Spin tracking studies for polarimetry at the ILC

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Abstract. At the International Linear Collider (ILC), the beam polarization is planned to be measured with a yet unequalled precision of 0.25\% by two Compton polarimeters located 1.8 km upstream and 150 m downstream of the \(e^+e^-\) interaction point (IP). The decisive quantity for the experiments, i.e. the luminosity-weighted average polarization, has to be determined from these measurements. A detailed understanding of the spin tracking and the depolarizing effects is mandatory in order to estimate how precise the polarization at the IP is known from these measurements performed 2 km apart. For that purpose, a beamline simulation including spin tracking has been set up. First results comprise the results of static misalignments, dynamic misalignments and beam-beam interaction are in preparation.

1. Polarimetry at the ILC

The International Linear Collider (ILC) \cite{ILC} is a proposed \(e^+e^-\) collider designed to provide collisions at a center-of-mass energy up to 500 GeV, with an upgrade option to 1 TeV. A beam polarization of \(\geq 80\%\) for electrons and \(\geq 30\%\) for positrons at the interaction point (IP) seems achievable, with a possible enhancement to about \(60\%\) for the positron beam.

High-precision measurements in electroweak processes are essentially limited by the precision of the measured beam polarization. Therefore, the beam delivery system (BDS) of each beamline will contain two dedicated Compton polarimeters \cite{Polarimeters}, one being located about 1 800 m upstream of the IP (upstream polarimeter, UP) and one being located 150 m downstream of the IP (downstream polarimeter, DP). The measurement precision of each polarimeter is aimed to be \(dP/P = 0.25\%\) for the entire range of beam energies from 45 GeV to 500 GeV. The decisive quantity is the luminosity-weighted polarization at the IP. A detailed understanding of the spin tracking and the depolarizing effects is mandatory in order to estimate how precise the longitudinal polarization at the IP is known from the polarimeter measurements.

Furthermore, the average luminosity-weighted polarization of a data sample can be extracted from \(W\)-pair production and can be used to cross-calibrate the Compton polarimeters. Assuming 60 \% positron polarization, the average electron polarization can be determined with an uncertainty of \(dP/P = 0.1\%\) from a data sample of 800 fb\(^{-1}\) \cite{DataSample}. This requires spin transport to be understood to the same level of precision.

A comprehensive simulation of spin transport needs to take into account several details beyond pure spin tracking:

- Static misalignments due to limited adjustment precision
- Dynamic misalignments due to ground motion

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• Feed-back correction systems to correct the effects of misalignments
• Special beamline elements: crab cavities, detector magnets (solenoid and anti-DID)
• Beam-beam collision effects including the crossing angle
• The polarization measurement: Compton scattering, tracking of the scattered particles and detector response

After these are included in the simulation, precision requirements on the correction systems can be derived and strategies can be developed to calibrate the polarimeters.

2. Spin Tracking
Spin tracking is performed here based on the Thomas-Bargmann-Michel-Telegdi (T-BMT) equation, which describes the propagation of a classical spin \( s \) vector through electromagnetic fields [4]:

\[
\frac{ds}{dt} = \Omega \times s
\]

\[
\Omega = -\frac{q}{m\gamma} \left[ (1 + G\gamma) B - \frac{G(p \cdot B)}{(\gamma + 1)m^2c^2} p - \frac{1}{mc^2} \left( G + \frac{1}{1 + \gamma} \right) p \times E \right]
\]

Here \( q \) and \( m \) are respectively the charge and the mass of the beam particle species and \( G = \frac{g - 2}{2} \) its magnetic anomaly (\( G \approx 0.00116 \) for \( e^\pm \)). The following quantities are given in the laboratory frame: \( s \) is the classical spin vector of the tracked particle, \( p \) its momentum vector and \( \gamma \) the relativistic gamma factor; \( E \) and \( B \) are the electric and magnetic fields, respectively. A detailed derivation of the T-BMT equation can be found in [5].

In the absence of electric and longitudinal magnetic fields, the spin vector \( s \) precesses around the magnetic field axis like the momentum vector \( p \), but with a precession angle

\[
\theta_s = (1 + G\gamma) \theta_p
\]

This can be used to estimate the effects of additional magnets not yet included in the simulation.

3. The Simulation Framework
To set up a simulation including all features listed in section II with sufficient precision, several different programs are combined for this purpose, as shown in figure 1.

