuning simulations in the CEPC

Yiwei Wang, Bin Wang, Yuan Zhang, Sha Bai, Jiyuan Zhai, Yuanyuan Wei
for the CEPC Accelerator Physics Group
• Introduction
• Lattice design requirement of the CEPC collider ring
  • Interaction region
  • RF region
  • ARC region
• Dynamic aperture w/o errors
• Error correction and dynamic aperture w/ errors
• Conclusions
Overall design requirement of the CEPC collider ring

- SR power per beam 30 MW (50 MW upgradable), 100 km, 2 interaction points
- Higgs mode hold the 1st priority and compatible with the ttbar/W/Z modes.
- Compatible with SPPC: 100km, section length, two machines share the most tunnels
Lattice design requirement of the CEPC collider ring

- Basically 2 folded symmetry
- 2 interaction regions @ IP1 and IP3
  - crab waist collision
  - local chromaticity correction for the interaction region
- 2 RF acceleration regions @ IP2 and IP4
  - shared cavities for two beam @ ttbar, Higgs
  - flexible switching between compatible modes
- 8 arc sections
  - dual aperture dipole and quadrupole magnets
- 4 short straight section
  - on/off axis injection regions for different modes
  - beam dumping, gamma source
- Providing polarized beam*


*Polarization preservation issues at the CEPC, Zhe DUAN, 16:40, 27 June, this workshop
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Higgs</th>
<th>Z</th>
<th>W</th>
<th>t̃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IPs</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Circumference (km)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>SR power per beam (MW)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Half crossing angle at IP (mrad)</td>
<td>16.5</td>
<td>16.5</td>
<td>16.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Bending radius (km)</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>120</td>
<td>45.5</td>
<td>80</td>
<td>180</td>
</tr>
<tr>
<td>Energy loss per turn (GeV)</td>
<td>1.8</td>
<td>0.037</td>
<td>0.357</td>
<td>9.1</td>
</tr>
<tr>
<td>Damping time τ/τ/τ (ms)</td>
<td>44.6/44.6/22.3</td>
<td>816/816/408</td>
<td>150/150/75</td>
<td>13.2/13.2/6.6</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>4.88</td>
<td>24.23</td>
<td>5.98</td>
<td>1.23</td>
</tr>
<tr>
<td>Bunch number</td>
<td>268</td>
<td>11934</td>
<td>1297</td>
<td>35</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>591</td>
<td>23</td>
<td>257</td>
<td>4524</td>
</tr>
<tr>
<td>(53% gap)</td>
<td></td>
<td>(18% gap)</td>
<td></td>
<td>(53% gap)</td>
</tr>
<tr>
<td>Bunch population (10^{11})</td>
<td>1.3</td>
<td>1.4</td>
<td>1.35</td>
<td>2.0</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>16.7</td>
<td>803.5</td>
<td>84.1</td>
<td>3.3</td>
</tr>
<tr>
<td>Phase advance of arc FODO (*)</td>
<td>90</td>
<td>60</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Momentum compaction (10^{-5})</td>
<td>0.71</td>
<td>1.43</td>
<td>1.43</td>
<td>0.71</td>
</tr>
<tr>
<td>Beta functions at IP β_{x} / β_{y} * (m/mm)</td>
<td>0.3/1</td>
<td>0.13/0.9</td>
<td>0.21/</td>
<td>1.04/2.7</td>
</tr>
<tr>
<td>(53% gap)</td>
<td></td>
<td>(18% gap)</td>
<td></td>
<td>(53% gap)</td>
</tr>
<tr>
<td>Emittance ε/ε (nm/pm)</td>
<td>0.64/1.3</td>
<td>0.27/1.4</td>
<td>0.87/1.7</td>
<td>1.4/4.7</td>
</tr>
<tr>
<td>Beam size at IP σ_{x}/σ_{y} (um/mm)</td>
<td>14/36</td>
<td>6/35</td>
<td>13/42</td>
<td>39/113</td>
</tr>
<tr>
<td>Bunch length (natural/total) (mm)</td>
<td>2.3/4.1</td>
<td>2.5/8.7</td>
<td>2.5/4.9</td>
<td>2.2/2.9</td>
</tr>
<tr>
<td>Energy spread (natural/total) (%)</td>
<td>0.10/0.17</td>
<td>0.04/0.13</td>
<td>0.07/0.14</td>
<td>0.15/0.20</td>
</tr>
<tr>
<td>Energy acceptance (DA/RF) (%)</td>
<td>1.6/2.2</td>
<td>1.0/1.7</td>
<td>1.2/2.5</td>
<td>2.0/2.6</td>
</tr>
<tr>
<td>Beam-beam parameters ξ_{x}/ξ_{y}</td>
<td>0.015/0.11</td>
<td>0.004/0.127</td>
<td>0.012/0.113</td>
<td>0.071/0.1</td>
</tr>
<tr>
<td>RF voltage (GV)</td>
<td>2.2</td>
<td>0.12</td>
<td>0.7</td>
<td>10</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>650</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal tune γ</td>
<td>0.049</td>
<td>0.035</td>
<td>0.062</td>
<td>0.078</td>
</tr>
<tr>
<td>Beam lifetime (Bhabha/beamstrahlung) (min)</td>
<td>39/40</td>
<td>82/2800</td>
<td>60/700</td>
<td>81/23</td>
</tr>
<tr>
<td>Beam lifetime (min)</td>
<td>20</td>
<td>80</td>
<td>55</td>
<td>18</td>
</tr>
<tr>
<td>Hourglass Factor</td>
<td>0.9</td>
<td>0.97</td>
<td>0.9</td>
<td>0.89</td>
</tr>
<tr>
<td>Luminosity per IP (10^{34} cm^{-2} s^{-1})</td>
<td>5.0</td>
<td>115</td>
<td>16</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- β_{y} * and emittance chosen for luminosity-adequate Ne for the luminosity and achievable energy acceptance for lattice design.

