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BEAM POLARIZATION STUDIES AT THE CEPC*

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Abstract

This paper reports the recent progress in the design studies of polarized beams for the Circular Electron Positron Collider (CEPC). The overall design concept is outlined, followed by a few highlights in the topics of polarized positron beam generation, spin resonance structure in circular accelerators, and spin rotators in the electron collider ring.

INTRODUCTION

The Circular Electron Positron Collider (CEPC) is a next-generation electron-positron circular collider [1, 2] that is designed to operate at center-of-mass energies of 91 GeV (Z-factory), 160 GeV (W-factory), and 240 GeV (Higgs-factory), with the potential to upgrade to 360 GeV (ttbar energy). The primary objective of CEPC is to enable ultra-precise measurements and explore new physics beyond the Standard Model. The resonant depolarization technique (RD) [3] is critical for obtaining highly accurate measurements of the masses of Z and W bosons, which necessitates transversely polarized e+ and e- beams with at least 5% to 10% beam polarization. On the other hand, longitudinally polarized colliding beams, which probe the spin dimension, can be highly advantageous for boosting certain channels, reducing background noise, and facilitating searches for new physics beyond the Standard Model. This requires longitudinal polarization of 50% or more at the Interaction Points (IPs), as well as a high luminosity. These applications require a thorough investigation of the generation and maintenance of polarized beams as well as the spin manipulation in the collider rings.

We propose to generate highly polarized electron and positron beams from the source, transport them throughout the injector chain and inject them into the collider rings. The CEPC injector chain, as outlined in the CEPC Conceptual Design Report, includes unpolarized electron and positron sources, a 10 GeV main linac, a full energy booster and associated transfer lines. Fig. 1 shows the envisaged modification of the CEPC accelerator complex to implement polarized beams. A polarized electron gun can be added to produce electron bunches with 80% or more polarization [4]. However, the development of polarized positron sources is still technically challenging [5] to meet the requirements of top-up injection for colliding bunches. Therefore, we tentatively assume electron beams are polarized while positron beams are unpolarized in the colliding beam experiments. Nevertheless, it is still possible to generate 20% or more beam polarization via the Sokolov-Ternov effect [6] for beam energy calibration in the positron damping ring, with the help of asymmetric wigglers [7]. Then, the polarized beams are transported through the injector chain whereby maintaining the beam polarization is essential. Previous studies for the SLC [8] and ILC [9] have shown small polarization loss in the linac and transfer lines. Spin-resonance crossings in the acceleration process in the booster could cause depolarization [10], but our studies [11, 12] have shown that the polarization loss can be small in the acceleration to 45.6 GeV and 80 GeV, due to the cancellation of strengths of spin resonances in the booster lattice with a high "effective" periodicity. These studies suggest it is possible to prepare beams with a high-level polarization and inject into the collider rings, which is essential for longitudinal polarized colliding beams, and could also benefit beam energy calibration.

For the collider ring, the radiative depolarization effects have been studied in depth [13], and solenoid-based spin rotators have been successfully included in the lattice at the Z-energies [14]. Simulations support that a high-level longitudinal polarization can be maintained for the colliding electron bunches in the top-up injection, without significantly sacrificing the luminosity. In addition, first attempts of resonant depolarization experiments are under way at BEPCII. A Compton polarimeter that measures the spatial distribution of scattered electrons is under design for the CEPC [15]. In the following sections, we'll present a few highlights in our studies, with more details reported elsewhere [16] and included in the CEPC Technical Design Report [17] to be released later this year.

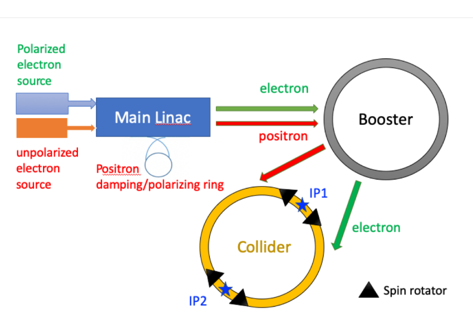

Figure 1: The envisaged modification of the CEPC accelerator complex to implement polarized beams.

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POSITRON DAMPING/POLARIZING RING

In the design outlined in the CEPC CDR [1], 3 nC unpolarized positron bunches are converted from the interaction of a 4 GeV, 10 nC unpolarized primary electron bunch with a target. After pre-acceleration, they are cooled in a positron damping ring to achieve the desired beam quality for later transportation. By default, 4 positron bunches will stay in the positron damping ring for 20 ms, to satisfy the needs to fill the colliding bunches. In this case, the extracted bunches are unpolarized. The possibility to polarize the positron bunches using the Sokolov-Ternov effect in the positron damping ring [18] or another dedicated ring of similar size [19] have been considered before. Very strong asymmetric wigglers are required to achieve a high-level polarization within 1 min or so for hundreds of bunches in the top-up mode, which is very challenging. However, it is more feasible to generate polarized positron bunches to satisfy the needs of RD measurements, which requires only a few bunches with a moderate-level of polarization. Assuming one or two additional positron bunches are stored in the positron damping ring for a longer time, say 10 min, to generate over 20% beam polarization, the self-polarization build-up time $\tau_{\rm DK}$ shall be reduced to about 30 min. This scheme supplies two types of positron bunches with distinct polarization and is compatible with the injection timing needs for the injector.

