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CONCEPTS OF LONGITUDINALLY POLARIZED ELECTRON AND POSITRON COLLIDING BEAMS IN THE CIRCULAR ELECTRON POSITRON COLLIDER*

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Abstract

This paper reports some preliminary study into the implementation of longitudinally polarized e+/e- colliding beams in the Circular Electron Positron Collider, at a center of mass energy of 91 GeV as a Z factory and energies beyond.

INTRODUCTION

The Circular Electron Positron Collider (CEPC) [1] is designed to provide un-precedented high luminosity at center-of-mass energies of 91 GeV (Z-factory), 160 GeV (W-factory) and 240 GeV (Higgs-factory), and will be a powerful instrument not only for precision measurements on these important particles, but also in the search for new physics. The use of spin-polarized electron and positron beams, on one hand, could provide precision beam energy calibration via the resonant depolarization technique [2,3], one the other hand, could provide an extra probe into the precision tests of the standard model as well as the search for new physics via colliding beam experiments. The resonant depolarization technique only requires about 10% beam polarization, and could be provided with the Sokolov-Ternov effect [4], in particular, asymmetric wigglers [5] are required to boost the self-polarization build-up at Z-pole. In contrast, the polarized colliding beam experiments have a more demanding requirement, it would be very interesting if longitudinally polarized e+/e- beams could be achieved at each interaction point (IP) with a beam polarization beyond 50%. In addition, the figure of merit in experiments involving polarized colliding beams is a function of both beam polarizations as well as the luminosity, it is essential to maintain a decent luminosity together with high beam polarizations.

Top-up injection is in the baseline design of CEPC [1], to cope with the relative short beam lifetime and maintain a high average luminosity. In this scenario, the average beam polarization is a compromise between the equilibrium beam polarization P_{DK} in the storage ring and beam polarization in the injected bunches P_0.

$$P_{\mathrm{avg}} = P_{\mathrm{DK}}\frac{1}{1+\tau_{\mathrm{DK}}/\tau_{\mathrm{b}}} + P_0\frac{1}{1+\tau_{\mathrm{b}}/\tau_{\mathrm{DK}}} \quad (1)$$

where τ_b is the beam lifetime, τ_{DK} is the time constant of beam polarization approaching the equilibrium level, $\tau_{\mathrm{DK}}^{-1} = \tau_{\mathrm{BKS}}^{-1} + \tau_{\mathrm{dep}}^{-1}$, where τ_{BKS} is the time constant of the Sokolov-Ternov effect, and τ_{dep} is the time constant of the depolarization effect related to the stochastic nature of synchrotron radiation. In fact, the equilibrium beam polarization P_{DK} could be approximated by [6]

$$P_{\mathrm{DK}} \approx \frac{92.4\%}{1+\tau_{\mathrm{BKS}}/\tau_{\mathrm{dep}}} \quad (2)$$

According to the simulations for a FCC-ee "toy" ring (with similar parameters of CEPC) [7], an estimation of key parameters regarding the self polarization at CEPC can be summarized in Table 1. It is obvious that self polarization build up is too slow at Z-pole, utilization of asymmetric wigglers could help boost the polarization build-up at the expense of local synchrotron radiation power consumption and increase of rms energy spread, moreover, to maintain a decent average beam polarization, τ_{DK} should be made comparable to τ_b, which hints a heavy usage of asymmetric wigglers and a possible deliberate increase of τ_b which could lead to a substantial decrease in the luminosity, and is not favored. At higher energies, using the self polarization for colliding beams suffer from a much smaller equilibrium beam polarization, a combination of Siberian snakes and asymmetric wigglers was proposed to suppress the synchrotron sideband spin resonances while maintaining a reasonable self polarization [8, 9], however, in top-up operation, the average beam polarization is expected to be even lower if the injected beam is non-polarized. On the other hand, if the injected beams are highly polarized, and the collider ring is well spin matched, i.e., $\tau_{\mathrm{DK}} \gg \tau_b$, then a high average beam polarization is expected.

Table 1: Key Parameters of Self Polarization at CEPC

Beam energy (GeV)	**45.5**	**80**	**120**
τ_b(hour)	2	1.2	0.22
τ_{BKS}(hour)	256	15.2	2.0
P_{DK}	> 50%	< 50%	≈ 0
τ_{dep}(hour)	> 300	< 20	very short

In this paper, we studied the scheme of injection of polarized beams into the collider ring, the focus is polarized beam generation and maintenance in the injector chain, beam polarization study in the collider ring including the spin rotator design will be reported in a future publication.

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POLARIZED BEAM GENERATION

Great global efforts have been put into the R&D of high performance polarized electron and positron sources. Up to now, the polarized electron gun technology is quite matured, capable to supply a nC-level electron bunch with a beam polarization above 80% [10]. In contrast, the technology of polarized positron source is less matured, utilizing the ILC polarized positron source [11] requires an electron drive beam with a beam energy larger than 100 GeV, which would greatly complicate the design of CEPC injector, other polarized positron source schemes [12] suffer from insufficient yield for the application at CEPC.

