Status of CEPC collider ring

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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
- 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
Status of the CDR scheme
Error Correction

More robust correction of error effects

<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>
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<td>Arc Quadrupole</td>
<td>0.10</td>
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<tr>
<td>IR Quadrupole</td>
<td>0.05</td>
<td>0.05</td>
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</tr>
<tr>
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</tr>
</tbody>
</table>

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IR=50μm

89% seeds survival

-$DA$ of bare lattice
---

IR=100μm

72% seeds survival

-$DA$ of each seed
---

B. Wang, Y. Y. Wei

89% seeds survival

-$DA$ of each seed
---

- mean value
- lower limits at 90%
---

- statistic errors

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Yiwei Wang

CEPC IARC 2021
Z-pole polarization

W.H. Xia, Z. Duan, Y. W. Wang, J. Gao

Design of spin rotators in the CEPC CDR lattice
- Implemented solenoid spin rotators (~100 m each) into the first short straight sections near IR
- **The spin rotators do rotate the spin direction as expected**
- But the limited space results in a very compact design with superconducting quadrupoles
- The local contribution to the chromaticity is very large, no DA after insertion
- A new modular design of spin rotator is ongoing to reduce the quadrupole strength and chromaticity.
Beam dump

1. One Dump for each of the electron and positron collider ring;
2. Use one kicker and one septum to get the beams into the dump line, so all bunches can be dumped in one turn;
3. **Horizontal and vertical dilution kickers** are used to change the position of different bunches at the dump, in order to reduce the beam damage to the dump.

① The Bunch distribution on the dump surface is first assumed to be 25cm x 25cm; Each bunch 2D-Gaussian: \( \sigma_x \sim 3\ mm, \sigma_y \sim 0.3\ mm \)
② Dilution kicker strength vibrate in 1e5 Hz.
MDI integration and alignment

Alignment scenario:
• Pre-align the SC magnets using **vibrating wire system** to “certain location” to compensate the effect of loads.
• Align the SC magnets in two cryostats using **optical system**.
• Measure misalignment using **SSW and adjust by corrector magnets** meet the alignment requirements.

SSW: single stretched wire

VWS is a candidate pre-alignment method, accuracy of magnet centers: ≤10 μm
Status of the high luminosity scheme
Key parameters of high luminosity scheme

Key parameters of CDR scheme for Higgs

- $L^* = 2.2\,\text{m}, \, \theta_c = 33\,\text{mrad}, \, \beta_{x^*} = 0.36\,\text{m}, \, \beta_{y^*} = 1.5\,\text{mm}, \, \text{Emittance} = 1.2\,\text{nm}$
  - Strength requirements of anti-solenoids $B_z \sim 7.2\,\text{T}$
  - Two-in-one type SC quadrupole coils (Peak field $3.8\,\text{T} & 136\,\text{T/m}$)

Key parameters of high luminosity scheme for Higgs

- $L^* = 1.9\,\text{m}, \, \theta_c = 33\,\text{mrad}, \, \beta_{x^*} = 0.33\,\text{m}, \, \beta_{y^*} = 1.0\,\text{mm}, \, \text{Emittance} = 0.64\,\text{nm}$
  - Strength requirements of anti-solenoids $B_z \sim 7.2\,\text{T}$ (6.8T with a shorter solenoid)
  - Two-in-one type SC quadrupole coils (Peak field $3.8\,\text{T} & 141\,\text{T/m}$) with room temperature vacuum chamber & Iron yoke

Reduction of the length from IP to 1st quadrupole without changing the front-end position of the FD cryo-module

- To make the lattice robust and provide good start point for DA
## Status of beam parameters

