High Energy Polarized e^+e^- Beams

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Recently, the wide discussion about Higgs-factory design again returns to problem of high energy polarized electrons and positrons. It's good known the radiative beam polarization at LEP-collider. It was obtained after spin resonance suppression at Z^0 pick, but didn't appear at energies above 70 GeV due to an enhancement of unavoidable depolarization effects. We examine in this paper various ideas for radiative polarization at TLEP/FCC-ee and formulate some estimates for the polarization buildup time and the asymptotic polarization. Using wigglers, a useful degree of polarization (for energy calibration), with a time constant of about 1 h, may be possible up to the threshold of W pair production. At higher energies such as the threshold of Higgs production, attaining a useful level of polarization may be difficult in a planar ring. With Siberian Snakes, wigglers and some imagination, polarization of reasonable magnitude, with a reasonable time constant (of not more than about 1 h), may be achievable at very high energies.

1. Introduction

There are four operating energies of principal interest, viz. the Z^0 pole (45 GeV), W-pair production threshold (80 GeV), Higgs production (technically $ee^- \rightarrow HZ$, 120 GeV) and t^+t^- pair production (175 GeV). All mention experiments require extremely high luminosity. Moreover, the first two experiments should be performed with high precision energy calibration. That's why, we does not consider a linear e^+e^- collider as a candidate to the Higgs-factory. High energy circular e^+e^- collider additionally to both for the luminosity and for longitudinal polarization is also able

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provide the precise beam energy calibration. We shall discuss both polarization topics below.

In our estimation we shall explore machine parameters from TLEP.¹ Later this machine has been renamed FCC-ee, but for contact with work by others we shall continue to use ‘TLEP’ occasionally.

2. Radiative Polarization

The first step is to calculate the Sokolov-Ternov polarization time for an isomagnetic ring of circumference $2\pi R$ and bend radius ρ without wigglers, depolarizing resonances or other complications:

$$\tau_P = 98.60 \frac{\rho^3}{B^3} \frac{R}{\rho}, \tag{1}$$

where time is in seconds, the lengths are in m and the energy is in GeV.

For the TLEP ring circumference and bend radius, the Sokolov-Ternov polarization time at the Z^0 pole is about 270 h. It’s approximately 40 times longer than for LEP.

The polarization time and a number of other important for our subject parameters are given in the Table 1 at the TLEP principal points. For comparison, the LEP parameters are shown at Z-pole and at 100 GeV.

It’s evident, that a speedup mechanism is required at 45 GeV. The only serious candidate to speed up the polarization time is to employ asymmetric wigglers. More less realistic estimation of this approach have been consider in² with asymmetric wigglers consisting of a triplet with bend radii in the ratios $-1 : 1/2 : -1$. If constrain the radiated power at 100 MW ($= 2 \times 50$ MW per beam), then polarization level $P_0 \simeq 60\%$ of P_{ST} can be obtained with rising time $\tau_p \approx 1$ h with freshly injected unpolarized electrons (or positrons). But, to get an average polarization in the operation mode ”top-up”, we should to take into account the high luminosity live time τ_l :

$$P_{avr} = \frac{P_0}{1 + \tau_p/\tau_l}. \tag{2}$$

Table 1. Parameter values at LEP and TLEP for various beam energies

	LEP		TLEP			
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Energy [GeV]	45.4	104	45.5	80	120	175
Energy spread, [%]	0.07	0.16	0.06	0.09	0.14	0.19
Synchrotron tune Q_s	0.065	0.83	0.65	0.21	0.096	0.1
Luminosity lifetime τ_l [min]	1250	310	213	52	21	15
Polarization time τ_p [min]	348	5.5	16238	966	127	19
Guide field [Gauss]	488	1119	136	243	364	531
Tune modulation index	1.11	4.56	0.095	0.78	3.98	7.56

It means, that the average polarization by high luminosity can be much less than P_0 and we need to inject polarized electrons.

All of this has long been known. Conclusion from that - TLEP should have full energy injection from electron synchrotron dedicated to accelerate polarized electron from injection (~ 20 GeV) up to the top energy. Of course, there are a number of problems, that shall be overcome on this way. First off all - spin resonances. The best way to avoid them is the application of Siberian snake, that keeps spin tune be $\nu = 1/2$ and makes it far away from all spin resonances.

In contrast to³ we advocate below the use of the solenoid-type snake design instead of the bending version proposed by Ya.S.Derbenev in 1995. The main reason is a need to minimize the vertical emittance excitation by quantum fluctuations of synchrotron radiation (SR) in the bending magnets of the snake. Another unpleasant features of the bending snake: unavoidable orbit excursion during beam acceleration and considerable SR power produced by its bends.

