DEPOLARIZATION AND BEAM-BEAM EFFECTS AT FUTURE e^+e^- COLLIDERS

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Abstract

In order to exploit the full potential of proposed future high-energy electron-positron colliders, precise knowledge of the polarization state of the beams is required. In this paper we present an updated analysis of the depolarization effects caused by the intense beam-beam interaction, which is expected to be the dominant source of depolarization. The impact of higher-order effects are considered and numerical results from the Guinea-Pig and CAIN simulations are presented for the latest International Linear Collider (ILC) and Compact Linear Collider (CLIC) machine parameters.

INTRODUCTION

The full physics potential of the ILC can be realized only with polarized e^- and e^+ beams [1]. Polarized e^- with a degree of polarization between 80% and 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 and 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 [2].

The positron source undulator operates on the main ILC e^- beam generating circularly-polarised photons. An overview of a suitable full-scale superconducting undulator module is given in [3]. Polarized positrons are produced via an electromagnetic shower instigated by the circularly polarized radiation striking a thin target. The production target has to be carefully designed to cope with the high heat load and strong thermal stresses [4, 5].

Previously detailed studies had been carried out for the ILC RDR baseline design. There are significant changes proposed for the new SB2009 baseline with different beam parameters and in which the undulator is moved to the end of the linac [6]. Using the ILC baseline undulator, it was previously assumed that a e^+ polarization of about 30% to 40% would be achievable which could be used to enhance physics at the ILC Interaction Point (IP). However the SB2009 changes require extra collimation and fine tuning of parameters in order to maintain the baseline e^+ polarization and possibly even increase it to 60%. The undulator-based method has previously been experimentally verified by the E166 experiment [7].

The characteristics of the physics processes at the IP depend on the luminosity-weighted polarization of the beams. As the polarimeters can only measure the polarization either side of the IP, it is mandatory to model the depolarization processes expected during the beam interaction.

In the following sections we present first a theoretical consideration of the spin-dependent beam-beam processes at the IP, and second, numerical simulations for the ILC and CLIC parameter sets.

POLARIZATION EFFECTS DUE TO BEAM-BEAM PROCESSES

In order to perform precision spin tracking through the strong field environment at the IP collision, it is necessary to review the main processes currently modelled and the theoretical simplifications and omissions. These theoretical calculations take place using the Bound Interaction (or Furry) picture which use exact solutions of the Dirac equation for an electron of 4-momentum $(\epsilon, \vec{p})$ in the strong electromagnetic field of intensity Υ and 4-momentum $(\omega, \vec{k})$ of the pinched charge bunches at the IP.

The Beamstrahlung

The Beamstrahlung process transition rate includes a spin dependent term which leads to depolarization through spin flip. This effect is expected to be small with a depolarization of about 0.05%, cf. [8, 9]. However this depolarization increases with energy as seen in table 2.

The calculation of Beamstrahlung transition rate W is complicated by an integrand which diverges at its lower bound corresponding to the radiation of soft photons [10]

$$W = \frac{\alpha m^2}{\pi\epsilon\sqrt{3}} \int_0^\infty \frac{du}{(1+u)^2} \left[\int_\chi^\infty K_{5/3}(y)dy - \frac{u^2}{1+u} K_{2/3}(\chi) \right]$$

$$\text{where} \quad \chi = \frac{2u}{3\Upsilon} \tag{1}$$

The divergence can be mitigated by inclusion of the electron self energy in the charge bunch field.

Spin precession

The spin precession is a classical effect but strong field quantum effects enter through the anomalous magnetic moment in the charge bunch field which we label a_e. Spin precession is described by the Thomas-Bargmann-Michel-Telegdi (T-BMT) equation:

$$\frac{\mathrm{d}\vec{S}}{dt} = -\frac{e}{m\gamma}[(\gamma a_e + 1)\vec{B}_T + (a_e + 1)\vec{B}_L \tag{2}$$

$$-\gamma(a_e + \frac{1}{\gamma+1})\beta\vec{e}_v \times \frac{\vec{E}}{c}] \times \vec{S} \tag{3}$$

The anomalous magnetic moment in the external field, which is different from the usual anomalous magnetic moment, has been calculated using the quasi-classical approximation for ultra-relativistic particles [11] and with Volkov solutions [12]. In both cases the spin dependent Mass Operator was utilised to obtain a^e. Higher order corrections to a^e can be obtained using equivalent processes within the Furry picture. To that end a calculation of the Vertex Correction in the charge bunch field, as a first step, is underway.

