Challenge of polarized beams at future colliders

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Abstract. A short overview is given about the potential of polarized beams at future colliders is given. In particular the baseline design for polarized beams at the ILC is presented and the physics case for polarized $e^-$ and $e^+$ is discussed. In order to fulfil the precision requirements spin tracking from the source to the interaction point is needed. Updates concerning the theoretical calculations as well as their implementation in simulation codes are reported.

1. Introduction

1.1. Overview about colliders with polarized beams

As shown in past experiments beam polarization is a very powerful tool to achieve the physics goals and optimize the results. The great success of the SLD experiments at the $e^+e^-$ collider SLC with the best single measurement of the electroweak mixing angle, $\sin^2\theta_{\text{eff}} = 0.23098 \pm 0.00026$ [1], was due to the application of polarized $e^-$ beams with about $P_{e^-} = 78\%$, although the LEP $e^+e^-$ experiment ($\sin^2\theta_{\text{eff}} = 0.23221 \pm 0.00029$) had much higher luminosity. At LEP itself only a small degree of polarization was available which was nevertheless very useful and was used for energy calibration only [2]. Polarization at HERA, the asymmetric circular $ep$-collider, reached an polarization of $P_{e^+} = 40\%$ in the colliding mode (about 70% in non-colliding mode) and was used to test the non-existence of right-handed charged currents [3]. Many of the designs of future colliders also foresee the option of polarized beams. For instance, future upgrades of $ep$ colliders, i.e. eRHIC [4] and LHeC [5], may discuss the use of this option in order to have access to the spin structure of the gluons.

The most prominent future collider with polarized beams is the $e^+e^-$ International Linear Collider (ILC), that is already in the engineering phase of its design. Already with the baseline design an polarized $e^-$ of about $P_{e^-} = 80\% - 90\%$ polarization is expected: using the same scheme for producing polarized electrons that was already successfully at the SLC. Furthermore the baseline $e^+$ source, based on undulator radiation [6], generates polarized $e^+$ with high
luminosity and an approximated polarization of about 30%. The degree of the polarization can easily be upgraded to about 60% [7]. Also a possible design for a future multi-TeV collider, CLIC, discusses the option of providing polarized $e^-$ and $e^+$ beams.

1.2. Physics motivation for polarized beams at the ILC
Polarizing both beams at the linear collider instead of only the $e^-$ beam has several advantages: improving statistics, enhancing rates and cross sections and suppressing background processes. Furthermore there exist also several examples were the use of both beams polarized is mandatory, for instance, in order to prove specific quantum numbers of new particles. The polarization of both beams is also needed to achieve the ultimate precision predicted for the measurements at GigaZ. The physics case and the need of polarized $e^-$ and $e^+$ has been established and quantified [8].

A striking feature of the current ILC design is that it provides without any upgrades a small $e^+$ polarization of about 30%. Numerous questions could already be addressed with such a small amount of polarization. In many cases polarized beams with $(P_{e^-}, P_{e^+}) = (80\%, 30\%)$ lead to already half of the physics gain that could be achieved with $(80\%, 60\%)$. These gains could not be achieved by only using higher electron polarization, even not with $100\%$ beam polarization [8, 9].

2. Schemes for polarizing beams at the linear collider
The electron source consists of a circularly polarized high-power laser beam and a high-voltage DC gun with a semiconductor photocathode. For the positron source a scheme, based on helical-undulator radiation, has been chosen as the most reliable solution for producing the required flux of order $10^{14}$ positrons per pulse, details see [7, 10]. 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 undulator-based source achieves the 1.5 yield requirements and imposes much less demands for capture issues and damping ring acceptance. This method has been experimentally tested in the E166 experiment at SLAC [11] and several prototypes for the ILC-type undulator have already been successfully tested, for details see [12]. It has also been studied and simulated that the undulator-based source has negligible impact on the emittance and on the energy spread of the $e^-$ beam [12].