Yiwei Wang
Final quadrupoles for all modes

- Higgs running keep the 1st priority
  - Strength of other modes doesn’t exceed the one of Higgs mode.
- The parameters near the IP are chosen based on a trade-off between the beam dynamics and the machine detector interface.
Lattice design of the interaction region

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

- Up to 3rd order chromaticity is corrected with pairs of main sextupoles, phase tuning and additional sextupoles respectively.
- Main resonance driving terms (RDT) due to sextupoles in 3rd and 4th order Lie operators are cancelled.
- The tune shift due to the finite length of the main sextupoles is corrected with additional weak sextupoles.
RF region Layout

- 1st priority of the Higgs running and switching between different modes
- Shared cavities for two beam @ Higgs, ttbar; Bunches filled in each half rings
- Independent cavities; bunches filled in each whole rings for the W and Z
- Maximize the performance and flexibility of future circular electron positron collider

Peak luminosity at different stages with SR power for **30/50MW per beam**

<table>
<thead>
<tr>
<th>Luminosity/IP [10^34/cm²/s]</th>
<th>Higgs</th>
<th>Z</th>
<th>W</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1</strong></td>
<td>5/8.3</td>
<td>38 (10MW limit)</td>
<td>16/26.7</td>
<td>-</td>
</tr>
<tr>
<td><strong>Stage 2</strong></td>
<td>5/8.3</td>
<td>115/192</td>
<td>16/26.7</td>
<td>-</td>
</tr>
<tr>
<td><strong>Stage 3</strong></td>
<td>5/8.3</td>
<td>115/192</td>
<td>16/26.7</td>
<td>0.5/0.83</td>
</tr>
</tbody>
</table>
The lattice was designed to satisfy the RF system design for different energies.