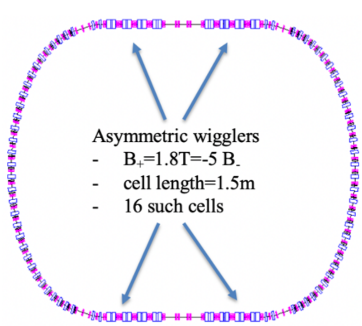

Figure 2: A schematic plot of a candidate lattice of the positron damping ring.

Fig. 2 shows the layout of a candidate lattice of the positron damping ring. In this design, the blue region represents the lattice sections that can accommodate asymmetric wigglers with a total length of up to 24 m. Beam parameters are summarized in Table 1. Simulations have shown promising results in both the dynamic aperture and equilibrium beam polarization. In addition, using stronger wigglers can help further increase the polarization of the extracted positron bunches and decrease the required preparation time. These aspects will be presented in more detail elsewhere.

SPIN RESONANCE STRUCTURE

In the examination of the depolarization effects in the acceleration process of the CEPC booster, we studied the structure of the imperfection and intrinsic resonances for a simplified lattice model of future 100 km-scale circular electron (positron) accelerators [11]. Such a lattice has a large

Table 1: Beam Parameters of the Positron Damping Ring

Parameter	Value
Beam energy, $a\gamma$	1.542 GeV, 3.5
Circumference	145 m
Wiggler magnetic field B_+/B_-	1.8 T/0.36 T
Wiggler total length	24 m
P_∞ w/ wigglers	90%
$\tau_{\rm BKS}$ w/o wigglers	52 min
$\tau_{\rm BKS}$ w/ wigglers	34 min
Store time	10 min
Polarization of extracted beam	22%

"effective" periodicity in terms of the lattice contributions to the strengths of imperfection ($\nu_0 = k$) and intrinsic resonances ($\nu_0 = k \pm \nu_y$), similar to that of the EIC booster [20]. Among imperfection and intrinsic resonances, super-strong resonances, where the contributions of all standard arc cells add up coherently, occur near $(mPM \pm \nu_B)/\eta_{\rm arc}, m \in \mathbb{Z}$, where P and M are the lattice periodicity and number of standard arc cells in each superperiod, $2\pi\nu_B$ is the total vertical betatron phase advance in all standard arc cells, $\eta_{\rm arc}$ is the proportion of the total bending angles of all standard arc cells over 2π, excluding the contribution from dispersion suppressors. The spacings between adjacent super-strong resonances are very large, while the first super-strong resonances near $\nu_B/\eta_{\rm arc}$ also correspond to very high beam energies. Meanwhile, the contributions from a large number of unit cells mostly cancel out for the resonances at much lower beam energies, away from the super-strong resonances.

Table 2: Parameters Relevant for Spin Resonance Structure

Parameter	Booster1 [11]	Booster2 [1]	Collider [1]
ν_y	353.28	261.2	365.22
P	8	8	8
M	140	97	145
$\eta_{\rm arc}$	140/142	97/99	145/147
ν_B	280	194	290
PM	1120	776	1160
$\nu_B/\eta_{\rm arc}$	284	198	294

In fact, this spin resonance structure is a general feature of future 100 km-scale electron rings. In Table 2 we list some key parameters for several lattices for the booster and collider rings of the CEPC. For instance, Fig. 3 shows the spectra of intrinsic and imperfection spin resonances for an imperfection lattice of Collider in Table 2, the spectra of the two booster lattices were shown elsewhere [11, 16] with similar features. Note that the radiative depolarization in the collider rings is quantified by the spin-orbit coupling function $\partial\hat{n}/\partial\delta$, whose amplitude becomes large near spin resonances, and shares the same feature of enhancement and cancellation for different beam energies ($a\gamma$). It is important to design the optics to avoid enhancement near key operation energies including 45 GeV, 80 GeV and 120 GeV.

