SPIN TRACKING SIMULATION OF A FUTURE INTERNATIONAL LINEAR COLLIDER[*]

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Abstract

The full physics potential of the International Linear Collider (ILC) is expected to be optimized by using polarized electron and positron beams [1]. To ensure that no significant polarization will be lost during the transport of the electron and positron beams from the source to the interaction region, spin tracking has to be included in all transport elements which can contribute to a potential loss of polarization. By this paper we investigate possible sources of depolarization such as the spin rotators, etc. for the current ILC baseline. The detailed spin tracking simulations and study the depolarization was performed by using BMAD computer code. The new results of our simulations for the ILC are presented.

INTRODUCTION

A substantial enhancement of the effective luminosity $L_{eff} = (1 - P_{e_+}P_{e_-})L$ is possible with polarized beams [2].

However, the exploitation of the increase by the factor $(1-P_{e_+}P_{e_-})$ is only possible in case of an efficient pairing of initial states $(+-)$, $(-+)$. It requires the same frequencies of the helicity reversal for the electron and the positron beam. The polarization of the electron beam can be flipped easily by reversing the polarity of the laser beam which hits the photocathode. A fast and random flipping between the beam polarization orientations reduces systematic uncertainties substantially. The orientation of the positron beam polarization could be arranged by using spin rotators. However, it is impossible to switch the high magnetic field in the spin rotator within very short time, e.g. from train to train as possible for the electron beam. However, there is no gain for the effective luminosity if the helicity of the positrons is reversed only from run to run (or even less often) the helicity of the electrons train-by-train. Further, in order to control systematic effects, a very high long-term stability is necessary. A possible solution of this problem would be to kick the positron beam to parallel spin rotation lines with opposite magnetic fields, similar as suggested in reference [3, 1].

POSITRON LINAC TO RING BEAMLINE

The longitudinal polarization of the positrons is generated at the source and has to be preserved prior to the DR. To preserve polarization in the DR it is required to change the direction of the spin from longitudinal into vertical, in order to be parallel or anti-parallel to the magnetic field. Building blocks of the Positron-Linac-To-Ring (PLTR) beamline are bending magnets and a solenoid. In the dipole field normal to the direction of particle motion the spin precesses around the direction of the magnetic field. This is used to rotate the spin from the longitudinal direction to the transverse horizontal direction. This rotation of the spin by 90 degrees requires a field integral of 2.3 Tm at 5 GeV. The rotation to the vertical direction is done using a solenoid. The spin precesses around the axis of the solenoid field which is parallel to the motion of the particles. At beam energies of 5 GeV the spin rotation from the horizontal to the vertical plane requires a solenoid field integral of 26.18 Tm (see eq. 3).

The spin precession angle, φ, in a bending arc (dipoles) is given by

$$\varphi = G\gamma\theta \tag{1}$$

where θ is the bending arc angle and $G = 0.001159652$ is the anomalous magnetic moment. The relativistic factor $\gamma = E/m_0c$, where E is the particle energy, m_0 is the electron rest mass and c is speed of light. To rotate the spin vectors in the horizontal plane by $n\cdot 90°$ from the longitudinal direction a total bending angle of $\theta = n\cdot 7.929°$ is required (n is an odd integer) for a 5 GeV beam.

The spin rotation angle caused by a solenoid is given:

$$\theta_{spin} \approx \frac{B_z\cdot L_{sol}}{B\rho} = 2\theta_{orbit} \tag{2}$$

where B_z is the longitudinal solenoid field, L_s is the length of solenoid, and $B\rho$ is the magnetic rigidity. To rotate the spin vector of 5 GeV polarized positrons by an angle $\varphi = 90°$, this solenoid magnetic field is required:

$$\int B_z dz = \frac{p\varphi}{e(1+G)} = 26.18\ \mathrm{T\ m} \tag{3}$$

PLTR line consists of two main parts. The first part contains an arc consisting of six FODO cells and 5 bending magnets (see Figure 1). A total bending angle of $\theta = 23.8°$ is chosen in the design. The RF structure is located after the arc. Altogether, the elements of the first part of PLTR beamline perform a spin rotation in the horizontal plane

