arXiv:physics/0512192 v1 21 Dec 2005

Monte Carlo based studies of a polarized positron source for International Linear Collider (ILC)

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The full exploitation of the physics potential of an International Linear Collider (ILC) requires the development of a polarized positron beam. New concepts of polarized positron sources are based on the development of circularly polarized photon sources. The polarized photons create electron-positron pairs in a thin target and transfer their polarization state to the outgoing leptons. To achieve a high level of positron polarization the understanding of the production mechanisms in the target is crucial. Therefore a general framework for the simulation of polarized processes with Geant4 is under development. In this contribution the current status of the project and its application to a study of the positron production process for the ILC is presented.

1. Introduction

A future International Linear Collider (ILC) provides an outstanding tool for the precise exploration of physics at TeV scale [1]. In contrast to hadron colliders, the well defined initial state and the cleanliness of the final states allow for a precise measurement of Standard Model and new physics processes. Having both, positron and electron, beams polarized will be a decisive improvement for physics studies. A recent review of the physics case of ILC using polarized positrons can be found in [2].

One possible layout for the production of polarized positrons is sketched in figure 1. Circularly polarized photons are created by sending the electron beam through a *helical undulator* [3]. In a thin target the photons are converted into polarized positrons via pair creation. In comparison to a conventional positron source this method substantially reduces the heat load in the positron target.

A demonstration experiment to quantify the yield of polarization of an undulator based positron source, E166 [4], is currently performed at SLAC. The experience gained with E166 is decisive for designing and optimising the polarized positron source of the ILC. The precise simulation of the positron production as well as the polarimetry processes is essential for a complete understanding of the data obtained at E166. A simulation toolkit for the investigation of polarized processes based on Geant4 is currently under development. In this contribution a status report of this project is given.

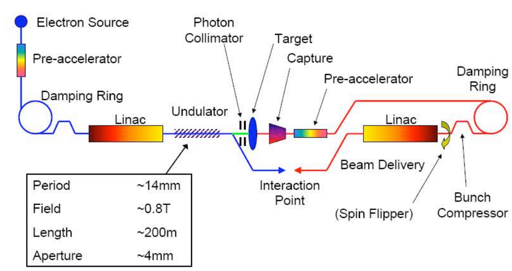

Figure 1. Possible layout of an ILC. Polarized positrons are created from polarized photons produced in a *helical undulator*.

2. Implementing polarization into Geant4

Geant4 is a toolkit for the simulation of the passage of particles trough matter [5]. Individual particles are tracked step by step and each step can lead to creation of particles, destruction of particles, or to a modification of the particle properties. The aspect of polarization has so far been widely neglected [1]. With our extension it will be possible to track also polarized particles (leptons and photons). Special emphasis will be put in the proper treatment of polarized matter, which is essential for the simulation of positron polarimetry. It is planned to create a universal framework for polarization and to implement it in an official GEANT4 release.

To realise this project, the following polarization dependent processes have to be considered

- Compton scattering,
- Bhabha/Møller scattering,
- Pair creation,
- Bremsstrahlung.

In addition to these well localised interactions, the influence of magnetic fields on the electron (or positron) spin has to be treated properly.

In the following section, a brief review of existing simulation tools for polarization transfer is given. In the subsequent sections the proposed framework for GEANT4 is presented.

2.1. Existing codes for the simulation of polarized processes

Several simulation packages for the realistic description of the development of electromagnetic showers in matter have been developed. A prominent example of such codes is EGS (Electron Gamma Shower)[6]. For this simulation framework extensions with the treatment of polarized particles exist [7,8,9]; the most complete has been developed by K. Flöttmann [7]. It is based on the matrix formalism [10], which enables a very general treatment of polarization. However, the Flöttmann extension concentrates on evaluation of polarization transfer, i.e. the effects of polarization induced asymmetries are neglected, and interactions with polarized media are not considered.

Another important simulation tool for detector studies is GEANT3 [11]. Here also some effort has been made to include polarization [4,12], but these extensions are not publicly available.