- bypass and section length for different RF stages, small average beta functions to reduce the multi-bunch instability.
Lattice design of the ARC region

- FODO cell to provide a large filling factor.
- 90/90 degrees’ phase advances for the Higgs and ttbar modes due to the emittance and nonlinearity cancelation.
- 60/60 degrees’ phase advances for the W and Z modes to fulfil the collective instability requirement.
  - suppress the impedance induced instability at Z mode
  - increase stable tune area if considering beam-beam effect and impedance consistently at W and Z modes
- The distance 0.35m and opposite polarity between two beams fulfill the requirement technical design of the twin-aperture of dipoles and quadrupoles.

Yiwei Wang
Optics Tuning and Corrections for Future colliders Workshop at CERN

Higgs/ttbar 90/90 degree
W/Z 60/60 degree

Dual aperture quadrupole and bend with opposite polarity in two ring
Optimization of ARC aberration for Higgs/ttbar modes

- Four –I sextupole pairs scheme for Higgs & ttbar modes
  - With small 2\textsuperscript{nd} order chromaticity esp. for the horizontal plane
  - 2\textsuperscript{nd} order chromaticity for the vertical plane generated in the ARC region are further corrected with IR knobs.
The distribution of sextupoles for Higgs & ttbar mode allowed to select –I sextupole pairs for W &Z modes.

Cancellation of main aberration has period of 23*3 cells. Give a good start point for the dynamic aperture optimization.

- Optimization of ARC aberration for W/Z

- Cancellation of beta distortion due to energy deviation

- Cancellation of dispersion distortion due to energy deviation

- Cancellation of 3rd RDT due to energy deviation

Yiwei Wang
Optics Tuning and Corrections for Future colliders Workshop at CERN
Lattice design of the CEPC half ring

ttbar: $\epsilon x=1.4\text{nm}$, $\beta=1.04\text{m}/2.7\text{mm}$

Higgs: $\epsilon x=0.64\text{nm}$, $\beta=0.30\text{m}/1\text{mm}$

W: $\epsilon x=0.87\text{nm}$, $\beta=0.21\text{m}/1\text{mm}$

Z: $\epsilon x=0.27\text{nm}$, $\beta=0.13\text{m}/0.9\text{mm}$
The detector solenoid are compensated locally with anti-solenoids

- 3T for $tt\overline{t}$/Higgs/W, 2T for the Z
- cancel the $\int Bzdz$ between the IP and the faces of the final quadrupole
- exists a transverse fringe field esp. at the fringe of anti-solenoid
- The vertical emittance increases due to the fringe field of the anti-solenoid combined with the horizontal crossing angle.

The solenoid field induced vertical emittance fulfill the parameter list.

<table>
<thead>
<tr>
<th></th>
<th>ttbar 3T</th>
<th>Higgs 3T</th>
<th>W 3T</th>
<th>Z 2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>EmitY nominal (pm)</td>
<td>4.7</td>
<td>1.3</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>EmitY (pm)</td>
<td>0.04</td>
<td>0.41</td>
<td>1.35</td>
<td>1.07</td>
</tr>
</tbody>
</table>
Energy sawtooth effects and correction

- With only two RF stations, the energy sawtooth is around ±0.4 % @ H and 1.3 % @ ttbar.
- The closed orbit distortion in CEPC collider ring is around 1 mm and becomes 1 um after tapering* the magnet strength with beam energy.
  - require adjusting range of magnets strength ±2.5% with the trim coil

*Ref: CEPC CDR, arXiv:1809.00285, 2018
The dynamic aperture requirement comes from the horizontal injection parameters, beam lifetime for the top-up injection.

<table>
<thead>
<tr>
<th></th>
<th>ttbar</th>
<th>Higgs</th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Emittance in</td>
<td>1.4 / 2.83</td>
<td>0.64 / 1.26</td>
<td>0.87 / 0.56</td>
<td>0.27 / 0.19</td>
</tr>
<tr>
<td>collider/booster [nm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA requirement from injection</td>
<td>11 $\sigma_x \times 7 \sigma_y$ off axis</td>
<td>13.5 $\sigma_x \times 7 \sigma_y$ off axis</td>
<td>8.5 $\sigma_x \times 5 \sigma_y$ off axis</td>
<td>11 $\sigma_x \times 5 \sigma_y$ off axis</td>
</tr>
<tr>
<td>Energy acceptance requirement</td>
<td>2.0</td>
<td>1.6</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>requirement [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam lifetime (mainly bhabha</td>
<td>18</td>
<td>18</td>
<td>21</td>
<td>72</td>
</tr>
<tr>
<td>and beamstrahlung) [min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dynamic aperture @ Higgs and ttbar