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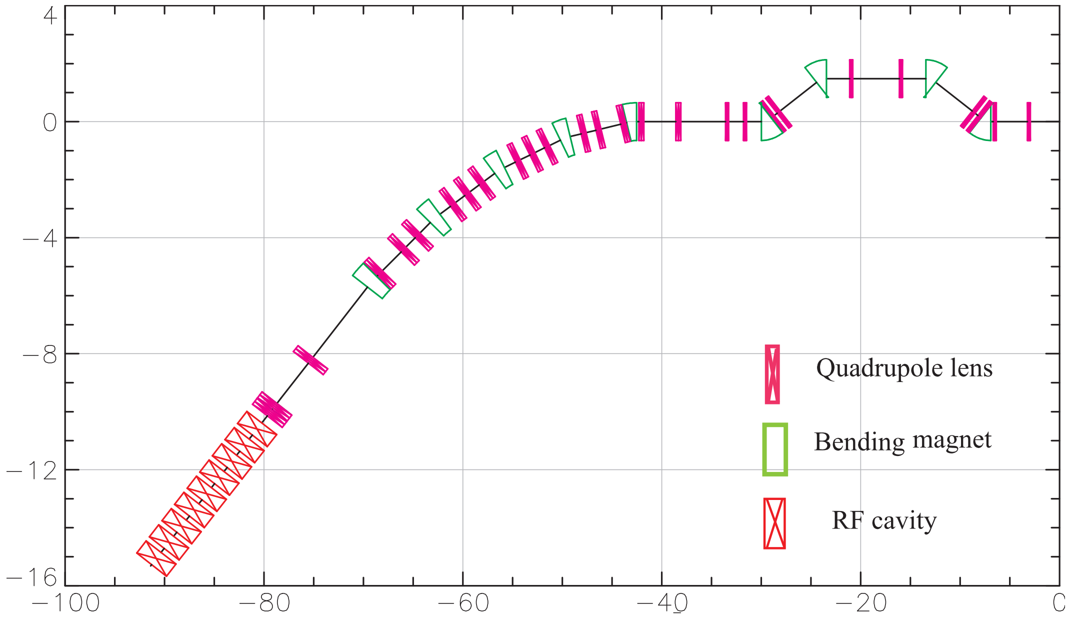

Figure 1: PLTR: floor plan.

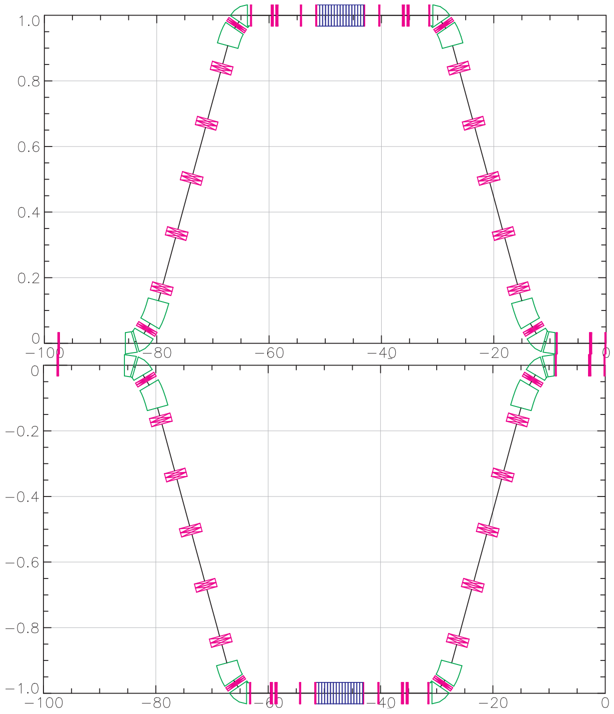

Figure 2: Spin flipper: floor plan.

and energy compression. The second part is located directly after the energy compressor (see Figure 2) and called fast helicity flipper that consists of two equal parallel beamlines with opposite magnetic fields. Each of this lines includes solenoid. This solenoidal magnetic field performs rotation of the spin from the horizontal to the vertical direction. A fast kicker magnet provides a rapid helicity switching between two parallel lines. More details about spin-flipper design can be found in [4].

SPIN TRACKING SIMULATIONS

The depolarization study of the PLTR beamline was done using the BMAD [5, 6] code, using the spinor-quaternion transfer map method. The spin motion is described by the T-BMT equation. In 2-component spinor notation it can be written as

$$\frac{d}{dt}\Psi = -\frac{i}{2}(\boldsymbol{\sigma}\cdot\boldsymbol{\Omega})\Psi \tag{4}$$

where $\boldsymbol{\sigma} = \boldsymbol{\sigma}^1, \boldsymbol{\sigma}^2, \boldsymbol{\sigma}^3$ are Pauli matrices and $\boldsymbol{\Omega}$ is the spin precession vector. The solution can be written as

$$\Psi = (a_0\mathbf{1}_2 - i\mathbf{a}\cdot\boldsymbol{\sigma})\Psi_i = \mathbf{A}\Psi_i \tag{5}$$

with the spinor $\Psi = (\psi_1, \psi_2)^T$ (ψ_1 and ψ_2 are complex numbers). The matrix $\mathbf{A}$ is called quaternion and describes the transfer map for each element. Tracking through any element is achieved via the application of these quaternions in sequence. This results in very fast tracking times.