[1] The only polarized process supported by the current release of GEANT4 is Compton scattering of linear polarized, low-energy photons on an unpolarized target.

2.2. Polarization framework for Geant4

The package GEANT4 is the newest member on the simulation front. It is entirely written in C++. It has a wide range of application, and slowly replaces the Fortran based simulation toolkits.

The proposed implementation of polarized processes is based on Stokes vectors and allows a convenient description of the polarization transfer by the matrix formalism [10]. In this formalism, a three-component *polarization vector* $\boldsymbol{\xi}$ is assigned to each particle and characterises completely the polarization state of any lepton or photon[2]. For the simulation of polarized media, a possibility to assign Stokes vectors to physical volumes has to be provided in GEANT4. This is handled by a new class, the so-called *polarization manager*. It also allows the evaluation of Stokes vectors in different frames of reference.

The general procedure is very similar to the polarization extension to EGS by Flöttmann [7]. Any interaction is described by a transfer matrix T, which characterises the process completely. It usually depends on kinematic variables like energy and angle, but it can also depend on polarization states (e.g. of the media). The final state polarization $\boldsymbol{\xi}$ is determined via matrix multiplication with the incoming Stokes vector $\boldsymbol{\xi}_0$,

$$\begin{pmatrix} I \\ \boldsymbol{\xi} \end{pmatrix} = T \begin{pmatrix} I_0 \\ \boldsymbol{\xi}_0 \end{pmatrix} . \tag{1}$$

The components I_0 and I refer to the incoming and outgoing intensities, respectively. In this framework the transfer matrix T is of the form

$$T = \begin{pmatrix} S & A_1 & A_2 & A_3 \\ P_1 & M_{11} & M_{21} & M_{31} \\ P_2 & M_{12} & M_{22} & M_{32} \\ P_3 & M_{13} & M_{23} & M_{33} \end{pmatrix} . \tag{2}$$

[2] This vector is already present in the current release of GEANT4, but it is only used in low-energy Compton scattering of linear polarized photons. The interpretation as Stokes vector allows for the usage in a more general framework.

The matrix elements T_{ij} can be identified as (unpolarized) differential cross section (S), polarized differential cross section (A_j), polarization transfer (M_{ij}), and (de)polarization (P_i). In the Flöttmann extension the elements A_j and P_i have been neglected, thus concentrating on polarization transfer only. Using the full matrix takes now all polarization effects into account. The structure is illustrated with a few examples in the following section.

3. Applications

Here, some preliminary results shall illustrate the field of application.

3.1. Polarized Compton scattering

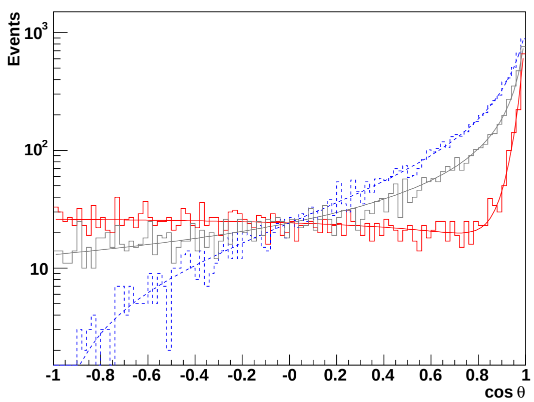

Figure 2. Comparison of the GEANT4 implementation (histogram) of polarized Compton scattering with an analytic formula (solid lines). The graph shows the dependence of the scattering angle on the polarization states of target (electron) and beam (photon).

The first process studied is Compton scattering. This process possesses all basic features: a polarization dependent differential and total cross section, polarization transfer and depolarization effects. Compton scattering is of great importance in polarimetry.

