SPIN TRACKING AT THE INTERNATIONAL LINEAR COLLIDER*

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Abstract

In the baseline design for the International Linear Collider an helical undulator-based positron source has been chosen that can provide positrons with a polarization of 30%. As an upgrade option motivated by physics reasons positron polarization can be increased up to 60%. In order to match the high precision requirements from physics and to optimize the physics outcome one has to control systematic uncertainties to a very high level. Therefore it is needed to run both beams polarized but provide also an unpolarized set-up for control reasons. In our study we present results on spin tracking for an unpolarized mode.

INTRODUCTION

A substantial enhancement of the effective luminosity $L_{\text{eff}} = (1 - P_{e_+}P_{e_-})L$ is possible with polarized beams [1, 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 $(+-)$, $(-+)$; this requires the same frequency of helicity reversal for the electron and the positron beam. An important task in experiments with polarized beams is to identify and reduce any systematic errors arising from the accelerator itself. The technique of "spin flipping" can be applied for this purpose. 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 controlled using spin rotators, specifically by inserting two parallel sections for spin rotation with opposite polarities, i.e. setting the spin parallel or antiparallel to the field in the damping ring main dipoles. This design gives the possibility of randomly switching between two helicities for the positrons [3, 4]. Resonant depolarisation within the damping rings offers an alternative method. To exclude systematic errors one could depolarize some of the bunches, and compare the data from polarized and unpolarized bunches under identical machine conditions [5]. Recent simulation results of the resonant depolarization technique applied for the ILC are presented in this paper.

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RESONANT DEPOLARIZATION

In an ideal, flat, circular storage ring without solenoids or spin rotators, the spin of each positron precesses around the vertical magnetic fields of the bending dipoles at the spin precession frequency f_s. The spin precession frequency is related to the orbital circulation frequency f_c by

$$f_s = f_c \nu_s, \tag{1}$$

where ν_s is the spin tune (i.e. the number of spin precessions during each turn around the ring). The spin tune is proportional to the beam energy via $\nu_s = G\gamma$, where G=0.00115965219 is the anomalous magnetic moment of the positron, and γ is the Lorentz factor.

A horizontal-field rf dipole can spin-flip a vertically polarized beam. A resonance occurs when the frequency of the rf magnetic field is synchronized with the spin tune and the circulation frequency according to:

$$f_r = f_c(n \pm \nu_s), \tag{2}$$

where n is an integer. Although the change in spin orientation on an individual pass through an rf dipole is small, when the rf dipole frequency is close to the resonant frequency, the kicks add up coherently, and the cumulative effect of the kicks is to tilt the spins strongly away from the vertical. If the frequency of the rf dipole is varied across the resonance at a rate that is neither too slow nor too fast, the adiabatic invariant[9, 10] which describes the equilibrium polarization state of the beam deteriorates. Resonant depolarization occurs when the final polarization is zero.

If there are only vertical magnetic fields, then the vertical beam polarization remains unchanged; however, whenever the spins on orbital trajectories observe periodic or quasi–periodic horizontal magnetic fields which are in resonance with the spin tune, depolarizing resonance occurs, which can destroy the polarization.

RF DIPOLE PARAMETERS

The resonance strength for one rf dipole is given by [6]:

$$\varepsilon = \frac{1 + G\gamma \int B_\perp \cdot dL}{4\pi B\rho} \tag{3}$$

where $B\rho = P/q$ is the beam rigidity, i.e. momentum per charge. By varying the RF dipole frequency from sufficiently far below to sufficiently far above the resonance frequency f_r, one can cross the depolarizing resonance in a way such that the final beam polarization, P_f, is related

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to the initial beam polarization, P_i by the Froissart-Stora formula [7]:

$$\frac{P_f}{P_i} = 2\exp\left(\frac{-\pi|\varepsilon|^2}{2\alpha}\right) - 1, \quad (4)$$

where α is the rate of resonance crossing (crossing speed), which is defined as follows. At the end of each orbital turn, particles pass through an rf dipole with transverse horizontal magnetic field, and the spin vector then precesses around the horizontal axis by an angle of $(1 + G\gamma)B_m L/B\rho$. Here, $B_m L = B_\perp L\cos(\varphi_{\mathrm{dip}})$ is the field of the rf dipole on the mth turn. At each revolution period, the dipole phase increases by $\Delta\varphi_{\mathrm{dip}} = 2\pi\nu_{\mathrm{dip}}$. The tune of the dipole oscillation is $\nu_{\mathrm{dip}} = \nu_0 + m(\nu_1 - \nu_0)/N$, where $\nu_0 = \nu_s - \pi\alpha N$ and $\nu_1 = \nu_s + \pi\alpha N$. If $\nu_{\mathrm{dip}} = \nu_s$ then the dipole is exactly on the spin resonance. To depolarize the beam, we scan the dipole frequency across the spin resonance. The rate of resonance crossing is defined by: $\alpha = (\nu_1 - \nu_0)/2\pi N$.