The undulator-based $e^+$ source leads to much less radiation damage at the target: for instance, it causes less activation (dose rate) by a factor of about 70 (25) and produces less neutrons by about a factor of 10 compared with the target at a conventional source [13]. Concerning the status of prototype targets for the ILC, see [14].

The successful accomplishment of the experiment E166 led also to the inclusion of polarization in the physics simulation program GEANT4 [15] that is important for the physics analyses at all future colliders and the updated version of the program is available [16].

An alternative scheme for the inclusion of polarized $e^+$ beams at the linear collider is based on laser-Compton-backscattering. Prototypes for this scheme have been successfully tested at ATF [17]. Several applications concerning this scheme are discussed for SuperB factories, a possible multi-TeV design for a future linear collider CLIC, for the energy-recovery linac (ERL) and for a $CO_2$ laser at the Brookhaven laboratory.

2.3. Spin tracking from source to the interaction point
It is important to ensure that no significant polarization is lost during the transport of the $e^-$ and $e^+$ beams from their sources to the interaction region. The largest effects are expected to result during the collision of the two beams at the interaction point [18]. 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 \cite{19}, the main linacs, and the high energy beam delivery systems; as overview, for instance, see \cite{20}.

### 3.1. Beam-beam interactions

The main sources of depolarization effects during the beam-beam interactions are the spin precession and the spin-flip processes, i.e. the Sokolov-Ternov (S-T) effect. Usually the spin precession effect is dominant, but at higher energy the depolarization due to the S-T effect increases \cite{21}. Spin precession is described by the Thomas–Bargman-Michel-Telegdi (T-BMT) equation,

\begin{equation}
\frac{d\vec{S}}{dt} = -\frac{e}{m\gamma}[(\gamma a + 1)\vec{B}_T + (a + 1)\vec{B}_L - \gamma(a + \frac{1}{\gamma + 1})\beta\vec{\gamma} \times \frac{\vec{E}}{c}] \times \vec{S},
\end{equation}

where $a$ describes the anomalous magnetic moment of the electron given by the higher-order corrections to the $ee\gamma$ vertex. In the environment of strong colliding beams, however, the usual perturbation theory cannot be applied. Therefore modified expressions for the anomalous magnetic moment in a medium have been derived \cite{22}. These expressions have been evaluated in the no scattering case, using the quasiclassical approximation that implies that the change in the momentum due to the strong fields is sufficiently slow. This condition is fulfilled if the Larmor radius of the particle due to the existing magnetic field in the bunches is much larger than the particle wavelength. It has been checked that even in the strong field environment of the ILC such a quasiclassical approximation can be used and the modified T-BMT equation can be applied to describe the spin precession sufficiently accurate, see also \cite{22, 23, 24}.

The production of incoherent background pairs \cite{25} is strongly dependent on the polarization state of the initial photons involved in the process \cite{26}. These photons are either real (beamstrahlung) or virtual and depend on the constant, crossed bunch electromagnetic fields. The CAIN \cite{23} program contained only full polarizations for the real photons. The polarization of virtual photons depends on the beam electric field $E_{x,y}$ at the point ($x, y$) where the pair is produced. For gaussian bunches an analytical expression has been derived \cite{27} and can be solved by using the condition for flat beams $\sigma_x \gg \sigma_y$. The cross-section for the Breit-Wheeler process is also required with full polarizations. In CAIN this cross section $\sigma^{\text{circ}}$ was written down only for the product of circular polarisations $\zeta_k \zeta_{k'}$ of initial photons $k$ and $k'$. The full cross-section $\sigma^{\text{full}}$ is a sum over all polarisation states and functions of final electron energy $\epsilon$ and momentum $p$ \cite{28}. A numerical investigation of these two cross-sections reveals that the usual peak at low energies with the full cross-section being substantially reduced for electron energies approximately less than 50 MeV. CAIN was modified with the above expressions and was run for all seven 500 GeV centre of mass collider parameter sets, cf. also \cite{21}. There was a 10–20% overall reduction in pairs, with no discernible impact on collision luminosity \cite{26}.

