Low Energy Positron Polarimetry for the ILC

R. Dollan[1]*, G. Alexander[2], T. Lohse[1], S. Riemann[3], A. Schälicke[3],
P. Schüler[4], P. Starovoitov[5], A. Ushakov[3]*

1- Humboldt Universität zu Berlin - Institut für Physik
Newtonstr. 15, 12489 Berlin - Germany

2- Physics Department, Tel Aviv University,
Tel Aviv 69978 - Israel

3- DESY in Zeuthen
Platanenallee 6, 15738 Zeuthen - Germany

4- DESY in Hamburg
Notkestr. 85, 22603 Hamburg - Germany

5- National Center for Particle and High Energy Physics,
Bogdanovitch street 153, 220040 Minsk - Belarus

For the International Linear Collider (ILC) a polarized positron source based on a helical undulator is proposed. In order to control and optimize the degree of positron polarization a low energy polarimeter at the source is required. Methods to measure the positron polarization near the creation point are currently under study and will be discussed in this contribution.

Introduction

The physics potential of the ILC will be substantially broadened if both beams - the electron and the positron beam - are polarized [2]. But in comparison to polarized electrons the generation of polarized positrons is a challenge. Polarized electron sources based on photo emission from GaAs induced by circularly polarized laser photons are operating and deliver electron polarization $P_{e^-} > 80\,\%$ [3]. Regarding polarization, the SLC polarized electron source [4], for example, already meets the ILC requirements. For the production of polarized positrons a helical undulator based system is foreseen for the ILC [5–7]. Circularly polarized photons are created by an electron beam traversing a helical undulator. The photons hit a thin target producing electron-positron pairs and the circular polarization of the photons is transferred into longitudinal polarization of the created e^+e^- pairs. After being captured, pre-accelerated and separated from the electrons and the initial photon beam the positrons are transported to the damping ring and finally to the interaction region while the beam polarization has to be maintained.

At the interaction region the beam polarization will be measured with high accuracy ($\approx$0.25 %) [8, 9]. However, for the optimization of the positron beam polarization as well as for the control of polarization transport also the degree of polarization near the positron source should be known at least with an accuracy of a few percent. Although an absolute polarization measurement is preferred, a low energy polarimeter should at least measure the relative beam polarization. It should be easy to handle, robust and fast.

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Table 1 shows the beam parameters at the positron source. Several methods to measure the polarization of such beam have been considered. To evaluate the feasibility and the performance of the respective methods simulation studies have been performed using GEANT4 with polarization extension [10, 11]. This extension was developed to describe the interaction of polarized beams with polarized matter.

Parameter	value
e^+/bunch, N_{e^+}	$2 \cdot 10^{10}$
bunches/pulse, N_b	2620
Rep. Rate, f_{rep}	5 Hz
Energy, E	30 - 5000 MeV
Energy spread, $\Delta E/E$	10 %
Normalized emittance, ε^*	$\sim$ 3.6 cm
Beam size, $\sigma_{x,y}$	$\sim$ 1 cm

Table 1: Beam parameters at the positron source based on the RDR design values [5].

Polarimeter options

Most polarization measurements are based on the same principle: the polarized beam to be measured hits a polarized target (beam or fixed target). The scattering process is spin dependent hence the counting rates or the distribution of the scattered particles differ for different spin orientation of the beam particles and an asymmetry can be measured. This asymmetry depends also on the target polarization, thus, knowing the latter the beam polarization can be determined.

Laser Compton Polarimeter

A laser Compton polarimeter will be used to measure the polarization at the interaction region of the ILC [5]. The photons of a high intensity laser hit the low emmitance positron or electron beam and are backscattered. The distribution of the scattered photons depends on the initial polarization of the positron or electron beam as well as on the laser polarization. Polarimeters of this type provide very high precision and were used, e.g. at SLC [12] and at HERA [13]. However, this method is not applicable for the low energy positrons at the source. The size of the positron beam before the damping ring will be too large to achieve reasonable interaction rates (see also Table 1). Also the asymmetry in the angular distribution of the scattered photons is very small for energies of a few GeV or below. Recent studies showed, that Compton polarimetry is possible after the damping ring at an energy of 5 GeV [14].

Bhabha Polarimeter

The cross section of Bhabha scattering (Eq. 1) depends on the polarizations, P_{e^+}, P_{e^-}, of the initial state particles;

$$\frac{d\sigma}{d\Omega} \sim \frac{(1+cos\vartheta)^2}{16\gamma^2 sin^4\vartheta}\left\{\left(9+6cos^2\vartheta+cos^4\vartheta\right) - P_{e^+}P_{e^-}\left(7-6cos^2\vartheta-cos^4\vartheta\right)\right\}. \qquad (1)$$

If the incoming particles are longitudinally polarized, the maximal achievable asymmetry is $7/9\, P_{e^+}P_{e^-}$ at a scattering angle $\vartheta = \pi/2$ (CMS) (see Fig. 1). This method has been used to measure the polarization of electrons with Møller polarimeters, for example at SLAC and at the VEPP-3 storage ring [15–18]. Corresponding to the design of the ILC [5] a Bhabha polarimeter could be applied after the positron pre-acceleration where the positron energy is in the range between 125 MeV and 400 MeV [19–22].

