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# SPIN TRACKING AT THE ILC

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## Abstract

Polarized  and  beams are foreseen for the future International Linear Collider (ILC) whose final basic design considerations are currently under discussion. High precision physics requires the polarization of both beams to be known with a relative uncertainty of about 0.5% or better. Therefore all possible depolarizing effects that could operate between the polarized sources and the interaction regions have to be under full control.

The ‘heLiCal’ collaboration aims to provide a full ‘cradle-to-grave’ analysis of all depolarizing effects at the ILC. This report gives a brief summary of ongoing work on the ILC spin-dynamics concentrating on recent results for depolarizing effects in the ILC damping rings, beam delivery system and beam-beam interactions. The effects during the beam-beam interactions have been evaluated for a range of ILC parameter sets.

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## *Abstract*

Polarized $e^-$ and $e^+$ beams are foreseen for the future International Linear Collider (ILC) whose final basic design considerations are currently under discussion. High precision physics requires the polarization of both beams to be known with a relative uncertainty of about 0.5% or better. Therefore all possible depolarizing effects that could operate between the polarized sources and the interaction regions have to be under full control.

The 'heLiCal' collaboration aims to provide a full 'cradle-to-grave' analysis of all depolarizing effects at the ILC. This report gives a brief summary of ongoing work on the ILC spin-dynamics concentrating on recent results for depolarizing effects in the ILC damping rings, beam delivery system and beam-beam interactions. The effects during the beam-beam interactions have been evaluated for a range of ILC parameter sets.

## OVERVIEW

The full physics potential of the ILC could be realized only with polarized $e^-$ and $e^+$ beams [1]. Polarized $e^-$ with a polarization degree of $P_{e^-} > 80\%$ up to 90% are foreseen for the baseline machine design. The electron source consists of a circularly polarized high-power laser beam and a high-voltage DC gun with a semiconductor photocathode. In the current Baseline Configuration Document (BCD) [2] of the ILC a helical undulator based positron source has been chosen as the most reliable solution for producing the required flux of order $10^{14}$ positrons per second. The design produces positrons via an electromagnetic shower instigated in a thin target by incident circularly polarized synchrotron radiation produced by the undulator operating on the main ILC $e^-$ beam. The method has been experimentally tested in the E166 experiment [3]. An overview of the 'heLiCal' contributions to the (polarized) $e^+$ source for the ILC is given in [4], prototypes of the helical undulator have been studied in [5] and a design of the pair-production target can be found in [6]. The undulator-based source can easily be upgraded to provide polarized $e^+$ with high luminosity and a polarization degree of about $P_{e^+} = 60\%$. To fulfill the physics goals, it is important to ensure that no significant polarization is lost during the transport of the $e^-$ and $e^+$ beams from the source to the interaction region. Transport elements downstream of the sources which can contribute to a loss of polarization include the initial acceleration structures, transport lines to the damping rings, the damping rings, the spin rotators (see also [7]), the main linacs, and the high energy beam delivery systems. As discussed below, where depolarization in the ILC damping rings, in the beam delivery system and during the beam-beam interactions has been analyzed, the largest depolarizing effect is expected to result from the collision of the two beams at the interaction point(s).

## DAMPING RINGS

In [8] it has been shown that at energies corresponding to spin-orbit resonances the beam can lose polarization after injection into a damping ring (DR). However, even when the energy is chosen appropriately, the synchrotron radiation, enhanced by the wigglers in a DR, has the potential to cause depolarization. Therefore further detailed studies are needed. In the current ILC BCD [2] design a circular 6 km-DR (OCS) at 5.066 GeV has been chosen.