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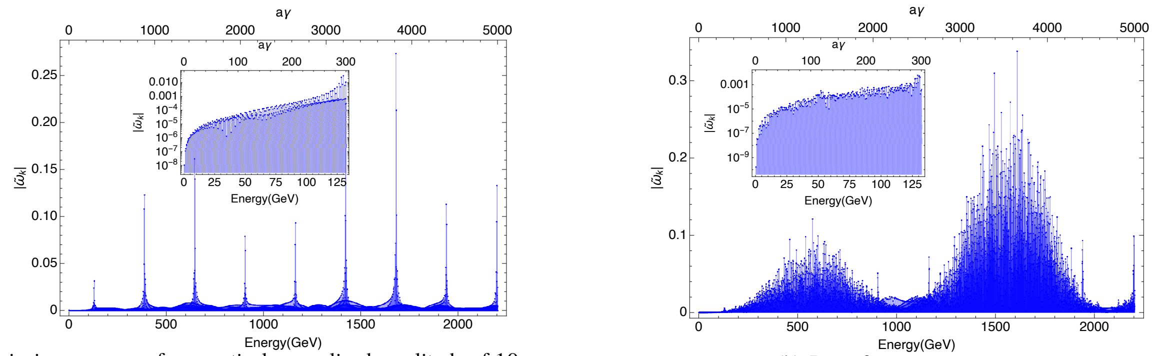

(a) Intrinsic resonances for a vertical normalized amplitude of 10πmm · mrad.

(b) Imperfection resonances.

Figure 3: Spectra of spin resonance for an imperfect lattice of Collider in Table 2.

SPIN ROTATORS IN THE COLLIDER

The detailed design of the spin rotators for the beam energy of 45.6 GeV is reported elsewhere [14]. Here, we'll summarize the main results, and focus on the case that the spin rotators are only included in the electron collider ring [16].

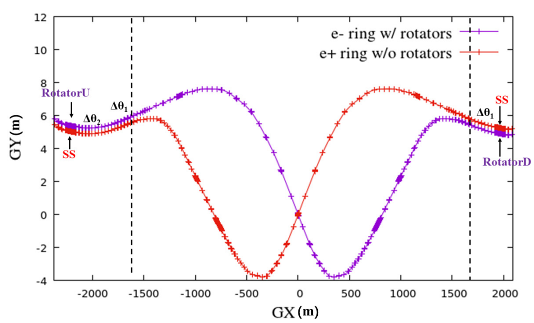

Figure 4: Geometry near one interaction region [14, 16], with solenoid rotators (RotatorU and RotatorD) for the e^- beam, and compensating straight sections (SS) for the e^+ beam.

Each spin rotator consists of a bending magnet section that rotates the spins from the longitudinal to the radial direction, requiring the total orbital bending angle to be an odd multiple k of 15.18 mrad, and a solenoid magnet section that rotate the spins from the radial to the vertical direction, requiring an integral strength of about 240 T·m (20 units of 1.5 m-long, 8 T superconducting solenoid magnets). The solenoid magnets are interleaved by quadrupoles to compensate for the transverse coupling [21]. The layout of a pair of spin rotators around one IP is illustrated in Fig. 4. The spin rotators are placed just out of the interaction region to make use of its S-shape geometry [22, 23]. The half crossing angle at the IP is 16.5 mrad, additional bending magnet sections ($\Delta\theta_1$ and $\Delta\theta_2$) are required in both spin rotators, next to the solenoid sections. In the counterpart region of the positron collider ring, the solenoid sections are replaced by straight sections (SS) with quadrupoles to match the optics. The circumference increases by about 2 km, the betatron tunes increase by 10 units, while other beam parameters almost remain unchanged. Simulations also indicate there is only a moderate shrink of dynamic aperture, which can be recovered via dedicated optimizations.

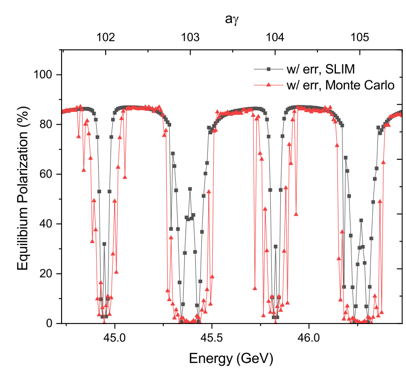

Figure 5: Simulated equilibrium polarization for the lattice in the presence of magnet errors in the solenoid rotators.

We also numerically evaluated the performance of the spin motion using the BMAD/PTC code [24, 25]. We introduced in the solenoid sections relative field errors for solenoids and quadrupoles with a root-mean-squared value of 0.05%, and relative roll errors for quadrupoles with a root-mean-squared value of 0.01%. Fig. 5 shows the simulated equilibrium beam polarization using the SLIM algorithm [26] in BMAD [24], and Monte-Carlo simulations implemented in PTC [27]. These simulations shows the robustness of the "anti-symmetric" spin rotator design against machine imperfections.

CONCLUSION

This paper summarizes the recent progress in the design studies of beam polarization at the CEPC. Generation of polarized beams from the source, acceleration in the booster and injection into the collider rings have been studied, promising a high-level of beam polarization. More technical aspects and potential extension to higher beam energies are being studied.

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