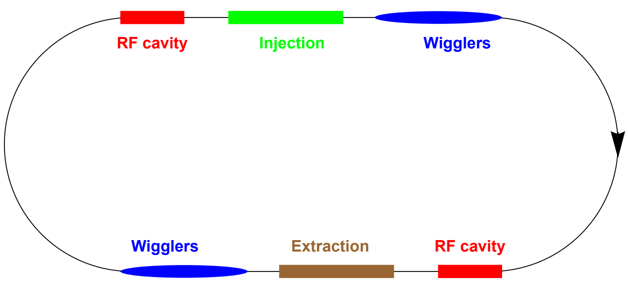

Figure 1: A schematic plot of the racetrack positron polarizing ring.

To this end, we propose to build a low energy positron polarizing ring to generate polarized positron beam via self polarization. To reduce the polarization build up time down to the order of half a minute, very strong asymmetric wigglers are required. In fact, in the parameter regime of concern, the central magnet of the asymmetric wigglers would dominate the synchrotron radiation effects in the storage ring. The polarization build-up time $\tau_{\mathrm{BKS}}^{-1} \propto E^2 B_+^3 L_+$, while the radiation energy per turn $U_0 \propto E^2 B_+^2 L_+$, where B_+ and L_+ are the field strength and total length of the central magnet. It is favored to choose a medium beam energy, and a central field strength as high as possible, to reach a short polarization build-up time while keeping a reasonably low synchrotron radiation power and RF voltage. As a field strength of 15 Tesla is considered as a practical limit for accelerator quality magnet design using the state of art Nb_3Sn conductor [13], based on which a preliminary parameter table of such a positron polarizing ring is shown in Table 2, a schematic plot is shown in Fig. 1.

Considering the top-up operation of the collider ring, the most demanding requirement is from Z-pole operation, the beam lifetime is about 2 hour, an average beam current of 461 mA and a total bunch number of 12000 requires frequent injections. If the positron beam stays in the polarizing ring for 20 s, i.e., the interval between adjacent injections is 20 s, an average beam current of 533 mA and a single bunch charge of 2.1 nC are required in the positron polarizing ring, these parameters appear feasible. However, initial injection from scratch would cost too long time if positron bunches stay in the polarizing ring for 20 s, it is more practial to initially inject non-polarized positron beam, and then

Table 2: Tentative Parameters of the Positron Polarizing Ring

Parameter	Value
beam energy(GeV)	2.5
circumference(m)	240
wiggler total length(m)	22
B_+/B_-(T)	15/1.5
U_0(MeV)	3.5
τ_{BKS}(s)	20
rms energy spread	~ 0.003
natural emittance(nm)	~ 25
damping time(ms)	~ 1
momentum compaction factor	0.001
RF voltage(MV)	4.8
bunch length(mm)	12.6
bunch number	200
bunch spacing(ns)	4
beam current(mA)	< 600
bunch charge(nC)	< 2.5
beam store time(s)	>20
beam polarization before extraction	>58%

inject polarized positron beam during top-up injection, this then leads to a gradual polarization build-up in the storage ring at a time constant of beam lifetime. For 80 GeV and 120 GeV operation, the requirement is less demanding, in fact, the positron bunches could be stored in the polarizing ring for over 40 s, so that a beam polarization of about 80% is achievable. Technology-wise, dedicated R&D of the ultra-high field asymmetric wigglers is actually in line with the ongoing efforts in developing high field dipole magnets for next-generation super proton-proton colliders [14–16]. Moreover, ultra-fast injection/extraction kickers with a full pulse width shorter than 8 ns are required to enable high efficiency transmission of the 200 bunches into and out of the polarizing ring. Detailed lattice design and beam dynamics study is under way and will be reported in a future publication.

POLARIZED BEAM ACCELERATION

When the polarized electron and positron beam get accelerated in the booster, a series of spin resonances are crossed, which could lead to substantial polarization loss. The following study focus on beam acceleration from 10 GeV to 45.5 GeV in the CEPC booster, and could be extended up to even higher beam energies. To evaluate the imperfection resonances, rms misalignment errors of 70 μm are introduced in quadrupoles and sextupoles of the CEPC booster lattice, the rms closed orbit is 37 μm horizontally and 28 μm vertically in one random lattice seed, the DEPOL code [17] is then used to calculate the strengths of imperfection resonances and intrinsic resonances (at a vertical normalized emittance of $10\pi \mathrm{mm} \cdot \mathrm{mrad}$), as shown in Fig. 2. Note that the normalized vertical emittance varies due to radiation damping and

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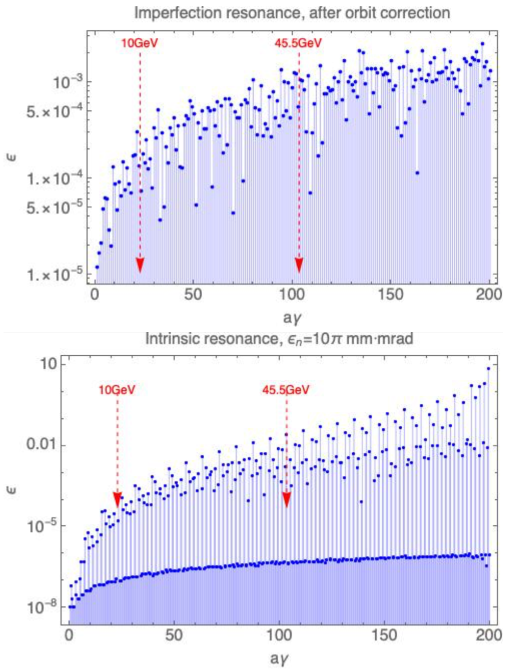

Figure 2: Resonance spectral of imperfection(upper) and intrinsic(lower) spin resonances of CEPC booster.

