Polarization Study for CEPC

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Acknowledgements:
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Outline

• Motivation
• Analytical Analysis of CEPC polarization
• Simulation Tool Development
• Conclusion
Motivation

• Energy calibration with polarized beam @ LEP was a major achievement from both accelerator and particle physics point of view.

• CEPC pre-CDR focused on accelerator design for 120GeV, with an appendix considering Super-Z option (U. Wienands & M. Sullivan).

• More detailed study of operation for Z & W are supposed to be contained in CEPC CDR, where beam polarization is one important aspect.
CEPC schemes regarding energy calibration

- **Single ring (pretzel orbit)**
  - Similar to LEP
  - Energy calibration of one beam
  - Energy calibration only after physics

- **Partial double ring\([1]\)+crab waist**
  - Similar to FCC-ee
  - Energy calibration of both beams possible
  - Beam energy monitoring throughout each fill with non-colliding bunches

\[1\] M. Koratzinos, Proc. IPAC 2015. He named this idea as the “bowtie” scheme.
### CEPC self-polarization parameters (54km)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Single Ring Z</th>
<th>Partial Double Ring Z</th>
<th>Partial Double Ring W</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy (GeV)</td>
<td>45.5</td>
<td>45.5</td>
<td>80</td>
</tr>
<tr>
<td>radius of curvature (km)</td>
<td>6.1</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>circumference (km)</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>momentum compaction factor</td>
<td>3.4e-5</td>
<td>3.5e-5</td>
<td>2.4e-5</td>
</tr>
<tr>
<td>energy spread (MeV) $\sigma_\varepsilon$</td>
<td>22.75</td>
<td>22.75</td>
<td>72.0</td>
</tr>
<tr>
<td>synchrotron tune $Q_z$</td>
<td>0.097</td>
<td>0.039</td>
<td>0.057</td>
</tr>
<tr>
<td>polarization build-up time (hour)</td>
<td>44.9</td>
<td>44.9</td>
<td>2.67</td>
</tr>
<tr>
<td>spin tune spread $\sigma_v$ = $\alpha \gamma \sigma_\varepsilon$</td>
<td>0.052</td>
<td>0.052</td>
<td>0.16</td>
</tr>
<tr>
<td>modulation index $\sigma$ = $\sigma_v$ / $Q_z$</td>
<td>0.530</td>
<td>1.34</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Wangdou 20160325 & Wangdou 20160329

It was experimentally shown in LEP increased energy spread leads to reduced equilibrium polarization. According to A. Blondel, 52MeV is tentatively regarded as the maximum energy spread allowing useful polarization for beam calibration. **Need detailed simulation to justify.**
**CEPC self-polarization parameters (88km)**

<table>
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<th>Parameters</th>
<th>Partial Double Ring Z</th>
<th>Partial Double Ring W</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy (GeV)</td>
<td>45.5</td>
<td>80</td>
</tr>
<tr>
<td>radius of curvature (km)</td>
<td>9.</td>
<td>9.</td>
</tr>
<tr>
<td>circumference (km)</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>momentum compaction factor</td>
<td>1.9e-5</td>
<td>1.9e-5</td>
</tr>
<tr>
<td>energy spread (MeV) $\sigma_\varepsilon$</td>
<td>18.2</td>
<td>56.</td>
</tr>
<tr>
<td>synchrotron tune $Q_z$</td>
<td>0.027</td>
<td>0.052</td>
</tr>
<tr>
<td>polarization build-up time (hour)</td>
<td>159</td>
<td>9.5</td>
</tr>
<tr>
<td>spin tune spread $\sigma_v=\alpha \gamma \sigma_\varepsilon$</td>
<td>0.041</td>
<td>0.127</td>
</tr>
<tr>
<td>modulation index $\sigma=\sigma_v/Q_z$</td>
<td>1.51</td>
<td>2.42</td>
</tr>
</tbody>
</table>

It was experimentally shown in LEP increased energy spread leads to reduced equilibrium polarization. According to A. Blondel, 52MeV is tentatively regarded as the maximum energy spread allowing useful polarization for beam calibration. **Need detailed simulation to justify.**
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Polarization wigglers

• 5~10% polarization is needed for energy calibration. ~ 1/10 polarization build-up time is needed. Polarization wigglers can further boost the process.