Incoherent processes

The spin dependent incoherent processes are currently simulated within the CAIN program [13] and involve the interaction of real beamstrahlung photons and/or virtual photons via the equivalent photon approximation [14]. The production of background pairs is strongly dependent on the polarization state of the initial photons. Though having little effect on the depolarization, the spin tracking for pair processes is important for reasons of background suppression and the related impact on the accelerator and detectors.

For incoherent pair production with real photons, the spin dependent Breit-Wheeler cross-section, obtained in the normal interaction picture, is used. Specific initial particle polarization states specified by stokes vector components ξ_i are required, however in CAIN only the second Stoke's vector components ξ_2 is included. The full cross-section however is a sum over terms containing all possible combinations of Stoke's vectors components [15, 16]. The CAIN program was modified accordingly.

The inclusion of polarization vectors in interactions with virtual photons (the Bethe-Heitler and Landau-Lifshitz processes) is problematic since the polarisation state of the virtual photon must be estimated. However virtual photon polarisation can be identified with the spectral component of the charge bunch electric field field density at the point of interaction [16, 17].

Coherent processes

Coherent processes are considerd in the Furry picture using Volkov solutions. The coherent production of pairs via the first order interaction between a beamstrahlung photon and beam field is included already in CAIN. The contribution is small for a machine specified by the SB2009 parameters, but overwhelmingly large for the proposed CLIC 3 TeV machine parameters, and corrections obtained from the Vertex Correction in the charge bunch field are being calculated.

Since the charge bunch field can act as a source of energy, then new effects in which colliding charges absorb energy are possible. The specific process under consideration is the 1-vertex (in Furry picture Feynamn diagrams) photon absorption process. Since the transition rate for this process is of the same order in the coupling constant as the Beamstrahlung, one must assume in the first instance that its contribution to the depolarization will be of the same order as the Beamstrahlung contribution.

Second order coherent processes are also possible, though not yet simulated, and include the Breit-Wheeler type pair production and the Compton Scattering in the charge bunch field. Each of these can contribute to the depolarisation. Naively, in comparison to the first order coherent process, the second-order cross-sections are diminshed by an order of the fine structure constant. However the charge bunch field has the effect of allowing the bound virtual lepton to reach the mass shell. The resulting resonances are rendered finite by inclusion of the electron self-energy in the external field and the second order transition rates can exceed those of the first order [18].

IP SPIN TRACKING SIMULATIONS

In general, two effects influence the spin motion in electric and magnetic fields: a) spin precession governed by the Thomas-Bargmann-Michel-Telegdi (T-BMT) equation and b) the spin-flip Sokolov-Ternov (S-T) effect via synchrotron radiation emission. Usually the spin precession effect is dominant, but at higher energy the depolarization due to the S-T effect increases [9]. The CAIN program was used to model both of these depolarization effects. In addition, models of the two kinds of background processes that occur during beam-beam interactions, the production of incoherent and coherent e^+e^- pairs, are also included.

The difference between the initial beam polarisation and the luminosity-weighted beam polarisation of the beams (ΔP_{lw}) have been evaluated for the ILC RDR baseline parameters [2], CLIC-G 2008 and CLIC 2010 designs [19] shown in table 1. A summary of the results obtained using CAIN are shown in table 2. In the ILC design, the predicted low values of the field strength parameter, υ, result in very small effects from the coherent first-order background pairs. At higher energy and also for the CLIC designs with much higher beamstrahlung, significant contributions from the coherent pairs are expected.

The absolute statistical uncertainties on the values of ΔP_{lw} calculated from CAIN are approximately 0.10%. Simulations using the CLIC 2010 parameter set and the Guinea-Pig simulation give values of ΔP_{lw} within 10% of the CAIN values if the contribution from coherent pairs is not included in the luminosity-weighted average.

