Preliminary Studies of Beam Polarization in CEPC

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Outline

- Background
- Questions & Answers about Beam Polarization
  (As a beginner)
1) What is Polarization?
2) Why Polarization?
3) How to...?
...
- My Work in the Future
- Summary
# Background

- Accelerators in the world with polarized beam[1].

<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
<th>Machine</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>BINP</td>
<td>Novosibirsk, Russia</td>
<td>VEPP-(2, 2M, 3, 4)</td>
<td>Colliding Electron - Positron Beams</td>
</tr>
<tr>
<td>BNL</td>
<td>Upton, NY, USA</td>
<td>AGS</td>
<td>Alternating Gradient Synchrotron</td>
</tr>
<tr>
<td>CERN</td>
<td>Geneva, Switzerland</td>
<td>LEP</td>
<td>Large Electron - Positron Project</td>
</tr>
<tr>
<td>DESY</td>
<td>Hamburg, Germany</td>
<td>HERA</td>
<td>Hadron - Elektron Ring Anlage</td>
</tr>
<tr>
<td>ELSA</td>
<td>Bonn, Germany</td>
<td>ELSA</td>
<td>Electron Stretcher Accelerator</td>
</tr>
<tr>
<td>KEK</td>
<td>Tsukuba, Japan</td>
<td>KEK-B</td>
<td>KEK B-Factory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KEK-PS</td>
<td>KEK Proton Synchrotron</td>
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<td>MIT-Bates</td>
<td>Middleton, MA, USA</td>
<td>SHR</td>
<td>South Hall Ring</td>
</tr>
<tr>
<td>Orsay</td>
<td>Gif-sur-Yvette, France</td>
<td>ACO</td>
<td>Anneau de Collisions d’ Orsay</td>
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<tr>
<td>SLAC</td>
<td>Palo Alto, CA, USA</td>
<td>SLC</td>
<td>Stanford Linear Collider</td>
</tr>
<tr>
<td>JLab</td>
<td>Newport News, VA, USA</td>
<td>CEBAF</td>
<td>Continuous Electron Beam Accelerator Facility</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

eRHIC, FCC-ee, JLEIC, ILC, Super-B, Super-TC, CEPC
Nov 14, 2018, The CEPC Study Group officially released the “CDR”.

<table>
<thead>
<tr>
<th>Mode</th>
<th>H(e+e⁻→ZH)</th>
<th>Z(e+e⁻→Z)</th>
<th>W(e+e⁻→W⁺W⁻)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy (GeV)</td>
<td>240</td>
<td>91</td>
<td>160</td>
</tr>
<tr>
<td>Luminosity (cm⁻²s⁻¹)</td>
<td>3 x10³⁴</td>
<td>32 x10³⁴</td>
<td>10 x10³⁴</td>
</tr>
</tbody>
</table>

CDR: Prof. Sergei A. Nikitin

Appendix 8: “Opportunities for Polarization in the CEPC”

TDR in the future:
Scenario of obtaining and usage of polarization.

I got this opportunity: Research on key issues of beam polarization at CEPC.
What is Polarization?

All of the particle species accelerated in modern particle accelerators have spin. **Spin** is an intrinsic form of angular momentum. This immediately suggests the possibility of utilizing the particle spins as an additional experimental tool.

- **Spin & Polarization**

  A spin \( (S) \)—a property of an individual particle.
  Polarization \( (P) \)—a property of the entire beam.
  i.e. The polarization vector is the statistical average of an ensemble of spin vectors. \( P = \langle s \rangle \).

- **Analogy between Polarization & Emittances[2]**

<table>
<thead>
<tr>
<th>Beam property</th>
<th>Damping</th>
<th>Diffusion</th>
<th>motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance</td>
<td>Radiation damping</td>
<td>Quantum excitation</td>
<td>Orbital motion</td>
</tr>
<tr>
<td>Polarization</td>
<td>Radiation polarization</td>
<td>Spin diffusion</td>
<td>Spin motion</td>
</tr>
</tbody>
</table>

Why polarization?