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**Figure 1.** Simulation software framework. Particle and spin tracking start at the beginning of the BDS with a beam generated according to the design beam parameters. Since only the way between the up-/downstream polarimeter (UP/DP) and the \( e^+e^- \) interaction point (IP) are of interest, the tracking is stopped at the DP. The collision effects at the IP are simulated for the incoming beams, then the disrupted beams are fed back into the tracking software. At the UP and DP, the detector responses for the incoming beams is simulated.
The particle tracking and spin transport is done with Bmad \cite{6} making use of the T-BMT equation. Static misalignments are generated in the tracking code; ground motion and orbit correction will be included as well.

The collision at the IP has two effects on the particle spins:

(i) Two colliding bunches disrupt each other due to the electromagnetic fields caused by their charge; their spin distribution is disrupted accordingly.

(ii) The generation of beamstrahlung photons causes a spin flip, i.e. depolarization.

In order to take those effects into account, Guinea-Pig++ \cite{7} or CAIN \cite{8} are envisaged to be employed.

A simulation of the measurement in a Compton polarimeter includes the simulation of the Compton scattering process, the tracking of the scattered particles and the simulation of their detection. This code (LCPolMC) is not yet publicly available.

For the data analysis and visualization, ROOT \cite{9} is used.

Simulation Input and Parameters

For particle and spin tracking through the BDS the ILC2007b lattice \cite{10} is used, the changes according to the SB2009 proposal \cite{11} are not included yet. A random particle distribution with the nominal beam parameters at the end of the main linac as specified in \cite{12} is generated as input for the simulation. The spin vectors are initialized randomly to be $\pm \vec{e}_z$, such that the initial average polarization is 80%.

Instead of $2 \cdot 10^{10}$ particles per bunch (nominal bunch population), $10^4$ particles per bunch are tracked in the simulation.

4. Correction of Misalignments

As a preliminary orbit correction, the following procedure is performed: At the IP, all momentum vectors are rotated by the same angle $\theta_{\text{cor}}$ such that the average transverse momentum is zero, which would be the result of an ideal correction of the beam angle. The effect of the correction dipoles on the spin is taken into account by equation (2), i.e. the spin vectors are rotated by the angle $(1 + G\gamma) \theta_{\text{cor}}$ about the same axis. Figure 2 illustrates the performance of this provisional orbit correction: Shown are the longitudinal polarizations for the case of perfect alignment as well as for three cases of random transverse misalignments. The sizes of the misalignments are Gaussian-distributed with zero mean and standard deviations $\sigma_{x,y} = 2 \mu m$. As different sets of random numbers with the same mean and Gaussian widths can have tremendously different effects on the polarization, three sets are shown as examples to illustrate the range.

Most changes in longitudinal polarization are due to magnets, e.g. the two dips around the UP are caused by the bending magnets of the polarimeter chicane. Bending magnets rotate the polarization vector, which is reversible, and thus does not lead to real depolarization. Directly downstream of the IP, a series of focusing and defocusing quadrupoles is installed to recapture the disrupted beam after the collision. Those quadrupoles act as lenses on particles as well as on spins, but again enhanced by the factor $1 + G\gamma$. That causes a “spin fan-out”, which is - in principle - reversible as well.

A number of particles is caught in the collimators (indicated by the arrows in figure 2). The helicities in the bunch are assumed to be isotropic at the beginning of the BDS. In general, polarization and particle energy can be correlated according to equation (3). As the total dispersion at the positions of the collimators should be negligible, only statistical changes in the longitudinal polarization are expected to occur (a subset of a sample with an average $z$-helicity $P_z$ does not necessarily have exactly the same average $z$-helicity). From the total number of simulated particles and the number of lost particles, the expected statistical errors $\sigma$ on the longitudinal polarization can be calculated for every case. None of the changes in the shown examples are larger than $2\sigma$, which is in agreement with a negligible dispersion. Since it is
proposed to move these collimators to new positions in front of the UP, this issue has not been investigated further.

![Diagram showing longitudinal polarizations along the BDS (left) behind the upstream polarimeter (UP) and (right) between IP and downstream polarimeter (DP): Perfect alignment is shown in black, while three different cases of Gaussian-distributed misalignments with \( \sigma = 2 \mu m \) are displayed in color. For the latter ones a beam orbit correction at the IP (such that \( \langle p_t \rangle = 0 \) ) was performed (dashed lines). The positions of two collimators are marked at which the beam loses 99 (perfectly aligned) and \( \sim 10^3 \) (misaligned) out of \( 10^4 \) particles. After the orbit correction, the longitudinal polarizations at the IP agree with those at the DP and behind the second collimator within 0.1 \%.