<table>
<thead>
<tr>
<th></th>
<th>ttbar</th>
<th>Higgs</th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IPs</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR power per beam [MW]</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Half crossing angle at IP [mrad]</td>
<td>16.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending radius [km]</td>
<td></td>
<td>10.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>180</td>
<td>120</td>
<td>80</td>
<td>45.5</td>
</tr>
<tr>
<td>Energy loss per turn [GeV]</td>
<td>9.1</td>
<td>1.8</td>
<td>0.357</td>
<td>0.037</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>1.21</td>
<td>5.94</td>
<td>6.08</td>
<td>24.68</td>
</tr>
<tr>
<td>Bunch number</td>
<td>35</td>
<td>249</td>
<td>1297</td>
<td>11951</td>
</tr>
<tr>
<td>Bunch population [10^10]</td>
<td>20</td>
<td>14</td>
<td>13.5</td>
<td>14</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>3.3</td>
<td>16.7</td>
<td>84.1</td>
<td>803.5</td>
</tr>
<tr>
<td>Momentum compaction [10^-5]</td>
<td>0.71</td>
<td>0.71</td>
<td>1.43</td>
<td>1.43</td>
</tr>
<tr>
<td>Beta functions at IP (bx/by) [m/mm]</td>
<td>1.04/2.7</td>
<td>0.33/1</td>
<td>0.21/1</td>
<td>0.13/0.9</td>
</tr>
<tr>
<td>Emittance (ex/ey) [nm/pm]</td>
<td>1.4/4.7</td>
<td>0.64/1.3</td>
<td>0.87/1.7</td>
<td>0.27/1.4</td>
</tr>
<tr>
<td>Beam size at IP (sigx/sigy) [um/nm]</td>
<td>39/113</td>
<td>15/36</td>
<td>13/42</td>
<td>6/35</td>
</tr>
<tr>
<td>Bunch length (SR/total) [mm]</td>
<td>2.2/2.9</td>
<td>2.3/3.9</td>
<td>2.5/4.9</td>
<td>2.5/8.7</td>
</tr>
<tr>
<td>Energy spread (SR/total) [%]</td>
<td>0.15/0.20</td>
<td>0.10/0.17</td>
<td>0.07/0.14</td>
<td>0.04/0.13</td>
</tr>
<tr>
<td>Energy acceptance (DA/RF) [%]</td>
<td>2.3/2.6</td>
<td>1.6/2.2</td>
<td>1.2/2.5</td>
<td>1.3/1.7</td>
</tr>
<tr>
<td>Beam-beam parameters (ksix/ksiy)</td>
<td>0.071/0.1</td>
<td>0.015/0.11</td>
<td>0.012/0.113</td>
<td>0.004/0.127</td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>10</td>
<td>2.2</td>
<td>0.7</td>
<td>0.12</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>650</td>
<td>650</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>HOM power per cavity (5/2/1cell)[kw]</td>
<td>0.4/0.2/0.1</td>
<td>1/0.4/0.2</td>
<td>-1.8/0.9</td>
<td>-/-5.8</td>
</tr>
<tr>
<td>Longitudinal tune QS</td>
<td>0.078</td>
<td>0.049</td>
<td>0.062</td>
<td>0.035</td>
</tr>
<tr>
<td>Beam lifetime (bhabha/beamstrahlung)[min]</td>
<td>81/23</td>
<td>39/18</td>
<td>60/717</td>
<td>80/182202</td>
</tr>
<tr>
<td>Beam lifetime [min]</td>
<td>18</td>
<td>12.3</td>
<td>55</td>
<td>80</td>
</tr>
<tr>
<td>Hour glass Factor</td>
<td>0.89</td>
<td>0.9</td>
<td>0.9</td>
<td>0.97</td>
</tr>
<tr>
<td>Luminosity per IP[1e34/cm^2/s]</td>
<td>0.5</td>
<td>5.0</td>
<td>16</td>
<td>115</td>
</tr>
</tbody>
</table>
• ttbar:
  • even with strong SR damping, 3D flip-flop appear easily without CW and longitudinal impedance
  • Real lattice design should consider asymmetric energy distribution (ref: K. Oide)
• Higgs: Ne=14e10 is preferred considering beamstrahlung lifetime
• Z: **Stable tune area** with both beam-beam and impedance is significant smaller than the case with beam-beam only.
• More check should be done, including code itself (especially ttbar)
Design of high luminosity lattice