In figure 2 the angular distribution of the scattered photon is presented. For this simulation

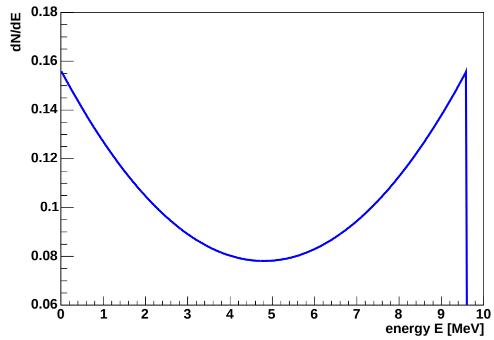

Figure 3. First harmonic of the photon energy distribution as created by a *helical undulator* [3], for electron energy E_e =50 GeV, undulator period λ_u =2.4 mm and undulator strength parameter K =0.17. The peak of the first harmonic (dipole) radiation is at 9.62 MeV.

a 100% circularly polarized photon beam and a 100% longitudinally polarized iron foil is assumed[3]. When flipping the electron spin from an anti-parallel configuration with respect to the photon spin (blue) to a parallel orientation (red), the distribution changes drastically, and the total cross section decreases. For illustration, the case where both, target and beam, are unpolarized is also plotted (black). A comparison with an analytic formula (solid lines) shows perfect agreement in all cases.

In a next step a more realistic simulation of target properties will be performed to study the effects of different polarized processes.

3.2. ILC positron source studies

The polarization transfer in a undulator based positron source has been investigated. Since the target is unpolarized, the total cross section, i.e. the interaction length, does not depend on the photon polarization. Consequently it is sufficient to concentrate on the polarization transfer from incoming photons to outgoing positrons.

The setup of the simulation consists of an incoming photon beam with the characteristic energy spectrum of a *helical undulator*, cf. fig. 3.

[3]Note, that this is an academic case, since the maximal degree of polarization in iron is $2/26 \approx 7.69\%$.

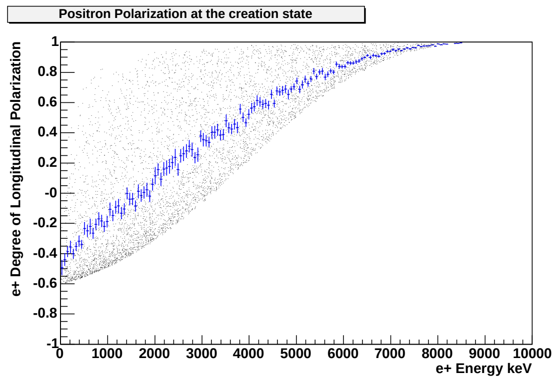

Figure 4. Degree of polarization of created positrons. The degree of polarization of the incoming photon beam is fixed to 100%, the energy spectrum of the photons is given in fig. 3. Each dot corresponds to a single answer of the transfer matrix. The mean degree of polarization is plotted as the (blue) profile histogram.

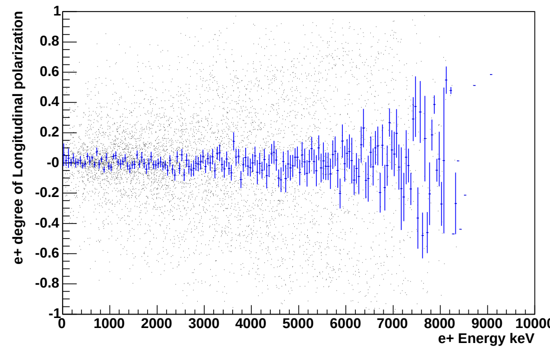

Figure 5. Check of the polarization routine: Degree of polarization of positrons created from randomly polarized photons.

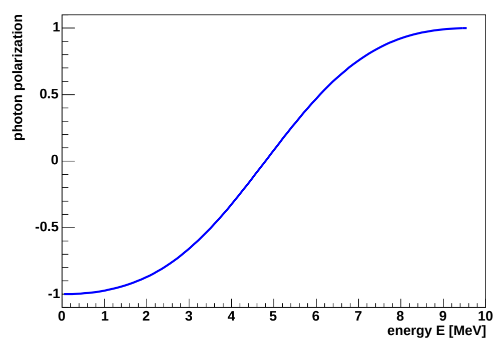

Figure 6. Degree of polarization of photons produced in a *helical undulator*.