- Tracking to get DA **without errors**, with turns for one transvers damping time, with 4 initial phases
- Higgs case optimized with 256 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances
- ttbar case optimized with 64 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances

**Effects included in tracking**
- Synchrotron motion
- Radiation loss in all magnets
- Tapering
- Crab waist sextupole
- Maxwellian fringes
- Kinematic terms
- Finite length of sextupole

![Graphs showing dynamic aperture comparison between Higgs and ttbar cases](image)

Yiwei Wang

Optics Tuning and Corrections for Future colliders Workshop at CERN
Dynamic aperture @ Z and W

- Tracking to get DA **without errors**, with turns for one transvers damping time, with 4 initial phases
- Higgs case optimized with 128 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances
- ttbar case optimized with  128 arc sextupoles + 8 IR sextupoles + 4 multipoles + 8 phase advances

Effects included in tracking:
- Synchrotron motion
- Radiation loss in all magnets
- Tapering
- Crab waist sextupole
- Maxwellian fringes
- Kinematic terms
- Finite length of sextupole
The anti-solenoid cancel the $\int Bzdz$ between the IP and the faces of the final quadrupole.

The Twiss function distortion due to solenoid field was corrected with final quadrupoles.

The solenoid effect on the dynamic aperture is small.

Effects included in tracking:
- Synchrotron motion
- Radiation loss in all magnets
- Tapering
- Crab waist sextupole
- Maxwellian fringes
- Kinematic terms
- Finite length of sextupole
- Solenoid

Ander Ma, Yingshun Zhu et al

Higgs without solenoid

Higgs with solenoid
Correction scheme for magnets errors

- 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.
  - Orbit correction is applied using orbit response matrix and SVD method.
- Dispersion correction
  - With dispersion free steering (DFS): orbit manipulation by knob correctors.
- Beta-beating correction
  - Correct the beta functions with sextupoles turned on based on AT LOCO
- Coupling correction
  - 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.
Error assumption

- With assumption of 100 um transverse misalignments
- BPMs placed at each quadrupoles
- H/V correctors placed beside focusing/defocusing quadrupoles

<table>
<thead>
<tr>
<th>Component</th>
<th>$\Delta x$ (mm)</th>
<th>$\Delta y$ (mm)</th>
<th>$\Delta \theta_z$ (mrad)</th>
<th>Field error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.01%</td>
</tr>
<tr>
<td>Arc Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
<tr>
<td>IR Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
<tr>
<td>Sextupole</td>
<td>0.10*</td>
<td>0.10*</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

*implement beam-based alignment techniques to reach rms offsets in the order of 10 um with respect to the beam
- with a large beta* lattice
- with quadrupole coils in the sextupoles
- 10um is possible as O(BPM resolution)=1um
The RMS orbit, dispersion and beta-beating of the whole ring are controlled after the global corrections.

- $\Delta X$ decreased to max 50um
- $\Delta Y$ decreased to max 50um
- $\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm
- $\Delta D_{y,rms}$ decreased from 31.9 mm to 0.9 mm
- $\Delta \beta/\beta_{x,rms}$ decreased from 5.2% to 1.0%
- $\Delta \beta/\beta_{y,rms}$ decreased from 83.2% to 2.8%
- $\Delta X$ decreased to max 50um
- $\Delta Y$ decreased to max 50um
- $\Delta D_{x,rms}$ decreased from 23.1 mm to 1.8 mm
- $\Delta D_{y,rms}$ decreased from 31.9 mm to 0.9 mm
- $\Delta \beta/\beta_{x,rms}$ decreased from 7.5% to 2.0%
- $\Delta \beta/\beta_{y,rms}$ decreased from 148.8% to 3.0%
The RMS orbit, dispersion and beta-beating of the whole ring for the Higgs/Z/W/ttbar modes are controlled after the global corrections.