- Shorter cell length to squeeze the emittance from CDR 1.2nm to 0.64nm
- Maximization of bend filling factor to minimize the synchrotron radiation
- **Optimization of the quadrupole radiation effect** (QD0 2m to 2.5m)
- Better correction of energy dependent aberration
- Reduction of dynamic aperture requirement from injection
- **Reduction of the length from IP to 1st quadrupole** without changing the front-end position of the FD cryo-module (2.2m to 1.9m)
Optimization of the ARC aberration

- 2nd order chromaticity is a main aberration for the optimization of momentum acceptance with 2-repeated sextupole scheme.
  - In previous versions, 2nd 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 4-repeated sextupoles
  - much less 2nd order chromaticity for the horizontal plane
  - not too sensitive to the errors

<table>
<thead>
<tr>
<th>Scheme with 2 repeated sextupoles</th>
<th>Proposed by K. Oide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q''=313, 410</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme with 4 repeated sextupoles</th>
<th>Proposed by Yiwei Wang</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q''=8, 139</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme with 8 repeated sextupoles</th>
<th>Proposed by Tianjian Bian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q''=9, 145</td>
<td></td>
</tr>
</tbody>
</table>
Dynamic aperture optimization

- With better correction of energy dependent aberration and shorter $L^*$ (without changing the front-end position of the final doublet cryo-module)
- Further optimization with algorithm of multi objective differential evolution (by J. Wu, Y. Zhang, Y. W. Wang)
- Dynamic aperture w/o error at Higgs energy fulfills the requirements.

Achieved (w/o error): $16\sigma_x \times 32\sigma_y \times 1.9\%$

Goal (w/ error): $8\sigma_x \times 15\sigma_y \times 1.6\%$
Interaction region for all modes

- For the interaction region, the IP beta functions are refitted with the different combination of final doulets and the matching quadruples.

![Diagram showing interaction region parameters](image)

By Y. Zhu, S. Bai, C. Yu

<table>
<thead>
<tr>
<th>Mode</th>
<th>QD</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>Q1a</td>
<td>Q1b+Q2</td>
</tr>
<tr>
<td>W/H</td>
<td>Q1a+Q1b</td>
<td>Q2</td>
</tr>
<tr>
<td>ttbar</td>
<td>Q1a+Q1b+Q1c</td>
<td>add quads</td>
</tr>
</tbody>
</table>

Higgs: \( L^* = 1.9 \text{m}, L_{Q1A} = 1.22 \text{m}, L_{Q1B} = 1.22 \text{m}, L_{Q2} = 1.5 \text{m}, d = 0.3 \text{m}, G_{Q1A} = 142 \text{T/m}, G_{Q1B} = 96 \text{T/m}, G_{Q2} = 56 \text{T/m} \)
ARC region for all modes

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

Microwave instability

$$I_{th} = \sqrt{2} \frac{E}{p e_0} \frac{\epsilon}{l} \frac{R_{Z}}{\epsilon_{eff}}$$

Transverse mode coupling instability

$$I_{th}^{*} = \frac{2Q_s}{e} \frac{E}{e} \frac{\epsilon_0}{\epsilon_{y,j}}$$

- Phase advance reduced from $90^\circ$ to $60^\circ$ and 29% additional sextupoles for W and Z modes