In more detail: two effects influence the spin motion in electric and magnetic fields: a) spin precession and b) spin-flip via synchrotron radiation. Spin precession is described

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by the Thomas–Bargmann-Michel-Telegdi (T-BMT) equation

$$\frac{d\vec{S}}{ds} = \vec{\Omega}(u,s) \times \vec{S}, \qquad (1)$$

where $\vec{S}$ denotes the spin vector in the rest frame, $\vec{\Omega}$ the precession vector, $s$ the distance around the ring, $u$ the position of the particle in the phase space. On the design orbit of a perfectly aligned ring the spins only experience the vertical dipole fields and with respect to the orbit, the spins precess around this field by an angle: $a\gamma\times$ the angle of orbit deflection, where $a$ is the electron gyromagnetic anomaly and $\gamma = E/m_e c^2$. Thus in one turn a spin precesses by an angle $2\pi a\gamma$ around the vertical. When the natural spin precession becomes coherent with the orbital oscillations, then the depolarizing effects tend to be particularly large (‘spin-orbit resonances’).

In damping rings the time to build up polarization via the Sokolov-Ternov spin-flip (S-T) is very large compared to the typical time that the beam stays in the ring. Therefore the S-T effect can be neglected. However, the stochastic nature of the emission of radiation causes spin diffusion. Since the beam is not in equilibrium, the analytical calculations of depolarization, in codes such as SLICK, are not applicable. Estimates of depolarization are then made with the code SLICKTRACK [9] which embeds the formalism of SLICK in a Monte-Carlo simulation of photon emission. Simulations with SLICKTRACK have confirmed that the specially installed additional sources of synchrotron radiation, the wigglers, quickly damp down the initially large transverse beam size and quickly increase the initially small bunch length and energy spread up to the theoretical (analytical) level. One should note that detailed lattice designs have been completed only for the $e^+$ DR’s, since the $e^-$ beam is expected to cause much smaller damping problems.

As part of a study to determine the optimal damping ring configuration for the ILC, the depolarization for two damping ring designs, the OCS ring and the 17 km TESLA ring, have been studied. Realistic misalignments (1/3 mm misalignments and 1/3 mrad roll for quadrupoles) and closed orbit corrections are included. The transverse emittances of the injected beam were twice as large as those for the planned setup. Two energies have been studied, 4.8 GeV (close to a first order synchrotron resonance) and 5.066 GeV, see Fig. 1 for the results of the OCS design. The curves show the mean squares of tilts of spins away from the direction of the equilibrium polarization. As expected, the loss of polarization is negligible for the time the beam stays in the damping ring.

SLICKTRACK shows that contrary to common expectations, the horizontal projections of a bundle of parallel spins which are tilted from the vertical at injection, do not fan out uniformly during damping. In fact the distribution of projections is in excellent agreement with a simple analytical model [10]: the width of the distribution of the spin projections on the horizontal plane should reach equilibrium with a value of about $24^\circ$, SLICKTRACK gives about $25^\circ$.

Note that radiative depolarization is negligible even with injected beams that have transverse emittances ten times larger than those planned for the real setup.

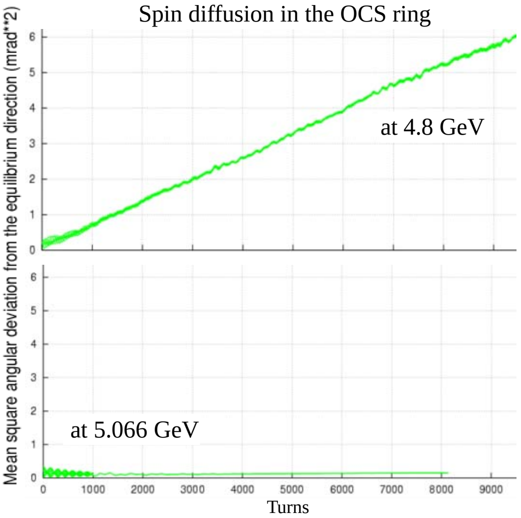

Figure 1: The mean square angular deviation from the equilibrium polarization in the ILC damping ring (OCS design) for two energies: 4.8 GeV (upper plot), i.e. close to the first order resonance, and at 5.066 GeV (lower plot).