Results

The beam energy spread yields a polarization loss, $\delta(\frac{\Delta P}{P}) = 1 - \cos(\delta\varphi)$ [7], where $\delta\varphi = \varphi(\delta\gamma/\gamma)$ is the deviation of the spin rotation angle from its nominal value φ due to energy deviation $\delta\gamma$. Hence, a large depolarization is observed for larger beam energy spread. The relative depolarization is $1 - \frac{\langle P_z\rangle}{P_0}$. The mean polarization, $\langle P_z\rangle$ is given by

$$\langle P_z\rangle = P_0 \exp\left(-\frac{1}{2}(G\gamma\alpha\sigma_E)^2\right) \tag{6}$$

where G is the anomalous momentum, α is the bending angle of the arc, and σ_E is the rms energy spread.

We assume that the energy distribution within the bunch is Gaussian

$$\frac{dN}{d(\delta\gamma)} = \frac{1}{\sqrt{2\pi}\sigma_E}\exp[-\frac{(\delta\gamma)^2}{2\sigma_E^2}] \quad (7)$$

with the rms value σ_E. The full width energy spread of the transformed bunch is $\Delta\gamma/\gamma$ and the corresponding rms energy spread is approximately $\sigma_E/\gamma \approx (1/4)\Delta\gamma/\gamma$. Taking into account equation 7, we fix the bending angle and estimate the impact of the bunch energy spread on beam polarization as shown in Figure 3. Here we can observe that an increase of the bunch energy spread leads to depolarization of the beam. It follows from equation 7 that polarization depends exponentially on the energy spread. The beam depolarization due to the energy spread is shown in Figure 4. In the worst case scenario the initial energy spread is $\Delta\gamma/\gamma = 3.5\%$, a bunch length of 34.6 mm and a normalized beam emittance of $\varepsilon_x + \varepsilon_y \leq 0.09$ m-rad the relative depolarization is relatively small and reaches at the end of the beamline 0.84%. At the same time it can also be seen from Figure 5 (polar angle θ and azimuthal angle ϕ of the spin) that the arc with bending magnets provides the spin rotation in the median plane and the solenoid performs the spin rotation into vertical direction so the beam has transverse polarization at the end of PLTR line (θ and ϕ are equal 90°).

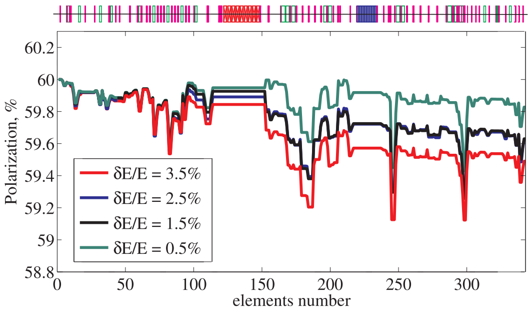

Figure 3: Impact of bunch energy spread on beam polarization.

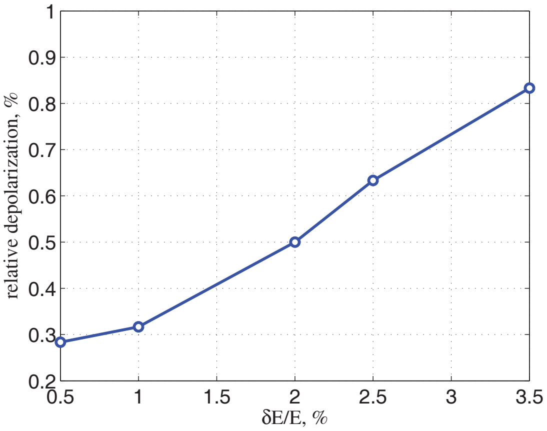

Figure 4: Relative depolarization due to energy spread.

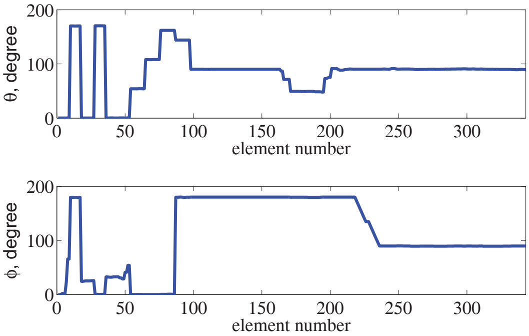

Figure 5: Average spin direction along the beamline. Polar angle θ and azimutal angle ϕ.

CONCLUSIONS

A positron spin tracking and depolarization study has been performed for the new ILC Positron Linac To Ring beamline. The PLTR bending angle of the arc is 23.8°. This arc contains 5 bending magnets and provides rotation of the spin in the horizontal plane. Fast kicker magnet provides rapidly helicity switching between two parallel lines then the solenoid which is a part of spin-flipper line rotates the spin into vertical direction. Numerical simulations carried out using the BMAD code show a relative depolarization of 0.84% in the worst case scenario, when the initial positron energy spread is 3.5%, a bunch length is 34.6 mm and a normalized beam emittance is $\varepsilon_x + \varepsilon_y \leq 0.09$ m-rad were taken.

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