- **Transverse polarization**
  Transversely polarized beams for energy calibration with resonant depolarization technique in precise experiment on Z-pole mass measurement.

  The level of polarization:
  About 10% is sufficient

- **Longitudinal polarization**
  Case[3]: (In the late 1980s)
  
<table>
<thead>
<tr>
<th></th>
<th>SLC(L-polarized)</th>
<th>LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$3 \times 10^{30}$</td>
<td>$1 \times 10^{32}$ (each of the four experiments)</td>
</tr>
<tr>
<td>$Z^0$ decays</td>
<td>~500 k</td>
<td>~5 million(each of the four experiments)</td>
</tr>
</tbody>
</table>

  The level of polarization:
  At least 40%~50%

Both can improve precision measurements!! Necessary!
• **Spin motion**
According to Thomas-BMT equation [4]

$$\frac{\text{d}s}{\text{d}t} = \Omega \times s.$$  
$$\Omega = -\frac{e}{mc} \left[ \left(a + \frac{1}{\gamma} \right) B_\perp + \left(\frac{a + 1}{\gamma} + 1\right) \beta \times E \right]$$

Where $a = \frac{1}{2}(g - 2)$ : the magnetic moment anomaly, i.e., the anomalous part of the particle g-factor

In a perfect planar storage ring, where $B = Be_3$,

$$\Omega = -\frac{e}{mc} \left(a + \frac{1}{\gamma}\right) B = (a\gamma + 1) \omega_{\text{rev}}$$

$\omega_{\text{rev}}$ : the orbital revolution frequency.

ONLY the $e_3$ -component of polarization is preserved.

• **Spin tune**
The ratio of the spin precession frequency to the orbital revolution frequency.

In the “accelerator frame”, the spin precession is measured relative to the orbit, hence

$$\nu_{\text{spin}} = (\Omega - \omega_{\text{rev}})/\omega_{\text{rev}} = a\gamma$$

It is the simplest BUT most important equation in spin dynamics.
How to obtain polarization?

- Polarized Particle Source

1) Polarized electron source (R&D)

This polarized electron gun will enable the Linac to produce a high-intensity and low-emittance beam with high polarization.

Design parameters of CEPC polarized electron source [5].

2) Polarized positron source (R&D)

![Diagram of positron source]

### DC Gun

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gun type</strong></td>
<td>Photocathode DC gun</td>
</tr>
<tr>
<td><strong>Cathode</strong></td>
<td>Super-lattice GaAs photocathode</td>
</tr>
<tr>
<td><strong>High Voltage of Anode</strong></td>
<td>200~350kV</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>&gt;80%</td>
</tr>
<tr>
<td><strong>Electron per bunch</strong></td>
<td>2x10^{10}</td>
</tr>
<tr>
<td><strong>Quantum efficiency</strong></td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>50Hz</td>
</tr>
<tr>
<td><strong>Drive laser</strong></td>
<td>790nm (±20nm), 10μJ@1ns</td>
</tr>
</tbody>
</table>

[5] Xiaoping Li, “Polarized electron source in CEPC” CEPC Workshop Asia/Shanghai, December 26, 2018
Radiative self-polarization

According to Sokolov-Ternov effect[6], relativistic electrons in a storage ring emit synchrotron radiation. A very small fraction of the radiated photons cause spin flip.

In a perfect planar storage ring, for a beam initially unpolarized, the time dependence for build-up to equilibrium is ($\hat{n}$ is the direction of equilibrium beam polarization)

$$P(t) = P_0(1 - e^{-\frac{t}{\tau_p}})$$

$$\hat{n} = -\hat{e}_3$$

spin tune = $a\gamma$

$$P_0 = 92.38\%$$

The time constant $\tau_p^{-1} = \frac{5\sqrt{3}}{8} c \epsilon_0 r_p \frac{\gamma^5}{\rho^3}$, CEPC @Z-pole(w/o dep.),

Straight lines

$$\frac{1}{\rho^3} \int \frac{1}{|\rho(\theta)|^3} \frac{d\theta}{2\pi} = \frac{1}{2\pi R} \int \frac{1}{|\rho(s)|^3} ds$$, isomagnetic fields

$$R = 15.9 \times 10^3 m$$, (the average machine radius)

$$\rho = 10.9 \times 10^3 m$$, (bending radius)

$$\tau_p \approx 2.74 \times 10^{-2} \frac{\rho^2[m]R[m]}{E^5[GeV]} \approx 262.53 h$$

That is a long time. We need to speed up it.