2.1. Siberian Snake

The snake has to be a solenoid with magnetic field proportional to the beam energy. By that, the snake has to be transparent to betatron oscillations. Such design has been considered in.⁵ According to that paper snake is divided in two identical solenoids with a number of regular quadrupoles in between Fig. 1. This is one of many schemes considered in⁴ for compensation of by solenoid induced coupling. The coupling is compensated providing that the 2x2 transportation matrices of the whole setup satisfy to the condition:

$$T_y = -T_x \quad (3)$$

Each half rotates spin around the longitudinal axis by the angle

$$\frac{\varphi}{2} = (1 + a) \frac{\int B dl}{B\rho} \quad (4)$$

Main advantage of such a scheme is a flexibility in tuning the optics of a spin rotator. For instance, one can switch off the solenoids completely and tune up the quads to provide the same beam transport map as it was before.

Fig. 1. Scheme of universal solenoidal snake.

The other requirement comes from the spin transparency condition. To cancel the contribution of the horizontal betatron oscillations to beam depolarization the matrix elements of such a partial spin rotator should be of the type shown in the Fig. 1. In case of the total spin rotation angle $\phi = 90^\circ$ both matrices $T_{x,y}$ became anti-diagonal, while in case of full snake $\phi = 180^\circ$ and matrices of such system should be adjusted to $\mp$ unity-matrix for the vertical and horizontal directions, respectively. However, such snake is not transparent for particles with the energy deviation. Rotation of spins by each solenoid is chromatic and this shall be accounted by calculation of the spin-orbit coupling vector $\mathbf{d}$ introduced by Ya.Derbenev and A.Kondratenko in 70-th for the complete description of the radiative kinetics of particles in storage rings.⁶ This vector value could be calculated either analytically or using the computer code ASPIRRIN.⁷ It comes into formula for the spin relaxation time in the following way:⁶

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} \lambda_e r_e c \gamma^5 \left\langle \frac{1 - \frac{2}{9}(\mathbf{n}_0 \cdot \mathbf{b})^2 + \frac{11}{18}\mathbf{d}^2}{|\rho|^3} \right\rangle \quad (5)$$

Here λ_e, r_e, c are the reduced Compton wavelength, classic radius of the electron and the light velocity, respectively. ρ is the curvature radius of the orbit and $\mathbf{n}_0$ is the unity vector along the equilibrium spin direction.

There are two possibilities to use snakes for polarization preservation during energy ramping in the booster storage ring of TLEP. The first one is a scheme with the odd number of snakes. And the second is based on use of two snakes installed at almost opposite points of a ring. We will discuss these two options in sequence.

2.2. Ring with odd number of snakes

When polarized electron beam is accelerated say from 20 GeV to 80 GeV it crosses more than 130 of integer spin resonances spaced by 440.65 MeV. A Siberian Snake solves this problem quite radically. Spin tune is equal 1/2 independently on the energy. But the snake generates the spin-orbit coupling in the arcs:

$$|\mathbf{d}| = \left| \frac{\pi}{2} \sin(\pi\nu_0) + i\nu_0(\pi - \tilde{\theta}) \right|. \quad (6)$$

The same spin tune 1/2 will be in a ring with equally spaced odd number of snakes the closed spin orbit looks like it is shown in the Fig. 2: everywhere in arcs spins are lying in the medium plane of an accelerator. Thus, all the spin resonances became eliminated! Still strong enough spin perturbation may destroy the regular spin motion making it non-adiabatic. It may happen, if any k -th harmonic amplitude of a perturbation exceeds or approaches to $|w_k| \sim 0.5$.

In a flat ring without snakes $\mathbf{n}$ is vertical and $\mathbf{d} \equiv 0$. In a ring with the odd number of snakes $\mathbf{n}$ is horizontal everywhere in arcs, as shown in the Fig.2.

Fig. 2. Schematic of spin rotation in a ring with 3 solenoid-type snakes.

But now, instead of (6), the averaged over the azimuth value of the spin-orbit coupling vector depends on the number of snakes N as follows:

$$\langle d^2 \rangle \simeq \frac{\pi^2}{3} \frac{\nu_0^2}{N^2} \quad (7)$$

It means: $|d| \sim \gamma$ and $\tau_p^{-1} \sim \gamma^7$. So, increasing the number of snakes one will reduce the depolarization rate quadratically with the number of snakes $\tau_p^{-1} \sim N^{-2}$. With 3 snakes in the isomagnetic ring with the bending radius $r=11$ km $\tau_p \simeq 320$ s at $E=45$ GeV and $\tau_p \simeq 6$ s at $E=80$ GeV - very strong energy dependence! In the Fig. 3 it is shown calculated by the code ASPIRRIN dependence of the factor (or equivalently $|F5|$) along the azimuth, counted there in meters.

Its linear behaviour is dictated by the chromaticity of the $\mathbf{n}_0$ direction in arcs, which is proportional to the factor ν_0/N , we discussed above.

