Simulation of positron production with EGS4 and Geant4

Stevan Arsenijević
Faculty of Physics
University of Belgrade
Studentski trg 12-16, 11000 Belgrade, Srbija
Email: arsen@ptt.yu

This report summarizes a study of a possible polarized positron source for the ILC project. We mainly concentrate on the use of a helical undulator for creating circularly polarized photons which hit the thin target to produce longitudinally polarized positrons. The simulation packages EGS4 and Geant4 were used to determine the yield, energy spectra and emission-angle distribution of the positrons produced within Ti an W targets. The EGS4 code system was also used to evaluate the mean polarization of outgoing positrons.

1 Introduction

1.1 ILC physics

The full exploitation of the physics potential of a future International Linear Collider requires the development of polarized positron beams. Having both beams polarized in a future high-energy e^+e^- collider offers many advantages like an increase of the signal over background, an enhancement of effective luminosity and a higher sensitivity for the detection of a non-standard model coupling. There are many difficulties in the production of a polarized positron beam and various techniques have been suggested. A very promising scheme for the technical realization is the use of a helical undulator.

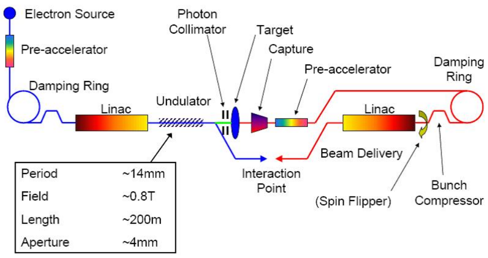

Fig. 1: *ILC machinery*

The general idea is to use an electron beam of about 250 GeV passing through a helical undulator and producing a beam of circularly polarized photons with energies of tens of MeVs. The same electron beam can be later used for collision with positrons, and a photon beam is converted in a thin target to positrons and electrons mostly by pair creation process. When a polarized photon creates an electron-positron pair in a thin target, the polarization state of the photon is transferred to the outgoing particles according to the expression given by Olson and Maximon [1] in 1959. The circularly-polarized photons created in the Undulator hit the target and create pairs of longitudinal polarized positrons and electrons. Most of the photons pass through target without interaction and keep their initial polarization which can be measured. One possibility to measure polarization of the positrons is to use Compton scattering after converting them back to photons which inherit the polarization of the positrons. That way we can determine the positron polarization by detecting the photons polarization.

In this report we also considered a polarized electron beam source for creating polarized positrons.

2 Methods

To study positron production from an electron or photon source, with a beam that has an energy of 50 MeV, hitting a thin Ti or W target, we used the Monte Carlo codes EGS4 and Geant4.

The main work is dealing with yield, energy spectra and emission-angle distribution. The EGS4 code was also used for polarization calculations, after implementing the Flöttmann polarization subroutine [2] into the existing EGS4 program with simple geometry. We compared our findings with results by J.C Liu and collaborators [3] at SLAC and achieved very good agreement.

2.1 Positron production

2.2 Physics processes

Basic photon interaction processes modeled by Monte Carlo code are pair production in the nuclear field, Compton scattering, photoelectric interaction and Rayleigh scattering. Photons can interact in the field of a nucleus and produce an electron-positron pair. A nucleus is required to conserve energy and momentum. This interaction scales as Z^2 for different nuclei, so materials with high atomic number convert photons into charged particles better than low atomic number materials. At energies of about 50 MeV, the pair production and bremsstrahlung interaction dominate. The pair production creates electrons and positrons, and the bremsstrahlung interaction of the electrons and positrons leads to more photons. That way we have a cascade process that convert high energy particles into large numbers of lower energy particles. For electrons passing through material basic processes are bremsstrahlung emission, Møller scattering ($e^-e^- \to e^-e^-$), Bhabha scattering ($e^+e^- \to e^+e^-$), positron annihilation ($e^+e^- \to \gamma\gamma$).

2.3 EGS4

EGS4 stands for Electron Gamma Shower Code Version 4 [4]. This simulation tool is written in MORTRAN / FORTRAN language. It was designed to simulate electromagnetic showers in various geometries for particles with energies above a few tens of keV up to a thousand GeV. Radiation transport of electrons, positrons or photons can be simulated in any element, compound or mixture. Both photons and charged particles are transported in steps of random length. The data preparation package PEGS4, creates data to be used by EGS, using cross section tables for elements 1 through 100. Materials were prepared with AE=0.521Mev, UE=60.0MeV, AP=0.01Mev, and UP=60MeV, being the upper and lower limit for electrons and photons respectively. Electron energy cutoff ECUT and photon energy cutoff PCUT for all regions were set at 1.511 and 1MeV, respectively. The materials we used are Ti and W In our simulation we assumed that the target is an infinite plane having the thickness of 0.2 radiation length or more, in the direction of the incoming particles, i.e. the z axis.

