Design and optimization of a polarized positron source for future linear collider using Geant4

Sabine Riemann, Andreas Schälicke and Andriy Ushakov
DESY, Platanenallee 6, 15738 Zeuthen, Germany
E-mail: andreas.schaelicke@desy.de

Abstract. A polarized positron source is one of the key ingredients of a future linear collider. The source performance is decisive in order to reach the goals of the physics programme. But it is a challenge to develop a high-intensity polarized positron source, which meets the machine requirements. Simulation programs which can calculate expected yield, polarization are indispensable tools in these R&D projects. Based on the Geant4 framework a new tool, PPS-Sim (Polarized Positron Source Simulation), has been developed for design and optimization of a polarized positron source. This program is able to simulate common positron production mechanisms. It describes both the production of polarized positrons, and the spin transport in electromagnetic components in a single framework.

1. Introduction
A new generation of electron-positron colliders is currently in the design phase. Examples are the International Linear Collider (ILC) and the Compact Linear Collider (CLIC). The clean initial state of such an electron-positron collider allows precision measurements within the Standard Model and beyond. Prominent examples are the exploration of decay channels of a Higgs-boson, or measurements of supersymmetric particles, which cannot be performed at the currently operational Large Hadron Collider (LHC). In order to meet the physics goal for the ILC both beams—electron and positron—are expected to be polarized. In Table 1 a summary of key parameters of selected positron sources is given.

While the techniques needed to produce a high-intensity electron beam with high polarization are known, the development of a high-intensity polarized positron source is a challenge and is topic of current R&D projects. In the base-line design of the ILC, the positron production is based on the usage of a helical undulator. A high energy electron beam passing the undulator produces polarized photons in the MeV energy range. These photons then hit a rotating titanium target, where electron-positron pairs are created. The produced particles are also polarized. With the help of a dedicated capture optics (optical matching device), the positrons are focused and matched into an accelerating cavity.

The task is to design a positron source, which has high positron yield and polarization, and at the same time allows a safe and reliable operation.
Table 1. Comparison of positron source requirements.

|                        | ILC[1]       | CLIC[2]      | SLC[3]       |
|------------------------|--------------|--------------|--------------|
| No. of particles / bunch | $2 \cdot 10^{10}$ | $3.72 \cdot 10^{9}$ | $5 \cdot 10^{10}$ |
| No. of bunches / pulse  | 2820         | 312          | 1            |
| Repetition rate         | 5 Hz         | 50 Hz        | 120 Hz       |
| Total beam current      | 45 $\mu$A   | 9.3 $\mu$A   | 1.0 $\mu$A   |
| CMS energy              | 500 GeV      | 3 TeV        | 91.2 GeV     |
| Positron polarization   | 30–60 %      | -            | -            |
| Positron production scheme | Undulator   | Hybrid       | Conventional |

2. Polarized Positron Source Simulation (PPS-Sim)

The program PPS-Sim has been developed to provide an easy-to-use tool for design and optimization of a polarized positron source. It is based on the Geant4, ROOT and Qt4 libraries. Geant4 is used to simulate the electromagnetic shower in the target, the polarization transfer, and the particle and spin tracking in electromagnetic fields. ROOT is used to import external data, and to store and analyze the simulation results. Qt4 libraries are employed to provide a Graphical User Interface (GUI).

The main source elements are the primary beam, the conversion target, the Optical Matching Device (OMD) and the accelerator cavity (RF).

During program execution observables like yield and polarization are calculated. The outgoing particle spectrum can be stored, and used for post-processing analyses, or provide the input for other simulation software, e.g. lattice codes like BMAD[4] or Zgoubi[5].

The graphical user interface (GUI) is provided to steer the simulation, and modify most source parameters. Alternatively the program can be run in batch mode, using a simple Geant4 macro commands to setup the simulation process. The results are stored in ASCII, or ROOT files.

2.1. Physics of PPS-Sim

The physics foundation of PPS-Sim is provided by Geant4, which is a toolkit for the simulation of the interactions of particles with matter[6]. Geant4 is the basis for most detector simulations in the HEP domain, and it is also used in medical and astro-particle physics applications.

Geant4 contains a powerful geometry package, and allows the simulation of electromagnetic and hadronic showers. A visualization package and a graphical user interface complete the package. In the past years, different extensions have been developed, which allow to use Geant4 in studies of accelerator physics applications with polarized lepton beams.

With Geant4 version 9.2, electromagnetic processes describing the interaction of polarized electrons, positrons and photons have been included into the Geant4 framework[7]: Compton scattering, Bhabha/Møller process, photo effect, pair production, Bremsstrahlung, and positron-electron annihilation.