## BEAM DELIVERY SYSTEM

After acceleration up to $E_b = 250$ GeV for the first stage of the ILC with $\sqrt{s} = 500$ GeV, the beams must be brought into collision in the beam delivery system via bending and focusing magnets. For a 250 GeV $e^-$ beam undergoing the total of 11 mrad of bend, the spin precession is approximately $332^\circ$. Thus a study of spin-transport through the beam delivery system is required. Preliminary calculations with SLICKTRACK running in a single pass mode indicate no significant loss of polarization, confirming the earlier work [11].

## BEAM-BEAM INTERACTIONS

The program CAIN [12] evaluates analytically the two sources of depolarization during beam-beam interaction at the linear collider, the T-BMT as well as the S-T effect.

A study of such depolarizing effects for NLC parameters has been made in [13], analyzing both sources of possible depolarization separately. The luminosity-weighted depolarization ($\Delta P_{lw}$) was about 0.2% at $\sqrt{s} = 500$ GeV and up to 0.5% at $\sqrt{s} = 1$ TeV for various NLC sets.

In this study the depolarizing effects of the $e^\pm$ beams have been analyzed for various ILC parameter sets: the four sets ‘Nominal’, ‘low Q’, ‘large Y’ and ‘low P’ [2], that are very conservative sets with respect to an expected luminosity of about $\mathcal{L} \sim 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ and the ‘TESLA’ set, that results in $\mathcal{L} \sim 3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. The ‘TESLA’ set is also completely covered in the ILC parameter space but leads to a more ambitious luminosity due to the smaller vertical emittance, see Table 1. All these sets result in only small depolarization: the sum of T-BMT and S-T effects for the luminosity-weighted depolarization is in the range between 0.06% (‘low Q’) up to 0.24% (‘low P’), see Table 2. The total depolarization is $\Delta P_{tot} \sim 0.273 \Delta P_{lw}$ [12]; that relation is valid in all our sets since the disruption parameter $D_x \ll 1$. For higher energy, e.g. at $\sqrt{s} = 1$ TeV in the ‘Nominal’ as well as in the ‘low P’ set (parameters correspondingly scaled with the $\gamma$ factor), the depolarization increases by about a factor 2. This is mainly due to the contribution from the S-T effect. The listed values have been derived for head-on collisions and 100% polarized beams. With partially polarized beams, namely the expected 90% (60%) polarization for the $e^-$ ($e^+$) beam at the ILC [1, 2], the absolute depolarization decreases correspondingly.

Table 1: ILC parameters sets for $\sqrt{s} = 500$ GeV, more details can be found in [2]. The repetition rate is 5 Hz.

| | Nominal | low Q | large Y | low P | TESLA |
|---|---|---|---|---|---|
| N /$10^{10}$ | 2 | 1 | 2 | 2 | 2 |
| $n_B$ | 2820 | 5640 | 2820 | 1330 | 2820 |
| $\gamma\epsilon_x^*$/mm rad | 10 | 10 | 12 | 10 | 10 |
| $\gamma\epsilon_y^*$/mm rad | 0.04 | 0.03 | 0.08 | 0.035 | 0.03 |
| $\beta_x^*$/mm | 21 | 12 | 10 | 10 | 15 |
| $\beta_y^*$/mm | 0.4 | 0.2 | 0.4 | 0.2 | 0.4 |
| $\sigma_z/\mu$m | 300 | 150 | 500 | 200 | 300 |
| $D_x$ | 0.162 | 0.0708 | 0.468 | 0.226 | 0.226 |
| L/$10^{34}$cm$^{-2}$s$^{-1}$ | 2 | 2 | 2 | 2 | 3 |

Table 2: Comparison of the luminosity-weighted depolarizing effects in beam-beam interactions at $\sqrt{s} = 500$ GeV for the ILC parameters sets: T-BMT (S-T) denotes effects due to spin precession (synchrotron radiation).

| Parameter set | Depolarization $\Delta P_{lw}$ | | |
|---|---|---|---|
| | T-BMT | S-T | total |
| Nominal | 0.08% | 0.02% | 0.10% |
| low Q | 0.04% | 0.02% | 0.06% |
| large Y | 0.17% | 0.02% | 0.19% |
| low P | 0.15% | 0.09% | 0.24% |
| TESLA | 0.11% | 0.03% | 0.14% |

Another topic being studied is the validation of the T-BMT equation for strong fields. However, for the current ILC parameter sets with the field parameter $\Upsilon \ll 0.2$ no major changes are expected at this stage.