• LEP type polarization wiggler is assumed, $B_+ / B_- = 6.25$.
• ~ 40min to reach 10% polarization.
• In partial double ring scheme, a scheme similar to FCC-ee can be adopted. A small fraction of non-colliding bunches, after 45min, every 10min one bunch is depolarized to continuously monitor beam energy.

1 wigller costs 8% SR power; 2 wigglers cost 10% SR power; 12 wigglers cost 20% SR power.
Longitudinal Polarized e+ / e- colliding beams

- SLC vs. LEP
- Longitudinally polarized e+ / e- beams @45GeV, tentatively speaking, pol > 40% is needed.
- Self-polarization needs too long time. Injection of pol e+/e- beams is needed.
- A whole chain of polarized beam generation, transportation, acceleration and storage is needed.
Longitudinal polarization maintenance @ Z-pole

- $\pi/2$ spin rotation around vertical direction requires a 15mrad horizontal bending @ 45GeV. (I. Koop HF2014)
- CEPC partial double ring scheme is compatible with such a layout & spin rotator design.
- Solenoid section can be spin matched.
- Spin matching requires spin transparency btw two solenoid sections.

D. P. Barber, et. al. PA, 17 (1985) 243.

FIGURE 3a A rotation system with antisymmetric dipole arrangement.

For CEPC 120GeV beam:
- Max. deflection per separator is 66$\mu$rad.
- Using Septum Dipole after separator to acquire 15 mrad


Decoupling FODO Optics: $T_x = -T_y$

Spin transparency:
- $T_x = -T_y \left\{ \begin{array}{ll} -\cos(\phi) & -2r \sin(\phi) \\ (2r)^2 \cos(\phi) & -\cos(\phi) \end{array} \right\}$
- $r = pc/eB$

Two $\phi^o$ solenoids
- $\phi = 90$ for Siberia snake, 45 for spin rotator
Simulation of equilibrium beam polarization

The DK formula of the equilibrium beam polarization:

$$
\begin{align*}
P_{dk} &= -\frac{8}{5\sqrt{3}} \int \frac{1}{|\rho|^3} \hat{b} \cdot \left( \hat{n} - \frac{\partial \hat{n}}{\partial \delta} \right) \langle s \rangle \\
&= \frac{1}{|\rho|^3} \int \left( 1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2 + \frac{11}{18} \left( \frac{\partial \hat{n}}{\partial \delta} \right)^2 \right) \langle s \rangle
\end{align*}
$$

(1)

Various algorithms have been developed for evaluation of $\hat{n}$ and $\frac{\partial \hat{n}}{\partial \delta}$.

- SLIM, ASPIRRIN, ...: linearized orbital and spin motion
- SODOM: linearized orbital and nonlinear spin motion (nonperturbative)
- SMILE: linearized orbital and nonlinear spin motion
- SpinLie: nonlinear orbital and spin motion
The Monte-Carlo approach\textsuperscript{[1]}

It is a good approximation

\[ P_{\text{eq}} = \frac{92.4\%}{1 + \frac{\tau_p}{\tau_d}}. \]  

(2)

The depolarization rate \( \tau_d \) can be simulated in a Monte-Carlo manner, \( \tau_p \) is easy to compute with knowledge of \( \hat{n} \).

