Imperfection and correction for CEPC

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THE IAS PROGRAM ON HIGH ENERGY PHYSICS (HEP 2021)
Content

Errors definition and requirements

The correction scheme

The correction results

Summary and to do list
The error correction is based on CEPC CDR lattice.

Small emittance ration (0.2%) and small beta functions.

Dynamics aperture (DA) requirements: $8\sigma_x \times 15\sigma_y$ & 0.0135 (on-axis injection).
Errors definition and challenges

**IR=50μm**

<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>0.1</td>
<td>0.01%</td>
</tr>
<tr>
<td>Arc Quadrupole</td>
<td>0.10</td>
<td>0.10</td>
<td>0.1</td>
<td>0.02%</td>
</tr>
<tr>
<td><strong>IR Quadrupole</strong></td>
<td><strong>0.05</strong></td>
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<td><strong>0.05</strong></td>
<td></td>
</tr>
<tr>
<td>Sextupole</td>
<td>0.10</td>
<td>0.10</td>
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<td></td>
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**IR=100μm**

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- The lattice with small beta functions is very sensitive to FF misalignments.
- Small vertical dispersion and the coupling correction.
- 1000 lattice seeds are generated for further correction.
The correction scheme

- **Software**: SAD and AT

- COD correction with *sextupoles off*

- **Turn on the sextupoles** and perform COD correction again.

- Dispersion correction (DFS)

- Beta beating correction (LOCO)

- Coupling and vertical dispersion correction (Local coupling parameter correction)
COD correction

- BPMs placed at quadrupoles (~1500, 4 per betatron wave) Horizontal correctors placed beside focusing quadrupoles (~1500)
- Vertical correctors placed beside defocusing quadrupoles (~1500)
- Orbit correction is applied using orbit response matrix and SVD method.

\[ \text{RMS}_{\text{COD}} < 0.05 \text{ mm} \]

IR=50µm  981 seeds converged  
IR=100µm  955 seeds converged
Dispersion correction

Dispersion free steering principle (DFS): \( \theta_c \)

\[
\mathbf{d} = \begin{pmatrix}
(1 - \alpha) \mathbf{u} \\
\alpha \mathbf{D}_u
\end{pmatrix} \quad \mathbf{M} = \begin{pmatrix}
(1 - \alpha) A \\
\alpha B
\end{pmatrix} \quad \mathbf{d} + \mathbf{M} \hat{\mathbf{\theta}} = 0
\]

\( \mathbf{u} \): Orbit vector

\( \mathbf{D}_u \): Dispersion vector

\( \hat{\mathbf{\theta}} \): Corrector strengths vector

\( \alpha \): Weight factor

\( A \): Orbit response matrix

\( B \): Dispersion response matrix

Result of one seed

Before DISP correction

After DISP correction
Dispersion correction

IR=50mm  943 seeds converged

IR=100mm  736 seeds converged

$\Delta D_{x,\text{rms}}$ decreased from 29mm to 4.3mm
Factor 7 improvement

$\Delta D_{x,\text{rms}}$ decreased from 31mm to 2.2mm
Factor 14 improvement

$\Delta D_{y,\text{rms}}$ decreased from 102mm to 2.3mm
Factor 44 improvement

$\Delta D_{y,\text{rms}}$ decreased from 42.7mm to 5.9mm
Factor 7 improvement
Beta-beating correction

- Correct the beta functions with sextupoles on.
- Based on AT LOCO: model based correction
  - Establish lattice model $M_{\text{mod}}$, multi-parameter fit to the orbit response matrix $M_{\text{meas}}$ to obtain calibrated model:
  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
  - Fit the dispersion at the same time.
- Application to correct beta-beating, dispersion and coupled response matrix.

\[
\chi^2 = \sum_{i,j} \frac{(M_{\text{mod},ij} - M_{\text{meas},ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2
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Result of one seed
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\]

Result of all seed
Errors definition and challenges

IR=50\(\mu\)m  891 seeds converged  
IR=100\(\mu\)m  724 seeds converged

\(\Delta \beta / \beta_{x,rms}\) decreased from 26.4\% to 2.8\%  
Factor 9 improvement

\(\Delta \beta / \beta_{x,rms}\) decreased from 37.6\% to 7.0\%  
Factor 5 improvement

\(\Delta \beta / \beta_{x,rms}\) decreased from 11.7\% to 5.1\%  
Factor 2 improvement

\(\Delta \beta / \beta_{x,rms}\) decreased from 37.7\% to 11.2\%  
Factor 3 improvement
## Correction results

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<th>Δx (mm)</th>
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<th>Δθz (mrad)</th>
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<tr>
<td>Arc quadrupole</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>IR Quadrupole</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>FF Quadrupole</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
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Coupling correction

- Neglecting beam-beam effects
  \[ \varepsilon_y = \varepsilon_{y0} + \kappa \varepsilon_x + \gamma E^2 (D_{yrms})^2 \]

- Local coupling parameter matching was developed for BEPCII.

- Both coupling and vertical dispersion are controlled.

- Using the trim coils of the sextupoles (~1000), 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, \( \bar{c}_{b,12} = M_c \vec{k}_s \)

  \( M_c \) : \( \bar{c}_{b,12} \) response matrix \( \vec{k}_s \) : skew-quadrupole vector
Results of emittance tuning

IR=50μm
891 seeds converged

IR=100μm
724 seeds converged

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)%
The blue lines are the DA of each seed, the yellow lines and green bands are the mean value and its corresponding statistics errors, the black line is the DA of bare lattice, and the red lines show the lower limits at 90% C.L.. For the on-axis injection, $8\sigma_x \times 15\sigma_y & 0.0135$ is required.
The optics correction is very challenging for the relaxed tolerance of the imperfections.

The lattices with IR=50mm and IR=100mm case are corrected, the passing rates are increased to 89.1% and 72.4%, respectively.

Optimize the DA plots which include the lower limit DA and the DA from bare lattice.
To do list

➢ Include more types of imperfections.
➢ Optimize the correction strategy to achieve finer tuning of optics.
➢ Study off-momentum correction.
➢ The development of the error correction algorithm for high luminosity lattice.
Thank you for your attention

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