How to speed up polarization?

- **Wiggler magnets @CEPC Z-pole[7]**

  1) Polarization time with $N_w$ wigglers

  $$\tau_p^w = \tau_p \left[ 1 + N_w \frac{B_+^2 L_+ + 2 |B^-|^3 L_-}{2\pi R \langle B_0 \rangle B_0^2} \right]^{-1}$$

  2) Fraction of radiation energy loss enhancement

  $$u = N_w \frac{B_+^2 L_+ + 2 |B^-|^3 L_-}{2\pi R \langle B_0 \rangle B_0}$$

  3) Factor of beam energy spread enhancement

  $$\frac{\Delta E_w}{\Delta E} = \left[ \frac{\tau_p^w}{\tau_p} \cdot \frac{1}{1 + u} \right]^{1/2}$$

<table>
<thead>
<tr>
<th>$N_w$</th>
<th>$B_+$</th>
<th>$L_+$</th>
<th>$B_-$</th>
<th>$L_-$</th>
<th>$\frac{\tau_p}{\tau_p^w}$</th>
<th>$u$</th>
<th>$\frac{\Delta E_w}{\Delta E}$</th>
<th>$\frac{P_w}{P_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.6T</td>
<td>1m</td>
<td>0.15T</td>
<td>2m</td>
<td>13.4</td>
<td>0.34</td>
<td>3.2</td>
<td>0.99</td>
</tr>
</tbody>
</table>

4) Equilibrium beam polarization with $N_w$ wigglers

$$P_0^W = \frac{e^{8 \int ds/|\rho^3(s)|}}{|e| 5\sqrt{3} \int ds/|\rho^3(s)|} = \frac{1 + N_w \frac{B_+^2 L_+ + 2 |B^-|^3 L_-}{2\pi R \langle B_0 \rangle B_0^2}}{1 + N_w \frac{B_+^2 L_+ + 2 |B^-|^3 L_-}{2\pi R \langle B_0 \rangle B_0^2}}$$

5)

$$P(t) = P_0^w (1 - e^{-\frac{t}{\tau_p^w}})$$

$$\tau_p^w = 19.6 \, h, \, t = 2.3 \, h, \, P_0^w = 0.913, \, P(t) = 10\%$$

10% polarization is enough for energy calibration.

How to use polarization?

- **Resonant depolarization technique**
  Resonant depolarization is the most accurate method of calibrating the beam energy in storage rings with vertical polarized beams.

According to Froissart–Stora formula[8]

\[ \frac{P_1}{P_i} = 2 e^{-\pi \varepsilon^2/(2|\alpha|)} - 1. \]

This formula shows the exact analytical solution for the depolarization of a spin polarized beam caused by the crossing of a single resonance driving term where \( \varepsilon \) is the resonance strength, and \( \alpha \) is the crossing speed.

**Types of resonances** (@CEPC booster 10\textasciitilde45GeV/440.65MeV)

**Imperfection resonances:**

\[ a\gamma = v_{spin} = k, \]

**Intrinsic resonances:**

\[ a\gamma = v_{spin} = k \pm v_y, \]

\[ a\gamma = v_{spin} = k \pm v_x \]

(Snake resonances ...)

**About 80 imperfection spin resonances and 320 intrinsic resonances on way from 10 to 45GeV.**

Resonant depolarization technique

The basic idea is as follows:

\[ \nu_{\text{spin}} = a \gamma \]

Since the values of \( a \) are known to great accuracy\(^9\), by measuring the spin tune, one can deduce the value of \( \gamma \) to a high precision. From a knowledge of the electron mass, one can then calibrate the beam energy to high accuracy.