- Implementation of \textit{synchrotron radiation} in a tracking code.
- Launch a beam of particles on the closed orbit, spin initialized parallel to the \( \hat{n} \)-axis.
- Track the beam for several damping times, and compute the beam polarization as an ensemble average of the particle spins.
- Fit \( \tau_d \) using the turn-by-turn polarization, following

\[ P(t) = P_0 \exp(-t/\tau_d). \]  

(3)

Polarization Simulation with PTC

• Polymorphic Tracking Code (PTC) \(^{[1]}\) is capable of orbital & spin tracking, as well as normal form analysis of one turn map.

• Lattice imperfection & correction can be implemented with MADX or BMAD and exported to PTC format. Fortran scripts are developed calling PTC as a library.

• Equilibrium polarization calculation including linear spin resonances:
  • First order normal form to obtain \( \hat{n} \) & \( \frac{d\hat{n}}{d\delta} \), then apply DK formula.\(^{[2]}\)
  • Equilibrium polarization calculation including linear & nonlinear spin resonances.
  • Monte-Carlo simulation of depolarization rate, similar to SITROS & SLICKTRACK.
  • This is essential for higher beam energy as in CEPC and FCC-ee.

Benchmark with first order spin resonance only

One version of VEPP-2000 lattice, solenoid around IPs are not spin matched and lead to reduced polarization near resonances.

ASPIRRIN does not take into account of synchrotron motion.

![Graph](image_url)
Benchmark against SODOM

A model ring (2112m) of FODO cells with several vertical bend. \( Q_x/Q_y/Q_z = 0.265/0.380/0.0623 \).

It took around 1 minute to track a particle for 3000 turns (5 damping time) on Hopper cluster @NERSC.

Figure 3: Comparison of the computed equilibrium polarizations for Model 1. "SODOM" is taken from the Yokoya’s paper [16] with his permission. "Monte-Carlo" is the Monte-Carlo simulation result with 50 particles, the statistical error is calculated with 20 such simulations. The agreement is good.
## Comparison of Monte-Carlo simulation code

<table>
<thead>
<tr>
<th>Code\features</th>
<th>orbit map</th>
<th>Photon emission</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITROS</td>
<td>2\textsuperscript{nd} order matrix</td>
<td>“Big photon” localized at several points</td>
<td>much slower compared to the others.</td>
</tr>
<tr>
<td>SLICKTRACK</td>
<td>1\textsuperscript{st} order matrix</td>
<td>“Big photon” localized at several points</td>
<td></td>
</tr>
<tr>
<td>PTC</td>
<td>nonlinear symplectic integrator</td>
<td>at each integration step of each dipole.</td>
<td>much slower compared to the others.</td>
</tr>
</tbody>
</table>

- It is not clear now if the more precise treatment in PTC have large effects on the simulation results.
- The lumped treatment in SITROS & SLICKTRACK can also be implemented within PTC with some effort.
Conclusion

• For CEPC partial double ring scheme, continuous monitor of both beam energies is possible as in FCC-ee.

• At what larger ring size can CEPC achieve useful polarization at W needs more simulation justification.

• Simulation tool based on PTC has been developed and benchmarked.

• Simulation study of a model ring for CEPC is under way.
Backup
Monte-Carlo simulation based on PTC

- Symplectic integrator for orbit & spin motion
- Modeling of synchrotron radiation (Added)

- Deterministic effect is modeled by
  \[ \delta = \delta - \frac{1}{2} \langle n \rangle \langle u \rangle. \]

- Stochastic effect is modeled by
  \[ \delta = \delta - \sum_{i=1}^{n_{\text{phot}}} \frac{\xi u_c}{E_{\text{beam}}} + \frac{1}{2} \langle n \rangle \langle u \rangle. \]

Poisson distribution

GEANT 4 implementation
N+4 integration nodes cover an element

any number(N) of body integration nodes (here 6)

Courtesy of D. Abell

The symplectic integrator of a body integration node

orbital kick

drift

drift

spin kick

photon-emission energy kick

Synchrotron radiation photons emitted at each integration step. Normally only photon emission in dipoles are taken into account.