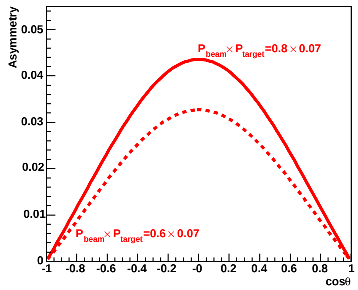


Figure 1: Two examples for the angular dependence of the Bhabha asymmetry (CMS, $P_{\text{beam}} = P_{e^+}, P_{\text{target}} = P_{e^-}$).

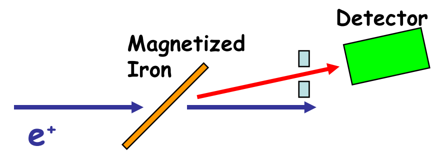
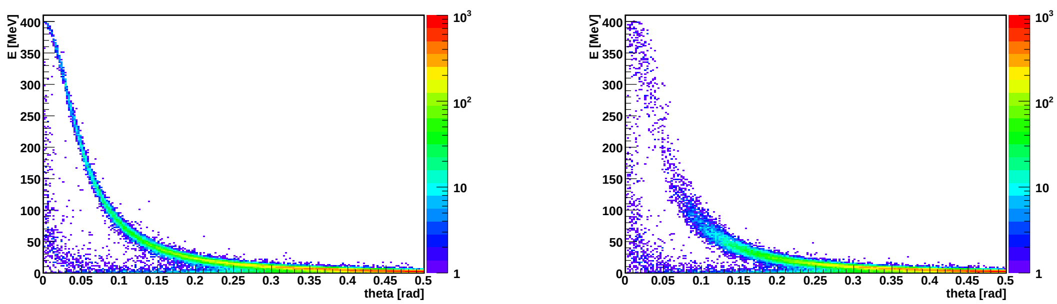


Figure 2: Sketch of a Bhabha polarimeter. Behind the target an appropriate mask system selects the angular range of interest.

Figure 2 shows the principle of a Bhabha polarimeter. The positron beam hits a thin magnetized iron foil. By reversing the target magnetization an asymmetry in the distribution of the scattered particles can be measured. Selecting only the scattered electrons, the background to the Bhabha process, which is dominated by Bremsstrahlung, can be significantly suppressed. First simulation studies have been done for energies of 200 MeV and 400 MeV.



(a) Target polarization $P_{e^-} = -100\%$.

(b) Target polarization $P_{e^-} = +100\%$.

Figure 3: The distribution of the Bhabha scattered electrons in bins of the energy E and the scattering angle ϑ (E_{beam}: 400 MeV, ΔE_{beam}: 10 %, target: 30 μm Fe).

Figure 3, for example, shows the distribution of the scattered electrons depending on their energy and the scattering angle for opposite target polarizations in the case of 400 MeV beam energy. The asymmetry of these two distributions is shown in Figure 4. It is obvious, that, in addition to the selection of the angular range of interest by an appropriate shi elding system, an energy spectrometer is needed. With optimal energy selection and angular cuts the average analyzing power is $A_{e^-}(P_{e^+}{=}100\,\%, P_{e^-}{=}100\,\%) \approx 40\,\text{-}\,50\,\%$ as the simulations show.

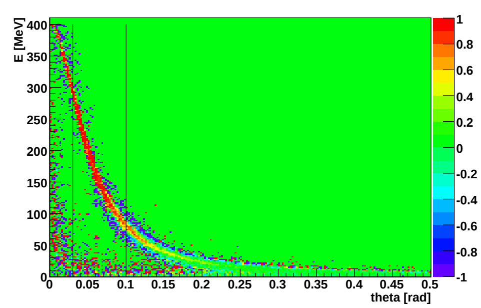


Figure 4: Asymmetry of the $E - \vartheta$ distribution of the Bhabha electrons. The vertical lines indicate the angular range of highest asymmetry.

To minimise the influence of multiple scattering in the target, the target foil should be as thin as possible. Estimations have shown that for the large beam size and the target thickness of about 30 μm the beam divergence is increased by less than 10 % for energies between 200 MeV and 400 MeV. So the low energy Bhabha polarimetry at the ILC positron source can be considered as almost non-destructive. A problematic issue is the heating of the target material. The temperature rise leads to a decrease in the magnetization of the target and thus to a reduction of the electron polarization. In an iron foil of 30 μm thickness hit by a 250 MeV beam with the parameters as shown in Table 1 a heat-up of approximately 10 K per bunch is obtained. Assuming cooling by radiation the target temperature reaches an equilibrium at $T_{eq} \approx 500$ K resulting in a reduction of the electron polarization to approximately 93 %. In addition, the distortion of the foil due to heating will have an influence on the accuracy of the measured asymmetry. To guarantee reliable measurements of the asymmetry the working temperature of the target has to be stable within relativ narrow limits.