Na Wang, CEPC Day, March 2020

Yuan Zhang

H/tt mode 90°/ 90°

W/Z mode 60°/ 60°
Magnets comparison

<table>
<thead>
<tr>
<th>SC magnet in IR</th>
<th>Higgs (CDR)</th>
<th>Higgs (high lumi.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC QD0 and QF1</td>
<td>L*=2.2m, d=0.6m, QD0: 2.0m, 136T/m QF1: 1.48m, 111T/m</td>
<td>L*=1.9m, d=0.3m, QD0: 2.5m, 142T/m, 96T/m QF1=1.5m, 56T/m</td>
</tr>
<tr>
<td>SC anti-solenoids</td>
<td>maximum 7.2T</td>
<td>maximum 7.2T</td>
</tr>
<tr>
<td>SC sextupoles</td>
<td>VSIRD: 0.6m, 1308 T/m^2 HSIRD: 0.8m, 1506 T/m^2 VSIRU: 0.6m, 1250 T/m^2 HSIRU: 0.6m, 1600 T/m^2</td>
<td>VSIRD: 0.6m, 1209 T/m^2 HSIRD: 0.8m, 1679 T/m^2 VSIRU: 0.6m, 1548 T/m^2 HSIRU: 0.6m, 1130 T/m^2 (safety factor 20% for strength )</td>
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Main magnets in ARC

<table>
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<tr>
<td><strong>Dipoles (dual aperture)</strong></td>
<td>Quantity, length and field</td>
<td>Quantity, length and field</td>
</tr>
<tr>
<td></td>
<td>2320, 28.686 m, 373 Gs</td>
<td>2944, 21.7 m, 390 Gs (Quant +27%, total length -4%)</td>
</tr>
<tr>
<td><strong>Quadpoles (dual aperture)</strong></td>
<td>2320, 2 m, 8.4 T/m</td>
<td>2944, 3 m, 10.6 T/m (Quant +27%, total length +90%)</td>
</tr>
<tr>
<td><strong>Sextupoles (single aperture)</strong></td>
<td>SF: 896, 0.7 m, 506 T/m^2 SD: 896, 0.7 m*2, 506 T/m^2</td>
<td>SF: 1024, 0.7 m, 1100 T/m^2 SD: 1024, 0.7 m*2, 1129 T/m^2 (Quant +14%, total length +14%)</td>
</tr>
</tbody>
</table>
RF staging for compatible modes

- 1st priority of the Higgs running and flexible switching
- Low cost at early stage
- Get high luminosity for all modes

Stage 1 (H/W run)
- Layout and parameters are same with CDR except longer central part
- Medium or low luminosity at Z

Stage 2 (HL-Z upgrade)
- Move Higgs cavities to center and add high current Z cavities.
- By-pass low current H cavities.

Stage 3 (ttbar upgrade):
- Add ttbar cavities (low current, high gradient, high Q)
- Nb3Sn@4.2 K or others to significant reducing the cost of cryo-system and AC power.
Alternative separation scheme at RF region

- With kicker instead of electro-static separator to reduce the impedance contribution (proposed by Jinhui Chen)
- Study on the field stability is undergoing.

<table>
<thead>
<tr>
<th></th>
<th>Kicker</th>
<th>Septum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated strength BL [T*m]</td>
<td>0.1624</td>
<td>1.4</td>
</tr>
<tr>
<td>Strength B [Guass]</td>
<td>203</td>
<td>1000</td>
</tr>
<tr>
<td>Effective length Leff [m]</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Half width of good field region Hgf/Vgf [mm]</td>
<td>10.1/3.8 @ 5E-4</td>
<td>18.9/3.8 @ 5E-4</td>
</tr>
<tr>
<td>Half width of beam stay clear Hbsc/Vbsc [mm]</td>
<td>9.6/3.6</td>
<td>9.2/3.6</td>
</tr>
<tr>
<td>Septum width width [mm]</td>
<td>-</td>
<td>5</td>
</tr>
</tbody>
</table>

Field for up to 182.5GeV. Septum is weak to suppress emittance growth.

Kicker: 18σx+3mm+d1/2, 18σy+3mm
Septum: 18σx+3mm+d2e/2, 18σy+3mm
18σx+3mm, 18σy+3mm
R&D Progress of CEPC vacuum system

- **RF shielding bellows**: Contact force is uniformly from different fingers and meets the target of 125±25g. Two prototypes of RF shielding bellows have been fabricated.

- **NEG coating**: 2m long vacuum pipe have been coated to explore the coating parameter at geometrical shape of 56×75. 6m long vacuum chambers will be coated by moving the solenoid by a horizontal coating equipment.

