Acta Phys. Pol. B 38 (2007) 3589
DESY-07-203

arXiv:0712.2340v1 [hep-ex] 14 Dec 2007

DESY-07-203

Polarised positrons for the ILC*

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For the planned International Linear Collider it is intended to have both – electron and positron – beams polarised. This offers a great benefit for many physics studies, but also provides a challenge for the engineering of the machine. A polarised positron source that meets the machine parameters is topic of current design studies and prototype experiments.

1. Introduction

The International Linear Collider (ILC) is an electron-positron collider, currently being in the design phase. The nominal centre-of-mass energy is 500 GeV and the design luminosity is $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [1, 2], which makes the machine well adapted for precision studies of the Standard Model (SM) and searches for new physics [3]. Machine upgrades include the extension of the energy range to 1 TeV, or a gamma-gamma and electron-gamma collider.

A key feature of the ILC is the possible polarisation of both beams (electrons and positrons), which was shown to be of paramount importance for many physics studies. But producing a high intensity polarised positron beam proved to be a challenge.

The degree of polarisation for the electron beam is expected to be at least 80%. For the positron beam, an undulator based source will provide a degree of 30% from the start, which will be improved to 60% in a future upgrade of the machine.

2. Physics with polarised positrons

The physics potential of the ILC utilising polarisation of electron and positron beam has been investigated in great depth [4]. Here we like to give only a brief motivation and perhaps an answer to the question: Why do we need polarised positrons?

* Presented at the XXXI International Conference of Theoretical Physics, "Matter to the Deepest", Ustroń, Poland, September 5–11, 2007.

P_{e^-},	P_{e^+}	$P_{\rm eff}$	$(1 - P_{e^+}P_{e^-})$	$\Delta P_{\rm eff}/P_{\rm eff}$
0%,	0%	0%	1.00	1.00 $\Delta P/P$
−80%,	0%	−80%	1.00	1.00 $\Delta P/P$
−80%,	+30%	−89%	1.24	0.57 $\Delta P/P$
−80%,	+60%	−95%	1.48	0.35 $\Delta P/P$

Table 1. Effective luminosity, effective polarisation and its uncertainties for different beam polarisation setups.

The first features that are usually addressed in this context are *higher effective luminosity and higher effective polarisation*: When electron and positron annihilate into a vector particle (e.g. γ/Z^o), only two helicity combinations contribute to the total cross section. Thus it is possible to write the polarisation dependent cross section as

$$\sigma_{p_{e^-}p_{e^+}} = (1 - P_{e^+}P_{e^-})\ \sigma_0\ [1\ -\ P_{\rm eff}\ A_{\rm LR}]\ , \qquad P_{\rm eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}}\ ,$$

where $\sigma_0 = (\sigma_{\rm RL} + \sigma_{\rm LR})/4$ denotes the unpolarised cross section, and $A_{\rm LR} = (\sigma_{\rm LR} - \sigma_{\rm RL})/(\sigma_{\rm LR} + \sigma_{\rm RL})$ gives the left-right asymmetry. The prefactor $(1 - P_{e^+}P_{e^-})$ is an effective luminosity increase. It can be seen that in case of no positron polarisation, the effective polarisation $P_{\rm eff}$ reduces to the electron polarisation P_{e^-}, on the other hand if positron polarisation P_{e^+} is present, the effective polarisation is increased (see also Table 1). But the most important aspect is a reduced dependence on the polarimetry uncertainties. In fact a measurement of the weak mixing angle $\sin\theta_{\rm eff}$ with a precision of $\mathcal{O}(10^{-5})$ is only possible by having both beams polarised.

Another important application of positron polarisation is the *reduction of backgrounds*. For example the process $e^+e^- \to W^+W^-$, which constitutes an important background to many beyond the SM physics analyses, can be reduced by factor 10 when the corresponding electron (+80%) and positron (-60%) polarisations are employed.

Positron polarisation can also help in the *separation between models of new physics*, by a direct probe of the spin in resonance productions, which may occur in R-parity violating SUSY scenarios (e.g. $e^+e^- \to \tilde{\nu}_\tau \to \mu^+\mu^-$) or via heavy gauge boson exchange ($e^+e^- \to Z' \to \mu^+\mu^-$) [4, 5].

Furthermore, polarised positrons provide an unique possibility for the understanding of non-standard couplings. For example, in the super-symmetric extension of the SM the separation of $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm L}$ and $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ is only possible with both beams being polarised [4].

Other aspects of polarisation of both beams include *transverse polarisation*, which might prove helpful for the identification signatures of extra dimensions in fermion production [4, 6].