<table>
<thead>
<tr>
<th>RMS</th>
<th>Higgs</th>
<th>Z</th>
<th>W</th>
<th>t̅t̅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit (μm)</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Dispersion (mm)</td>
<td>1.8/0.9</td>
<td>2.8/1.4</td>
<td>2.7/1.8</td>
<td>0.6/0.3</td>
</tr>
<tr>
<td>Beta-beating (%)</td>
<td>1.0/2.8</td>
<td>2.0/3.0</td>
<td>0.5/2.5</td>
<td>1.1/1.2</td>
</tr>
</tbody>
</table>
The emittance coupling fulfill the requirement (<0.2%)

All of 100 lattice seeds with errors are corrected.

90% lattice seeds with error correction achieve $11\sigma_x \times 27\sigma_y \times 1.6\%$ after global correction.

Correction with more errors and the IR tuning are undergoing.

---

Effects included in tracking

- Synchrotron motion
- Radiation loss in all magnets
- Tapering
- Crab waist sextupole
- Maxwellian fringes
- Kinematic terms
- Finite length of sextupole

---

<table>
<thead>
<tr>
<th>Component</th>
<th>$\Delta x$ (mm)</th>
<th>$\Delta y$ (mm)</th>
<th>$\Delta \theta_z$ (mrad)</th>
<th>Field error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.01%</td>
</tr>
<tr>
<td>Arc Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
<tr>
<td>IR Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
<tr>
<td>Sextupole</td>
<td>0.10*</td>
<td>0.10*</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

---

Yiwei Wang
Optics Tuning and corrections for Future Colliders Workshop at CERN
Emittance and dynamic aperture with error @ Z

- The emittance coupling fulfill the requirement (<0.5%)
- All of 100 lattice seeds with errors are corrected.
The emittance coupling fulfill the requirement (<0.34%).

All of 100 lattice seeds with errors are corrected.

<table>
<thead>
<tr>
<th>Component</th>
<th>(\Delta x) (mm)</th>
<th>(\Delta y) (mm)</th>
<th>(\Delta \theta_z) (mrad)</th>
<th>Field error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.01%</td>
</tr>
<tr>
<td>Arc Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
<tr>
<td>IR Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02%</td>
</tr>
<tr>
<td>Sextupole</td>
<td>0.10*</td>
<td>0.10*</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>
The beam lifetime including both beam-beam and lattice are optimized with large number of nonlinear knobs with algorithm of multi-objective differential evolution (MODE)

Further check of beam lifetime with bare lattice + beam beam (weak-strong) + beamstrahlung fulfill the requirements of the H/W/tt̅ modes. Beam lifetime study of Z mode is on the way.

<table>
<thead>
<tr>
<th></th>
<th>ttbar</th>
<th>Higgs</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam lifetime requirement for top-up injection [min]</td>
<td>18</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>Bhabha lifetime [min]</td>
<td>81</td>
<td>39</td>
<td>60</td>
</tr>
<tr>
<td>Required lattice + beambeam + beamstrahlung beam lifetime [min]</td>
<td>24</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>Simulated lattice + beambeam + beamstrahlung beam lifetime [min]</td>
<td>278</td>
<td>139</td>
<td>139</td>
</tr>
<tr>
<td>Crab sextupole strength [%]</td>
<td>49</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

Lattice of the CEPC collider ring design fulfill the requirements of the parameters list, geometry and key hardware.

Dynamic aperture w/ main errors for H/Z/t\(\bar{t}\) modes achieve the requirements from the top-up injection. DA study of W mode is on the way.

Correction with more errors and the IR tuning are undergoing.

Further check of beam lifetime with bare lattice + beam beam + beamstrahlung fulfill the requirements for the H/W/t\(\bar{t}\) modes. Beam lifetime study of Z mode is on the way.