As a first approximation, the polarization of the photon beam is assumed to be 100%. The degree of polarization of the positrons created in pair production depends also on the energies of the incoming photon and the outgoing positron. In general the degree of the positron polarization is increasing with the energy fraction of the created positron, see figure 4.

A simple first check of the polarization routine is provided by assuming an equal mixture of left and right circularly polarized photons as incoming beam. In this case one expects to obtain an unpolarized positron beam. Indeed, in figure 5 this behaviour can be observed.

Now the polarization spectrum of the *helical undulator* as plotted in figure 6 will be included in the study. The simulation shows the marginal influence on the obtained degree of positron polarization. In particular, high energy positrons are nearly 100% polarized, see figure 7.

For a realistic simulation of a polarized positron source based on a *helical undulator* the effects of bremsstrahlung, multiple scattering, Coulomb and screening correction have to be taken into account. In figure 8 the influence of these processes on the obtained positron energy spectrum is investigated. It is shown, that only a small fraction (green) of all produced positrons (blue histogram) will escape from the target. The energy spectrum of positrons that leave the target is shifted to lower values in comparison to their spectrum at the creation point (red). Consequently, the target acts as a filter for high energy positrons and the created positrons have suffered a substantial loss of energy. The effect of bremsstrahlung and multiple scattering on the degree of polarization of the produced positrons will be the subject of further investigations.

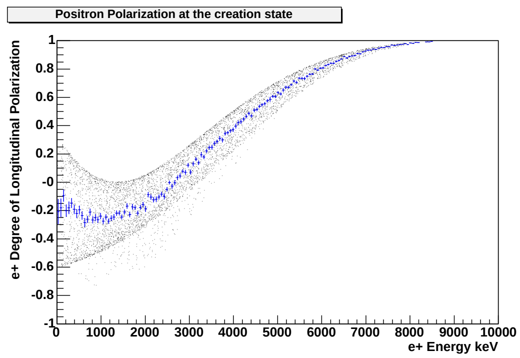

Figure 7. Degree of positron polarization created by photons produced in a *helical undulator* using a realistic spectrum of photon energy and photon polarization.

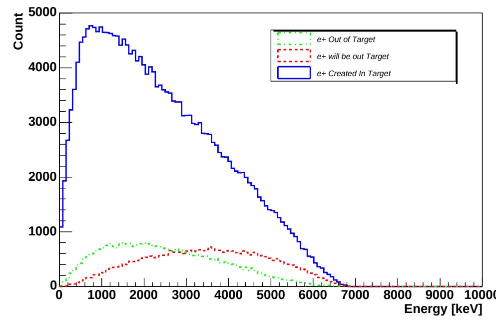

Figure 8. Positron energy distribution. The energy of all produced positrons at the creation point (blue) is compared with the energy of the positron fraction that will eventually manage to leave the target (red), and the energy of these positrons at the exit point of the target (green).

4. Conclusion

In this report the current status of a project to implement polarization into the framework of GEANT4 has been presented. For this task the Stokes formalism is employed, providing a systematic approach for a consistent treatment of polarized leptons and photons. Some preliminary results demonstrate the applicability of this new extension to polarimetry (Compton scattering) and polarization transfer studies (positron source). These analyses represent the first steps toward a realistic target simulation of an undulator based positron source for the ILC.

Acknowledgement

The authors are indebted to A. Stahl as the initiator of this project, and also like to thank T. Lohse for fruitful collaboration, and S. Riemann, P. Starovoitov and J. Suarez for helpful discussions. K.L. and A.S. are grateful for the assistance by K. Flöttmann and J. C. Liu concerning the EGS polarization extension. R.D. acknowledges support by the European Community (EUROTeV contract number RIDS 011899).

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