Compton Transmission Polarimeter

An alternative method to measure the positron polarization is Compton transmission polarimetry. This method is based on the spin dependence of Compton scattering. The method is well known and has been used successfully at experiments at SLAC(E166) and KEK [6, 7, 23]. A fraction of the positron beam is sent onto a thick target (1 to 3 radiation lengths) of high Z-material and is converted via Bremsstrahlung into polarized photons. The photons traverse a magnetized iron block and undergo Compton scattering with the shell electrons of the iron atoms. Behind the iron the survival rate of the photons is measured (Figure 5). The transmission probability $T^{\pm}(L)$ for photons through the iron block of length L depends on the polarization state of the photons P_γ and the shell electrons $P_{e^-}^{Fe}$ in the iron:

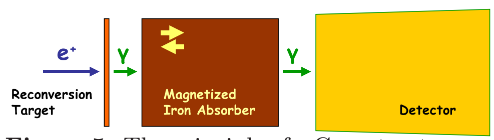


Figure 5: The principle of a Compton transmission polarimeter

$$T^{\pm}(L) = e^{-nL\sigma_0} e^{\pm nL P_{e^-}^{Fe} P_\gamma \sigma_P} \quad , \tag{2}$$

n is the number density of atoms in the iron and σ_0 and σ_p are the unpolarized and the polarized Compton cross sections, respectively. The magnetization of the iron block and thus the electron polarization $P_{e^-}^{Fe}$ is reversed and the positron polarization can be determined from the resulting asymmetry in transmission.

The working point of a Compton transmission polarimeter is at energies well below 100 MeV, hence the ideal position at the ILC would be located after the capture section at energies of about 30 MeV. At energies higher then a few tens of MeV the pair-production cross section becomes more and more dominant over the Compton cross section and the method becomes inefficient. The advantages of a polarimeter of this type are the compact dimensions (O($\sim$1 m)) and the simple and robust setup. Disadvantages are the high energy deposition (O($\sim$kW)) in the target hence only a fraction of the positron beam can be used for measurements. Finally, the asymmetries are very small ($A \lesssim 1$ %).

Simulation studies using the polarization extensions of GEANT4 [11] were performed to test the performance of a Compton transmission polarimeter at the ILC. The parameters and results of these simulations are shown in Table 2. The optimization of target and absorber regarding e.g. heating of the material, beam fraction to use for polarimetry etc. are subject of an ongoing study.

Simulation parameters:	
beam energy E_{beam}	30 MeV
target material	tungsten
target thichness	$2X_0$
Fe absorber thickness	15 cm
electron polarization P_{e^-}	7.92 %
Simulation results:	
positron polarization P_{e^+}	asymmetry A
30 %	≈ 0.4 %
60 %	≈ 0.8 %

Table 2: Results of a GEANT4 simulation for a Compton transmission polarimeter

Other options

Mott Polarimeter
Mott polarimeters measure transverse beam polarisation and are based on the electron scattering in the Coulomb field of heavy nuclei. Polarimeters of this type are widely used at operating energies of 10 eV to 1 MeV [24]. At higher energies (above ~10 MeV) the Mott scattering probability becomes very small and is dominated by Bhabha scattering and Bremsstrahlung. Furthermore, spin rotators would be needed to measure the longitudinal beam polarisation. Both facts make the Mott polarimetry not suitable for the ILC positron source.

Synchrotron radiation
The spin dependence of synchrotron radiation can be used to measure the transverse polarisation of positrons or electrons. This has been demonstrated at the VEPP-4 storage ring using a magnetic "snake" [25, 26]. At the ILC the method could be applied in the damping ring, where the positron energy is higher (5 GeV) and the beam polarization has to be transverse anyway. However, the effect is very small ($\sim 10^{-4}$ - 10^{-3} at $E_{beam} \approx$10 - 100 GeV [26]). In addition, the short storage period of the positrons in the damping ring (O(ms)) will make it difficult to reduce the systematic uncertainties sufficiently to observe this effect at all.

Summary

Options for a design of a **L**ow **E**nergy Positron **Pol**arimeter (LEPOL), to be placed at the ILC positron source have been described and discussed. The high intensity of the positron beam as well as it's large spatial extension limit the number of polarimeter options. A Bhabha polarimeter, measuring the asymmetry in the distribution of the scattered electrons, is a promising candidate for a positron polarimeter at the ILC source. A detailed design study for a LEPOL is in progress.

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