Depolarisation results from simulations of the ILC SB2009 parameter set are not included here as CAIN does not yet implement the travelling focus required to achieve high luminosity in this design.

The inclusion within CAIN of the incoherent pair producing processes with a complete set of spin components (described above), allows a detailed examination of the impact of polarised beams on beam-beam pairs arising from the IP. This study was carried out for the SB2009 parameter set which, compared to ILC RDR baseline, specifies a stronger charge bunch field and attendant spin tracking effect. A significant reduction in low-energy pairs results, with overall pair numbers reduced by 17% (Fig. 1).

Table 1: Parameters sets for the ILC and the CLIC designs.

	ILC RDR	CLIC-G	CLIC 2010
$\sqrt{s}$/GeV	500	3000	3000
N /10^{10}	2	0.37	0.37
n_B	2625	312	312
$\gamma\epsilon_x^*$/mm mrad	10	0.66	0.66
$\gamma\epsilon_y^*$/mm mrad	0.04	0.02	0.02
β_x^*/mm	20	4.0	6.9
β_y^*/mm	0.4	0.09	0.068
σ_z/μm	300	45	44
$\mathcal{L}_{99\%}/10^{34}\text{cm}^{-2}\text{s}^{-1}$	2.0	2.0	2.0

Table 2: Comparison of the luminosity-weighted depolarizing effects in beam-beam interactions for the ILC RDR and for the CLIC-G and CLIC 2010 parameter sets with fully polarised incident beams. T-BMT (S-T) denotes effects due to spin precession (synchrotron radiation).

Parameter set	Depolarization ΔP_{lw}		
	ILC	CLIC-G	CLIC 2010
T-BMT	0.17%	0.10%	0.09%
S-T	0.05%	3.40%	3.81%
incoherent	0.00%	0.06%	0.00%
coherent	0.00%	1.30%	1.51%
total	0.22%	4.80%	5.53%

CONCLUSION

An analysis of depolarization and higher-order processes during the beam-beam interaction at a linear collider has been carried out.

In line with previous studies, the ILC RDR baseline is predicted to result in, neglecting theoretical uncertainty, a depolarization of $0.22 \pm 0.1\%$. For the current CLIC-G parameters, a much higher depolarization of $5.53 \pm 0.1\%$ is expected due to the strong beamstrahlung and higher Υ parameter.

The current CAIN implementation used in this study includes updates allowing for full polarization of beamstrahlung photons that create background pairs. Studies of beam-beam pair production with full spin tracking shows a significant suppression of low energy pairs of 17% for the SB2009 parameter set. The inclusion of additional spin tracking processes in CAIN is ongoing.

New theoretical studies are currently underway for higher order corrections to the T-BMT and spin flip processes in the strong field environment of the IP beam-beam interaction. Both the anomalous magnetic moment in the charge bunch field as well as other spin-dependent processes are being evaluated using the Volkov solution for the particle wave function in an external field. These studies become particularly relevant at higher energies and for a high beamstrahlung parameter Υ, such as those in the SB2009 parameter set (compared to the ILC RDR baseline) and the CLIC machine.

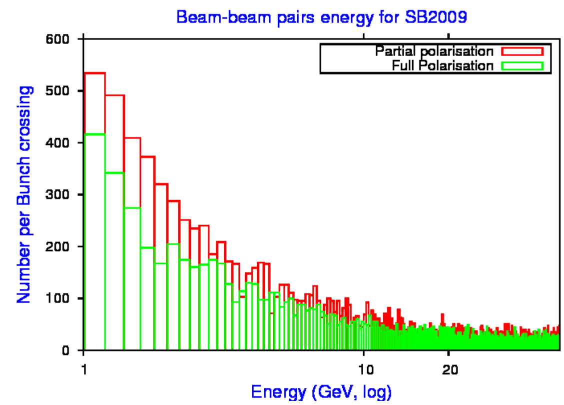

Figure 1: SB2009 beam-beam pairs with spin tracking.

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