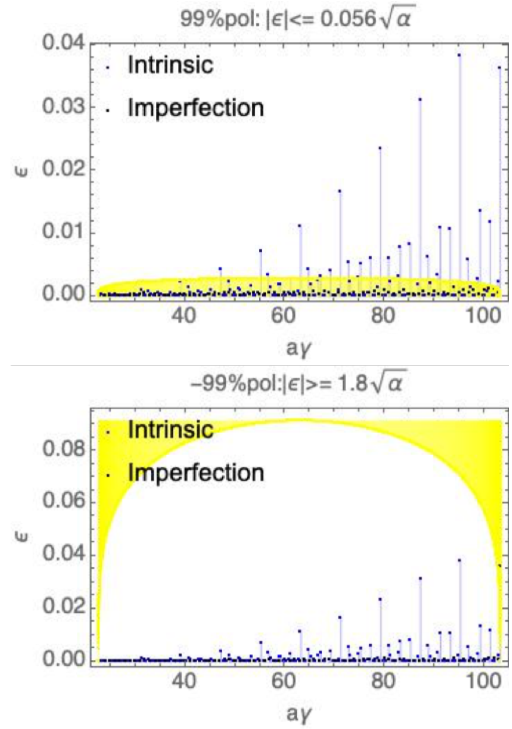

Figure 3: Spin resonance spectral of CEPC booster, in yellow region 99% initial polarization is maintained after resonance cross. The upper and lower plots show the fast crossing and adiabatic crossing scenarios, respectively.

quantum excitation in the acceleration process, assuming the equilibrium vertical beam emittance at 45.5 GeV is 1/10 of the natural emittance, and the energy ramping follows a half-cosine curve and it takes 2.6 s to accelerate from 10 GeV to 45.5 GeV, the normalized emittance decreases from about 100πmm · mrad down to about 20πmm · mrad, and the intrinsic resonance strengths scale with $\sqrt{\epsilon_{n,y}}$ accordingly.

According to the Froissart-Stora formula [18], there are two scenarios that no significant polarization loss during crossing a single isolated spin resonance, i.e., either fast ramping through a resonance, or adiabatically crossing a resonance with a full spin flip. As shown in Fig. 3, crossing of many resonances are beyond the safe region of the two scenarios, and actually no beam polarization is expected after the beam is accelerated to 45.5 GeV. Nevertheless, the fractional part of the vertical betatron tune is 0.21, and thus the adjacent imperfection and intrinsic resonances are well separated in the calculated energy range, implementation of one or two Siberian snakes [19] are expected to maintain the beam polarization through acceleration.

A proper design of Siberian snakes is under investigation. Utilizing transverse field snake, like the helical dipole design or interleaved horizontal and vertical bends design, suffer from large orbit excursion at injection energy, and large synchrotron radiation power consumption at extraction energy. One particular full snake design is composed of a series of identical helical dipole partial snakes, the total helical dipole length is 1 km for an orbit excursion of 4.2 cm at 10 GeV and U_0 of 20.7 MeV at 45.5 GeV. Utilizing solenoids, on the other hand, suffer from a large integral field required at the extraction energy, in particular, the required solenoid integral field ranges from 105 T·m at 10 GeV and 476 T·m at 45.5 GeV. To this end, compact design using superconducting solenoid seems challenging since the energy ramping is very fast. Implementation of a full Siberian snake into the booster lattice takes a lot of space and seems nontrivial. Nevertheless, it seems promising to keep the same solenoid field fixed during acceleration, so that it becomes partial snake for higher beam energies, as illustrated in Fig. 4. Detail study is under way to place the betatron tunes near the integer to avoid depolarization due to the intrinsic resonances.

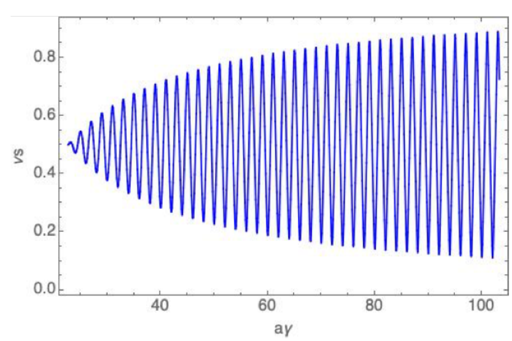

Figure 4: Evolution of the closed orbit spin tune in CEPC booster with a non-ramping solenoid snake.

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