Application of the Froissart-Stora formula assumes that the depolarizing resonances are narrow and well-separated, so that the beam crosses only one resonance. There are three distinct regimes for the rate of resonance crossing shown in Table 1.

Table 1: Three Distinct Regimes

Crossing rate	Polarization	Effect
Fast	$P_f \approx P_i$	No depolarization
Medium	$P_i > P_f > -P_i$	Depolarization
Slow	$P_f \approx -P_i$	Spin-flip

NUMERICAL SIMULATIONS

Spin tracking simulations of the resonance depolarization technique were performed with two different approaches, using the computer codes SAMM [8] and SPRINT [9, 10]. SAMM carries out element-by-element tracking through a specified lattice, with the spin dynamics described by the Thomas-BMT equation:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}, \quad (5)$$

where frequency of spin precession is

$$\vec{\Omega} = -\frac{e}{\gamma m}\left[G\gamma\vec{B}_\perp + (1+G)\,\vec{B}_\parallel\right]. \quad (6)$$

SAMM calculates the instantaneous polarization as the average of the spin vector over M particles in a bunch at a single point in the ring as follows:

$$\vec{P}_{\mathrm{inst}}|_j = \frac{1}{M}\sum_{i=1}^{M}\vec{S}_i|_j, \quad (7)$$

where j is the revolution turn.

Spin tracking in SPRINT is based on the transport of a unit quaternion with the spin-orbit coupling included by a renormalized first-order expansion in the orbital coordinates. This results in a very fast tracking time. SPRINT calculates multi-turn polarization as an average of instantaneous polarization at each revolution turn j:

$$\vec{P}_{\mathrm{mult}} = \frac{1}{N}\sum_{i=1}^{N}\vec{P}_{\mathrm{inst}}|_i, \quad (8)$$

where N is the specified number of turns for averaging.

In the lattice for the ILC damping ring, two rf dipoles were inserted in a straight section (i.e. without other dipole magnets). The distance between the magnets was chosen so that the orbital phase advance is π: as a result, the two rf dipoles form a closed orbit bump when their strengths are in a fixed ratio (determined by the beta functions at the dipoles).

The beam is stored in the damping rings for $T_{\mathrm{store}} = 100$ ms, which is the time between machine pulses. The total number of turns N that each particle makes in the ring is then given by the store time and the circulation frequency: $N = T_{\mathrm{store}} f_c = 9256$.

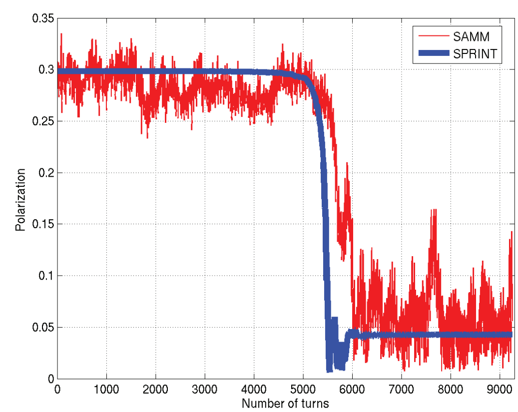

Figure 1: Positron polarization as a function of turn number in the ILC damping ring, calculated using SAMM and SPRINT.

Figure 1 shows a resonance crossing simulated with SPRINT (blue) and with SAMM (red). It should be noted that the parameters for Figure 1 are not optimized for complete beam depolarization but are presented here to compare the two different approaches. It can be seen that instantaneous polarization (red curve) is fluctuating wildly even a long way from resonance, since the tracked ensemble did not start at equilibrium. Taking this into account, the results from the two codes are in reasonable agreement.