In addition, Geant4 allows the tracking of particles in electromagnetic fields. The precession of a spin $S$ in electrical field $E$ and magnetic field $B$ is governed by the T-BMT equation,

$$\frac{dS}{dt} = -\frac{e}{m\gamma} \left[ (\gamma a + 1)B_T + (a + 1)B_L - \gamma \left( a + \frac{1}{\gamma + 1} \right) \beta e_v \times \frac{E}{c} \right] \times S,$$

where $a \approx 1.159652 \cdot 10^{-3}$ is the electron magnetic moment anomaly.
2.2. Primary beam
The simulation of the positron source starts with a given spectrum of a primary beam, defined by energy, polarization, position, and momentum direction of the initial particles. PPS-Sim directly supports the generation of a photon beam from a helical undulator (undulator-based source), or an electron beam (conventional source). Alternative production schemes, like Compton or hybrid-target sources, can be incorporated using external input-files containing the particle spectra. Figure 1 shows the photon energy distribution for the case of an ILC positron source with the undulator placed at 150 GeV electron beam energy.

![Figure 1. Photon energy distribution and polarization for an ILC positron source with the undulator placed at 150 GeV.](image1)

For the undulator-based source the degree of positron polarization can be increased by placing a photon collimator between undulator and target. The collimator will decrease the photon yield, but the average polarization of the photons hitting the target will be increased. In PPS-Sim the collimator is implemented as a radial cut on the input spectrum. In Figure 2 positron yield and polarization are given for different collimator radii.

![Figure 2. Relative positron yield and polarization for different collimator radii.](image2)

2.3. Conversion target
The positrons are produced via pair-production from photons hitting a conversion target. The photons could be primary particles (e.g. undulator-based source), or secondary particles produced via Bremsstrahlung process (e.g. conventional source).

Different targets can be investigated: a solid disc target (e.g. a rotating wheel), or a target cell with windows (e.g. liquid lead target).

The peak energy deposition density (PEDD) in targets or windows is a key parameter for a reliable operation of a source. It is directly related to the development of shock-waves and radiation damage. A special running mode of PPS-Sim allows to determine PEDD distributions in the target, two examples are given in Figure 3.

![Figure 3.](image3)

2.4. Optical matching device (OMD)
The positrons leaving the conversion target are collected using an OMD. Three options have been implemented in PPS-Sim: adiabatic matching device (AMD), Lithium lens, and quarter wave transformer (QWT).

The AMD is a tapered solenoid with high field strength at the beginning and low field strength at the end. The field along the beam (and solenoid) axis \( B_0(z) \) can be described as

\[
B_0(z) = \frac{B_{\text{ini}}}{1 + g z},
\]
where $B_{ini}$ is the initial field and $g$ is the taper parameter. Typical values for ILC type AMD are $B_{ini} = 6$ T and $g = 30$ m$^{-1}$.

The field of the Lithium lens implemented in PPS-Sim is described by an analytical function. Assuming that the current $I$ in the lens has only a $z$-component and an equal density everywhere inside the lens, it is in cylindrical coordinates given by $B_z = B_r = 0$ and

$$B_\phi(r) = \frac{\mu_0 I r}{2\pi a^2}, \quad \text{for } r \leq a,$$

where $\mu_0$ is the permeability of free space, and $a$ the radius of the lens.

The QWT consists of two solenoids. The first one has a higher and the second a lower field. Currently, PPS-Sim assumes that the field inside the solenoids is constant and in the region between them is changed linearly.

The OMD is used to focus the produced positrons into the first accelerating structure. In the case of the ILC this will be a standing wave RF cavity surrounded by a solenoid providing a constant magnetic field. In PPS-Sim the RF field is approximated by a simple E-field with sinusoidal time and $z$-dependence. The strength of B- and E-field and the RF phase can be chosen freely.

3. Applications

The program can be used to study different positron production mechanisms. The default for the International Linear Collider is an undulator-based positron source, with an auxiliary low-intensity conventional source, i.e. based on an electron beam hitting the production target. Different alternatives are currently under investigation.

3.1. Compton scheme

One option is the Compton source, where circularly polarized photons are created from Compton scattering of a high-intensity low-energy electron beam inside a laser cavity. The backscattered photons have similar properties as undulator photons. A typical spectrum is shown in Figure 4. Using this input spectrum, the resulting positron properties can be calculated. An example is presented in Figure 5. The biggest problem is to produce a photon beam of high enough intensity, and this is topic of current research [8].
3.2. Hybrid Target

Another alternative is the production of a photon beam with a crystal Tungsten target [9]. If the electron beam axis is properly aligned with the crystal axis, the Bremsstrahlung spectrum can be enhanced. After the first target, a second—amorphous—target is used to produce electron and positrons from the Bremsstrahlung photons. Charged particles that are produced in the crystal target can be separated from the photon beam, using a dipole magnet. The aim of this configuration is to reduce the PEDD in the production target. The positrons created with this scheme are not polarized.

Figure 4. Photon energy and angular distribution of a Compton source.

Figure 5. Positron yield and polarization of Compton photons hitting a titanium target with varying thickness.

4. Summary

The development of Geant4 applications for positron source simulations allows to combine the positron production and tracking in one single tool. PPS-Sim is a flexible tool that includes a variety of source options. The undulator-based, conventional, Compton and hybrid-target schemes of positron generation can be simulated and optimized. The different primary beams, conversion targets and OMD’s can be selected. The graphical user interface is easy to use and to extend. The visualization of the geometry is useful for development and debugging. PPS-Sim is an open-source code and available for download from [10].

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