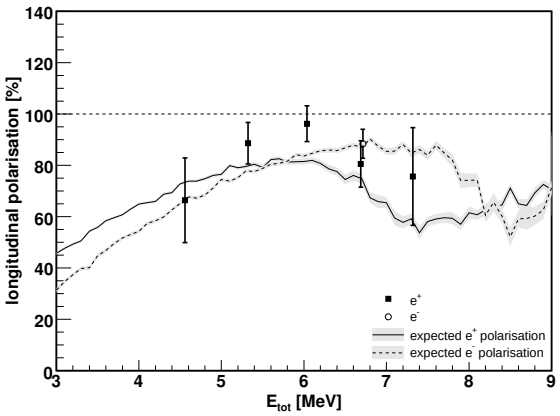

Fig. 1. Preliminary E166 results of positron (and electron) beam polarisation.

3. The E166 experiment

In the baseline design of the ILC [2] polarised positrons are produced from circularly polarised photons created in an helical undulator hitting a thin Ti target. The spin of the photon is transferred to the electron-positron pairs produced, resulting in a net polarisation of the particles emerging from the target. The positrons are captured just behind the target in a dedicated capture optics, i.e. an adiabatic matching device, and their degree of polarisation has to be maintained until they reach the collision point.

A proof-of-principle experiment to demonstrate production of polarised positrons in a manner suitable for implementation at the ILC has been carried out at SLAC [7]. A helical undulator of 2.54 mm period and 1-m length produced circularly polarised photons of first harmonic endpoint energy of 8 MeV when traversed by a 46.6 GeV electron beam. The polarised photons were converted to polarised positrons in a 0.2-radiation-length tungsten target. The polarisation of these positrons was measured at several energies using a Compton transmission polarimeter. Yield and polarisation of the photon beam was also continuously monitored.

The experiment collected data during June and September 2005. The measured asymmetries in the positron and photon polarimeters were translated into polarisation, using the analysing power obtained in Geant simulations. Preliminary results [8, 9] show good agreement with the expectations. In Figure 1 the measured degrees of polarisation of positrons for 5 different energy points are presented. At one energy point also the electron polarisation has been measured. The results are compared with expectations obtained by Geant4 simulations using the new EM polarisation extension.

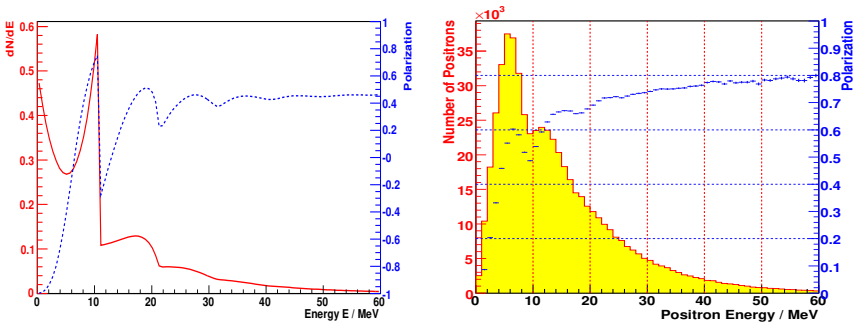

Fig. 2. Left: Energy (solid) and polarisation (dashed) of photons created in a helical undulator. Right: Energy (histogram) and polarisation (dashed line) of positrons after the production target of thickness $d = 0.4X_0$

4. Polarised Geant4

Programs that can simulate the complex interaction patterns of particles traversing matter are indispensable tools for the design and optimisation of particle detectors. A major example of such programs is Geant4 [10, 11], which is widely used in high energy physics, medicine and space science. Different parts of this tool kit can be combined to optimally fulfil the users needs. A powerful geometry package allows the creation of complex detector configurations. The physics performance is based on a huge list of interaction processes. Tracking of particles is possible in arbitrary electromagnetic fields. However, polarisation has played only a minor role so far.

Starting with version 8.2 a new package of QED physics processes has been added to the Geant4 framework, allowing studies of polarised particles interactions with polarised media [12, 13, 14].

The implementation of polarisation in the library in Geant4 follows very closely the approach by [15]. A *Stokes vector* is associated to each particle and used to track the polarisation from one interaction to another. Five new process classes for Bhabha/Møller scattering, electron-positron annihilation, Compton scattering, pair creation, and bremsstrahlung with polarisation are now available for physics studies with Geant4. The implementation has been carefully checked against existing references, alternative codes, and dedicated analytic calculations.

Applications include design and optimisation of a polarised positron source and beam polarimetry for a future linear collider facility. Figure 2 shows the energy spectrum and degree of polarisation for photons created in helical undulator with strength $K = 1$ and period $\lambda = 1\,\mathrm{cm}$, as well as the corresponding energy and polarisation spectra for the produced positrons.

5. Summary

Having not only the electron beam but also the positron beam polarised is highly advantageous for most physics studies, vital for many precision measurements, and essential for model analyses. The E166 experiment successfully demonstrated the undulator based production scheme for polarised positrons. A newly developed extension to Geant4 now allows to simulate the interactions of polarised particles with (polarised) matter, which are already used in many ongoing R&D around the polarised positron source.

Acknowledgements

The author likes to thank all colleagues involved in R&D of the ILC positron source. Particular thanks goes to my collaborators in the E166 experiment, the LEPOL Collaboration, and the Geant4 Collaboration.

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