Beginning at the IP, also the longitudinal polarizations after the provisional orbit correction are shown in figure 2. The longitudinal polarizations at the IP agree (to a precision of 0.1 \% and better) with those at the DP and those behind the collimators. Apparently, the misalignments cause no significant changes in the longitudinal polarizations between UP and the collimators. Therefore it can be assumed that without collimators the longitudinal polarizations at the IP would agree to a precision of better than 0.1 \% with those measured at the UP as well.

5. Conclusion and Outlook
A comprehensive simulation framework is set up to investigate the spin transport between the BDS polarimeters and the IP to permille-level precision. First results suggest that the orbit correction systems at the IP can also recover the longitudinal polarization of the beam. In order to derive precision requirements on the beam position monitors and the correction kicker magnets, a full orbit correction system needs to be implemented. For dynamic misalignments (ground motion), the effects on the polarization with respect to the response time of the correction system needs to be investigated.

Furthermore, beam-beam collision effects need to be considered and the lattice needs to be completed: detector magnets and crab cavities are not included in the ILC2007b lattice, and the changes according to the SB2009 proposal need to be implemented as well.

Acknowledgments
The authors would like to thank Anthony Hartin, Kenneth Moffeit, Yuri Nosochkov, David Sagan, Andrei Seryi, Jeff Smith and Michael Woods for fruitful discussions and support.

References
[1] ILC Global Design Effort and World Wide Study 2007 ILC Reference Design Report - Volume 1 Executive Summary ed J Brau et al. arXiv:0712.1950v1 [physics.acc-ph]
[2] Boogert S et al. 2009 Polarimeters and energy spectrometers for the ILC beam delivery system *Journal of Instrumentation* JINST 4:P10015 doi:10.1088/1748-0221/4/10/P10015

Bartels C et al. 2010 Design and Construction of a Cherenkov Detector for Compton Polarimetry at the ILC DESY 10-225 arXiv:1011.6314

[3] Bechtle P et al. 2009 Measurement of the beam polarization at the ILC using the WW production LC-DET-2009-003 [http://www-flc.desy.de/lcnotes](http://www-flc.desy.de/lcnotes)

Mönig K 2004 Polarisation measurements with annihilation data LC-PHSM-2004-012

[4] Bmad manual version 12.5 [http://www.lepp.cornell.edu/~dcs/bmad/bmad-manual-12.5.pdf](http://www.lepp.cornell.edu/~dcs/bmad/bmad-manual-12.5.pdf)

[5] Montague B W 1984 Polarized beams in high energy storage rings *Physics Reports* **113** 1

[6] Bmad version bmad_dist_2010_0713_d [http://www.lepp.cornell.edu/~dcs/bmad](http://www.lepp.cornell.edu/~dcs/bmad)

Sagan D 2006 Bmad: A relativistic charged particle simulation library *Nuclear Instruments and Methods in Physics Research* A **558** 356 doi:10.1016/j.nima.2005.11.001

[7] GuineaPig++ [https://trac.lal.in2p3.fr/GuineaPig](https://trac.lal.in2p3.fr/GuineaPig)

Le Meur G et al. 2008 Description of Guineapig++, the C++ upgraded version of the GUINEA-PIG beam-beam simulation program EUROTeV-Report-2008-067

[8] CAIN [http://lcdev.kek.jp/~yokoya/CAIN/cain235/CainMan235.pdf](http://lcdev.kek.jp/~yokoya/CAIN/cain235/CainMan235.pdf)

Yokoya K and Chen P 1988 Depolarization due to beam-beam interaction in electron - positron linear colliders SLAC-PUB-4092

[9] ROOT Version 5.20: [http://root.cern.ch](http://root.cern.ch)

[10] ILC2007b lattice [http://www.slac.stanford.edu/accel/ilc/lattice/edr(ILC2007b](http://www.slac.stanford.edu/accel/ilc/lattice/edr/ILC2007b)

[11] SB2009 - Rebaselining Proposal [http://lcdev.kek.jp/SB2009](http://lcdev.kek.jp/SB2009)

[12] ILC Global Design Effort and World Wide Study 2007 *ILC Reference Design Report - Volume 3 Accelerator* ed N Phinney et al. arXiv:0712.2361v1 [physics.acc-ph]