The coherent production of pairs via the first order interaction between beamstrahlung photon and beam field is already included in CAIN. However the second order stimulated Breit-Wheeler process also takes place in the presence of the bunch fields. The cross-section calculation involves solutions of the Dirac equation in an external field. Naively, in comparison to the first order coherent process, the second-order cross-section should be diminished by an order of the fine structure constant. However the bunch field has the effect of allowing the second order cross-section to reach the mass on-shell. The resulting resonances are rendered finite by inclusion of the electron self-energy and the stimulated Breit-Wheeler cross-section can exceed the first order coherent process. A detailed theoretical and numerical investigation is required to gauge in detail the effect on produced pairs \cite{24}.

### 3.2. Spin transport

The SLICKTRACK \cite{29} Monte Carlo computer has been used to analyze the spin motion in the ILC damping ring (DR), main linac (ML) and beam delivery system (BDS). The simulation,
applied for the 6km DR lattice at 5.0 GeV show that the sum of the mean squares of the angle of
the tilts of spins away from the direction of the equilibrium polarization will be less than
0.1 mrad\(^2\), even after 8 damping times. Also close to the spin-orbit resonance at 4.8 GeV the
sum of the mean squares of the angles is only about 40 mrad\(^2\), i.e. still negligible. In case a
large energy spread was included in the simulation of about ±25 MeV, much greater than the
natural energy spread of the DR, the deviation was found to be 20 mrad\(^2\), which is once again
negligible [30].

A striking result is that the horizontal projections of the spin vectors of an \(e^-\) or \(e^+\) bunch
do not fully decohore, even after 8000 turns. In other words, if the spins are not perfectly oriented
vertically at injection then their projections do not fan out uniformly in the horizontal plan
during the damping [30].

SLICKTRACK has also been modified to simulate precise spin tracking in the ILC beam
delivery system with an 2mrad crossing angle, including realistic misalignments. Consistent
with [20] it was found that a depolarization of < 0.06\% can be expected.

Since the main linac in the current ILC design follows the Earth curvature, a spin precession
of about 26 degrees is expected and the ratio between final and initial polarizations is about
\(\cos(10^{-4}\text{rad})\) [30].

4. Conclusions

Polarized beams are required to achieve the physics goals, to maximize the results and is a basic
ingredient for many present and future accelerator designs. The ILC provides already in the
baseline a polarized \(e^-\) source with about \(P_{e^-} = 80\% - 90\%\) and a polarized \(e^+\) beam with about
\(P_{e^+} \sim 30\%\), extendable to at least \(P_{e^+} \leq 60\%\), using undulator radiation as \(e^+\) source. The
scheme has been successfully tested at the E166 experiment and several undulator prototypes
have been accomplished that already achieve the ILC requirements.

Precise spin tracking is a substantial condition for successfully applying polarized beams for
physics. Much progress has been made describing spin tracking during beam-beam interactions,
in the damping ring, the main linac and the beam delivery system. Theoretical updates of the
used calculations and the description of coherent and incoherent background processes including
higher-order contributions have been accomplished. The analytically-based program CAIN has
also been correspondingly updated.

With the code SLICKTRACK several simulations for different ILC lattices have been
performed, showing that only small depolarization can be expected at the ML and in the
BDS, however, no full decoherence of horizontally spin components in the DR can be expected.
Properly alignment even for nominally unpolarized beams is therefore needed.

In order to guarantee that the produced polarization can be successfully analyzes=d for
physics analyses accurate polarimeters are needed. It is still under discussion which the frequency
for flipping the helicities between the possible polarization configurations is required. However,
in order to fulfil both the high-luminosity as well as the high precision goals for physics analyses
at the ILC, flipping of the helicities of the \(e^-\) beams as well as the \(e^+\) beam is absolutely
needed [9]. News on the positron source engineering design for the ILC and further polarization
issues can be obtained from the working group of the ILC positron source group, see also [10].

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