Figure 2 shows the ratio of final to initial polarization in the ILC damping rings as a function of the resonance strength ε. The red circles show values computed with SPRINT, using the actual lattice with two rf dipoles. The green line shows a fit of the analytical Froissart-Stora formula to the tracking data (red circles) using the resonance

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strength as a fit parameter. Finally, the blue line shows the final polarisation expected from the Froissart-Stora formula, for a resonance strength calculated with the assumption that only a single RF dipole is presented. The difference in resonance strength of $\Delta\varepsilon/\varepsilon = 0.2 \cdot 10^{-4}/2.5 \cdot 10^{-4} = 8\%$ can be explained by the fact that resonance strength in the Froissart-Stora formula calculated using (3) ignores the spin phase advance between the two rf dipoles and the forced orbital oscillations. These effects are included in the simulation of the real lattice with SPRINT.

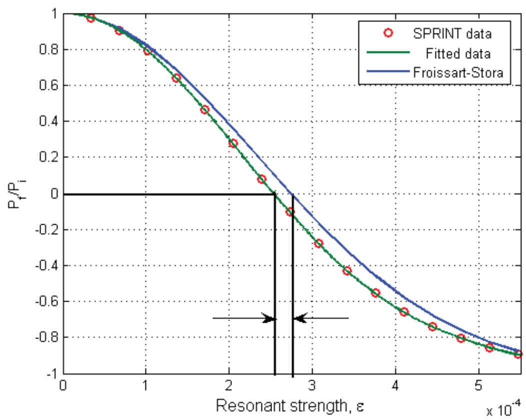

Figure 2: SPRINT tracking data and Froissart-Stora fit compared to F.-S. formula with ε from Eq. 3.

The impact of synchro-betatron motion on the evolution of the multiturn polarization is shown in Figure 3. The normalized emittances of the positron beam are $\epsilon_{n,x} = \epsilon_{n,y} = 0.01\,\mathrm{m}\cdot\mathrm{rad}$ transversely, and $\epsilon_{n,z} = 0.05\,\mathrm{m}\cdot\mathrm{rad}$ longitudinally. The red curve corresponds to motion on an invariant torus with amplitude equal to one σ (where σ is the rms beam size), the green curve corresponds to motion with amplitude equal to 2σ, and the blue curve corresponds to motion with amplitude equal to 3σ respectively. It can be observed that the turn (i.e. the dipole tune ν_{dip}) at which the resonance is crossed varies with the orbital amplitudes of the tracked particles. This indicates the presence of an amplitude-dependent spin tune shift. Varying the amplitude causes the resonance to move. A continuous range of amplitudes will result in a continuous range of spin tunes. The various degrees of depolarization achieved depending on the amplitude of the synchro-betatron motion indicates partly destructive interference with spin-orbit resonances, rather than the RF dipole resonance. This has to be studied in greater detail in the future. Moreover, this makes clear that radiation damping and synchrotron radiation effects (which directly affect the beam size) have to be taken into account to find the optimal conditions for beam depolarization.

CONCLUSIONS

Our first results indicate that it is feasible to obtain an operation mode with unpolarized beams in the ILC, using resonant depolarization. Different methods used for simulations show a reasonable level of agreement. The resonant depolarization conditions identified in the simulations are

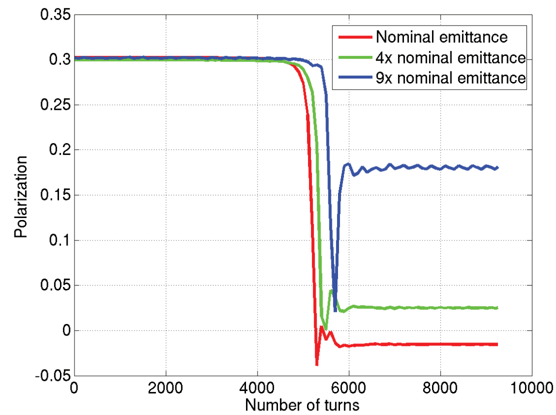

Figure 3: Effect of amplitude of synchro-betatron motion on resonant depolarization. Particles are launched on an invariant torus with amplitude corresponding to one σ of the beam with the nominal emittance (red line); with amplitude 2σ of the nominal beam, i.e. one σ of a beam with four times the nominal emittance (green line); and with amplitude 3σ of the nominal beam, i.e. one σ of a beam with nine times the nominal emittance (blue line). The differences between the three cases indicate amplitude-dependent spin tune shifts.

not final because the effects of synchrotron radiation and radiation damping have not so far been included. Beam dynamics effects as well as spin tracking must be investigated for both polarized and unpolarized modes.

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