Specific steps:
A radio-frequency magnetic field is applied in the horizontal plane to kick the spins. The frequency for the kicks to act coherently on the spins is one of the two possibilities

\[ f_{\text{rf}}^+ = (a \gamma - k) f_c \]
\[ f_{\text{rf}}^- = (k - a \gamma) f_c \]

Where \( k \) is an integer. \( f_c \) is the orbital revolution frequency.
The frequency of the kicker \( f_{\text{rf}} \) is swept across the resonant value, when the kicker frequency is close to the resonant frequency, depolarization occurs.

Resonant depolarization = Imperfection resonances
= External spin resonance + a\( \gamma \)
How to measure polarization?

Møller polarimeter
The scattering cross-section is spin-dependent, hence the particle loss rate depends on the beam polarization. The particle loss rate is linear in \( P^2 \) \[10\]

\[
\dot{N} = -\frac{N^2 c}{\sqrt{2} V y^2 \sigma_x \sigma_y} (a + b P^2)
\]

Here \( N \) is the total number of particles in the beam, \( V \) the volume of the beam and \( a \) and \( b \) are suitably defined functions. \( \sigma_y \) is the vertical rms divergence. the radial rms divergence is \( \sigma_x \).

VEPP-2, ACO, VEPP-2M, VEPP-4, VEPP-4M ...

Compton polarimeter:
Lasers polarimeter:
SPEAR, VEPP-4, LEP ...

FCCee, CEPC

A beam of circularly polarized laser photons is shot at the electron (or positron) beam, and the backscattered photons are detected.

Figure: Schematic of the LEP polarimeter
• **Siberian snakes**

A Siberian Snake is theoretically defined as a device which rotates a particle spin through $180^\circ$ around an axis in the horizontal plane, while leaving the orbital motion unaffected. It can overcome resonances.

Why are such devices so named?
Firstly, the basic idea was proposed by Derbenev and Kondratenko who were then at the Institute of Nuclear Physics at Novosibirsk in Siberia.
Secondly, the orbit excursions twist like a snake in this device.

• **Spin rotators**

Spin rotators are used to rotate the polarization direction from the vertical to the horizontal plane, and back again. Most particle physics experiments with polarized beams in colliding beam accelerators require longitudinally polarized beams.

Schematic layout of BNL complex for polarized proton operations.[11]

Schematic design of a proposed solenoid spin rotator for $e^+e^-$ colliding beams at VEPP-4.[12]
1) A source of polarized electron beam is required. Beam intensity may be lower.

2) Polarimeters are required.

3) Siberian Snakes are needed during beam acceleration.

4) Spin rotators are needed to provide longitudinal polarization at IP.

(My work in the future)
Questions to be answered

To overcome/avoid depolarization during acceleration:
1) How many Siberia Snakes?
2) Which type of Snakes?
3) Where to insert Snakes?
4) How to overcome higher-order spin resonances?
5) How to minimize orbit excursion in the Snakes?
6) ...

To speed up the process of radiate self-pol:
1) How many wigglers?
2) What are the parameters of wigglers?
3) Where to insert wigglers?
4) ...

Longitudinal Polarization at IPs:
1) Which type of Spin rotators?
2) Where to insert rotators?
3) ...
Summary

- Polarized electron/positron beams are needed at CEPC to do beam energy calibration and polarization-dependent physics experiments.

- I have learnt some basic theoretical knowledge about beam polarization. For example, Thomas-BMT equation, Sokolov-Ternov effect, Froissart-Stora formula and so on.

- I did some simple calculations with parameters of CEPC. It takes a lot of time to obtain polarization with radiative self-polarization. Special wiggler magnets can speed up this process.

- My work in the future:
  1. To insert wigglers into the collider ring to speed up radiative self-polarization progress for beam energy calibration.
  2. To overcome/avoid depolarization during acceleration at booster.
  3. To realize the collision of the longitudinally polarized beams at the IPs.

A lot of work need to be done. Work hard!
I am grateful to Prof. Jie Gao for giving me an opportunity.
I thank Prof. Nikitin for the work he has done to CEPC Beam Polarization;
I thank Dr. Duan for teaching me a lot.

Thank you for your attention!