Fig. 3. Azimuth dependence of the modulus of the spin-orbit coupling vector $|d(s)|$.

Let's estimate the polarization loss during acceleration in a synchrotron. Assuming that energy ramp proceeds linearly during a time T one can calculate:²

$$P_{rad}(T) = \exp\left(-\int \frac{dt}{\tau(t)}\right) = \exp\left(-\frac{T}{8\tau_T} \frac{1 - \left(\frac{E(0)}{E(T)}\right)^8}{1 - \frac{E(0)}{E(T)}}\right) \quad (8)$$

For $E(0) = 20$ GeV, $E(T) = 80$ GeV and taken $\tau_p = 6$ s, $T=10$ s, one gets $P_{rad}(T) = 0.76$ - not small! With $T=20$ s the result is also not very bad: $P_{rad}(T) = 0.57$ and may be considered as acceptable.

2.3. Ring with even number of snakes

At higher than 60 GeV beam energies the synchrotron satellites of integer and intrinsic resonances may overlap and make polarization life time very short. That is one of the plausible explanations of the LEP's observations.² The strength of the synchrotron satellites is proportional to a spin tune chromaticity. In a flat ring without snakes the spin tune chromaticity equals just to the tune ν_0 :

$$\gamma \frac{\partial \nu}{\partial \gamma} = \nu_0 = 180 \leftarrow E = 80 \text{ GeV} \quad (9)$$

We see that at 80 GeV the tune chromaticity becomes extremely large. But there is a trick which can help to solve a problem. We can make same polarity of the longitudinal field in two 90° spin rotators - one on the left and another on the right side from the IP. Then the whole device became a full Siberian Snake.

Now, let do the longitudinal polarization not in one but in 2 or 4 detectors that divide 360° ring-azimuth on unequal segments and spin changes the direction from a vertical to anti-vertical after passing of each snake. Let $f < 0.5$ is a fraction of the total circumference occupied by two short arcs, interleaved by two long arcs. Then the spin tune is equal to:

$$\nu = (1 - 2f)\nu_0 \quad (10)$$

With f chosen close to 0.5 it becomes arbitrarily small, but still not zero! Accordingly, the spin tune chromaticity becomes also much smaller than ν_0 , and this could make the polarization life time much longer.

Such asymmetric division of the circumference on 2 or 4 sectors by the even number of snakes in general looks very profitable also for the acceleration of polarized beams to super-high energies.² The only drawback is that spin tune is not constant during the energy ramp and may cover a wide dynamic range, say: $0.08 < \nu < 0.8$. As example we made evaluation of the radiative depolarization time for the TLEP booster ring equipped with two full snakes spaced by the fraction of the turn $f = 0.499$. Results of calculations by the code ASPIRRIN are shown on the Fig. 4.

One can see that even at $E = 175$ GeV the depolarization time in such a ring exceeds 100 s.

Fig. 4. Radiative depolarization time energy dependence for a ring with two Siberian Snakes.

3. Polarization Measurement and Beam Energy Calibration

Compton backscattering of the circularly polarized laser light on highly relativistic electron exhibits extremely large analysing power to the longitudinal component of an electron polarization.⁹

In the Fig. 5 is plotted the dependence of the Compton scattering analysing power versus the energy of the scattered photon. At the edge it reaches the huge value of 75%!

For polarization measurements we should rely of course on detection of such events. The counting rate of photons might be so high that many events overlap in time. One possibility is to measure the average over the full spectrum photon energy asymmetry, as it was done by the HERA team.¹⁰ But that asymmetry is

Fig. 5. Spectral density of the analysing power of the Compton scattering of the circularly polarized laser light photons with $\omega_0 = 2.33$ eV on $E=45.5$ GeV electrons

much lower, not exceeding 18%. Therefore we recommend to detect not photons but the scattered electrons, measuring their energy using magnetic spectrometry.

The longitudinal Compton polarimeter due to its very high sensitivity to longitudinal component of a spin can provide also turn by turn measurement of the coherent free spin precession during energy calibration. In this approach Compton counting rate will be modulated by spin tune (similar to μ -(g-2) measurement). This method is a good alternative to the famous resonant depolarization approach.

4. Conclusion

Use of Siberian Snakes for the acceleration of a polarized beam in a synchrotron is an obvious tool to solve such a difficult task.

Three snakes (odd number in general) will ensure preservation of the polarization in a booster synchrotron of TLEP complex up to 80 GeV. For polarized beam acceleration to 100-175 GeV it suits more the two snakes approach. With even number of snakes radiative depolarization is suppressed due to much lower spin-orbit coupling.

Spin tracking simulations should validate these statements and provide the solid basis for the choice of the number of snakes needed to solve all the discussed above tasks.

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