- **Vacuum chamber**: The prototypes of copper & aluminum vacuum chambers with a length of 6 m have been fabricated and tested, which meet the engineering requirements.
Modification on chamber shape

Beam physics:
- Solution on quadrupole wakes and betatron tune shift
- Electron cloud density increased
  - can be controlled by NEG coating
- Serious instability caused by resistive wall impedance
  - strictly limit NEG coating thickness < 200nm

Technique on vacuum, magnets and power supply:
- Easier manufacture of vacuum chamber
- Lower power consumption of magnets

Y. D. Liu, Na Wang

from elliptical to round

Elliptical chamber: SEY<1.3
Round chamber: SEY<1.2

Graph showing the comparison between elliptical and round chambers.
Optimization of the dual-aperture quadrupole

- Add a shim at the center
  - The b1 and b3 component can reduce a lot.
  - The harmonics varies a little at different energy.
  - No large variation introduced by the trim coil.

<table>
<thead>
<tr>
<th>n</th>
<th>Bn/B2-L</th>
<th>Bn/B2-R</th>
<th>Bn/B2-L</th>
<th>Bn/B2-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1557.30</td>
<td>-1557.27</td>
<td>-13.51</td>
<td>13.53</td>
</tr>
<tr>
<td>2</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>3</td>
<td>126.14</td>
<td>-126.18</td>
<td>-1.11</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>0.52</td>
<td>0.52</td>
<td>0.51</td>
<td>0.53</td>
</tr>
<tr>
<td>5</td>
<td>1.70</td>
<td>-1.71</td>
<td>-0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>6</td>
<td>-0.04</td>
<td>-0.03</td>
<td>-0.04</td>
<td>-0.03</td>
</tr>
</tbody>
</table>
Optimization the final quadrupoles

- Different design options of CEPC Q1a have been studied and compared.
- With relaxed dipole field requirement (< 30 gauss) and use FeCoV yoke, the magnet weight can be significantly reduced (55% of origin).
- Using one layer coil, magnet weight can be further reduced. (42% of origin)

✓ Recommendation:
Baseline design: 2 layers coil, FeCoV yoke;
Alternative design: 1 layer coil, FeCoV yoke.

Y. S. Zhu

BH curve of DT4 and FeCoV
Summary

• The collider ring design of CDR scheme is more solid and the R&D based on the CDR scheme is undergoing.
• The high luminosity scheme of CEPC collider ring with $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ & 30MW has been designed by mainly squeezing the $\beta y^*$ and emittance.
  • New aberration correction scheme in ARC region
  • Dynamic aperture w/o error at Higgs energy fulfills the requirements.
  • Phase advance reduced from 90° to 60° for W/Z mode to suppress impedance instability and increase stable tune area
• New RF staging scheme
• Alternative separation scheme at RF region to reduce the impedance contribution
• Lower injection emittance from booster
• The vacuum shape from elliptical to round solve the quadrupole wakes effects
• For dual-aperture quadrupole, $b_1$ and $b_3$ component can reduce a lot with shim at the center
• QD0 weight can be reduced to 42% of origin by relaxed dipole field requirement, FeCoV yoke and 1 layer coil
• More work to be done for high luminosity scheme
Backup
Long dual-aperture dipole design

• As the magnetic length is up to 28.7m, a 5.7m pure dipole model will be built to check the field quality, mechanical strength and deformation.
  • Solid iron with DT4;
  • Two turns of aluminum busbars with cooling hole;
  • Anodizing treated insulation coil;
  • Silvered contact face to reduce contact resistance.
Challenge and Response: Resistive wall impedance instability

**Resistive wall impedance**

Round pipe of Copper (3mm) with NEG coating (200nm)

High luminosity $Z$ operation: 
- Bunch lengthening 90%;
- Energy spread increasing 4%

Coupled bunch instability
- Instability growth time 1.7ms, more efficient feedback for its suppression

Strictly control on the coating thickness for impedance source to restrain the instability!
MDI vacuum layout

- All the accelerator components are within the detective angle of $\text{acos}0.99$. 

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