CAIN includes also coherent and incoherent production processes. For coherent processes, polarization effects are included. Due to the small $\Upsilon$ for all ILC sets, however, production of coherent pairs is completely negligible. Full spin correlations are not yet included in the production of incoherent pairs and have been calculated in CAIN only in the equivalent photon approximation (EPA). However, for the bremsstrahlung process this approximation can only be applied for specific kinematic conditions [14]. For all ILC parameter sets the contribution of the bremsstrahlung to the incoherent processes is between 35% and 47%. Therefore, contributions to the depolarization by including the spins of the produced pairs and no EPA, are expected. The work is still ongoing and will lead to a corresponding update of the simulation code.

## CONCLUSIONS AND OUTLOOK

We studied possible depolarizing effects at the ILC at the damping ring, at the beam delivery system and during the beam-beam interactions for various ILC parameters.

- As expected intuitively, the depolarization in damping rings with a carefully corrected orbit is negligible. Nevertheless, as a new lattice design is now under development, this rolling study to include extra effects will be continued.
- With good alignment there is no noticeable depolarization in the BDS. However, it is clear that the effects of misalignments will require careful further studies.
- Depolarizing effects in beam-beam interactions have been evaluated for various ILC parameter sets. The expected depolarization is at most about 0.2% (‘large Y’, ‘low P’ sets) and the smallest effects are $< 0.1\%$ for the ‘low Q’ scenario. At higher energy $\sqrt{s} = 1$ TeV the effect will increase by about a factor 2.
- There are still theoretical uncertainties due to the use of the EPA for the incoherent processes; for strong fields the validation of the T-BMT equation in its current use has to be checked.
- As a results of this work the CAIN code will be updated and a comparison with the simulation code GUINEA-PIG [15] is foreseen.

## REFERENCES

[1] G. Moortgat-Pick *et al.*, hep-ph/0507011, submitted to Phys.Rep.; www.ippp.dur.ac.uk/˜gudrid/power/.

[2] The current ILC Baseline Configuration Document (BCD) could be found on: http://www.linearcollider.org/wiki/.

[3] J. Kovermann et al., *Undulator-based production of polarized positrons*, E166 Collaboration, these proceedings.

[4] J.A. Clarke et al., *Status of the heLiCal contribution to the polarised positron source for the ILC*, these proceedings.

[5] Y. Ivanyushenkov et al., *Development of a superconducting helical undulator for the ILC positron source*, J. Rochford et al., *Magnetic modelling of a short-period superconducting helical undulator for the ILC*, these proceedings.

[6] I.R. Bailey et al., *Development of a Positron Production Target for the ILC Positron source*, these proceedings.

[7] P. Schmid, N.J. Walker, *A Spin Rotator for the ILC*, these proceedings; P. Schmid, EUROTeV-Report-2005-024.

[8] A. Wolski, D. Bates, Linear Collider collaboration Tech Notes LCC-0155.

[9] D.P. Barber et al., Cockcroft-04-01.

[10] K. Heinemann, DESY Report, 97 (1997), physics/9709025; D.P. Barber et al., DESY M-94-13 (Rev).

[11] J. Smith, ‘ILC LET Workshop’, CERN, February 2006; www.lepp.cornell.edu/˜js344/LC/talks/spin_tracking.pdf.

[12] K. Yokoya, P. Chen, SLAC-PUB-4692, 1988; K. Yokoya, ’User’s Manual of CAIN’, Version 2.35, April 2003.

[13] K. A. Thompson, SLAC-PUB-8716; A.W. Weidemann, Int.J.Mod.Physics A, 2537 (2000).

[14] A. M. Altukhov, Sov. J. Nucl. Phys. 14, No. 2 (1972), 220.

[15] D. Schulte, Ph.D. thesis, University of Hamburg, 1996, TESLA-97-08.