Flöttmann's polarization subroutine considers polarization transfer processes only in the bremsstrahlung, pair production and Compton reactions. The depolarization processes in other reactions, e.g., Bhabha, Møller and Rayleigh scattering, were not considered so the polarization we calculate is a higher estimation of the actual polarization. That is not so important when we have a photon beam, because pair production is the dominant process for yielding positrons. Møller (e^-e^-) is occurring only to electrons which after that don't have enough energy to create photons which create positrons and Bhabha (e^+e^-) was found to be very rarely occurring. Since we are interested in only high energy positrons (>25 MeV), Flöttmann's method is suitable. On the other hand, when we consider an electron beam, then Møller scattering is common, and only 10% of the produced positrons are produced from electrons that didn't went through that process. The neglection of this process in the polarization subroutine should be taken into account when analyzing the result of positron polarization, in the case of electron beam. The longitudinal polarization, the fourth Stokes parameter ξ_3 has a long term stability in an electromagnetic shower evolution.

In the following sections we consider positrons from the W and Ti targets (0.2 radiation length thick) hit by an electron or photon beam with 50 MeV kinetic energy, and a longitudinal polarization ξ_3, were analyzed after they left the target as a function of yield, energy-angle distribution and the polarization.

2.4 Geant4

Geant4 simulates electromagnetic and nuclear interactions during the passage of particles through matter, at energies from eV to TeV. Geant has been a FORTRAN software library package with functions for GEneration ANd Tracking of particles, but now Geant4 is a huge C++ software project developed by CERN and

Tab. 1: *Comparison of positron yield and mean longitudinal polarization for positron >25MeV.*

Beam	target	EGS4	Geant4	J.C Liu	mean pol.	mean pol. J.C Liu
electron	W	0.00061	0.00054	0.00048*	0.83	0.84*
electron	Ti	0.00046	0.00035	0.00035	0.85	0.86
photon	W	0.037	0.037	0.034*	0.84	0.88*
photon	Ti	0.033	0.033	NA	0.86	NA

* result given by J.C Liu [3] using W-Re target with 75% tungsten and 25% rhenium

KEK. It's a common tool used in nuclear, accelerator, space and medical physics. With respect to the size of the code and the number of contributors, it's considered the largest Monte-Carlo simulation of physical processes. It provides a complete set of tools for all domains of radiation transport: Geometry and Tracking, Physics processes and models, Biasing and Scoring, Graphics and User Interfaces, Propagation in fields. Among many advantages of Geant4 are that it can simulate geometries of complex setups efficiently and also enables user to tailor simulation component and address accuracy needs. The physics processes we considered in Geant4 for photons are pair production, Compton scattering and photoelectric effect. For electrons and positrons we have multiple scattering, ionization, bremsstrahlung and annihilation.

3 Results of investigations

Most of the calculations in EGS4 and Geant4 were made with 10^7 incoming particles, although EGS4 need 10 times less computational time for simulation than Geant4. In Table 1 we can see a comparison of high energy (>25 MeV) positron yield and mean polarization given for incoming electron and photon beam and two different materials, Ti and W, with thickness 0.2 radiation length. The results we obtained in EGS4 and Geant4 are almost the same for the photon beam but for the electron beam there is a difference. Also, when comparing to result from J.C Liu [3], it should be mentioned that they used Ti and W-Re alloy (75% tungsten and 25% rhenium) target. Still, there is a good agreement of Geant4 results and the one of J.C. Liu for electron beam. It can be noted that the same team in [5] has the result for positron yield 6.2×10^{-4} with electron beam hitting a W-Re target and that's the same as EGS4 result in this report. But, the most important result is that the high energy positron yield for incoming photons is ~80 times higher than of the electron beam, so from now on we'll concentrate on photon beam solely. The polarization of all produced positrons is in all cases about 50%, but for high energy ones it's above 80%. This result should be considered as a higher estimation of the real polarization, since not all processes have been taken into account.

3.1 Comparison of two programs

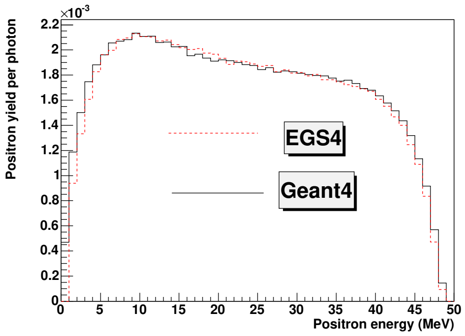

Fig. 2: *Comparison of EGS4 and Geant4 positron yield for photon 50 MeV beam hitting a 0.2 r.l. tungsten target.*

Figure 2 presents the comparison of energy distributions made with EGS4 and Geant4 for 0.2 r.l tungsten. We see pretty good agreement, so these two programs give almost the same energy and angular distribution. From now on we'll use EGS4 for simulation since it's much faster, being the older program written in the time when memory saving was important, and on the other hand Geant4 is more complex since it has a wider range of application.

3.2 Comparison of two materials

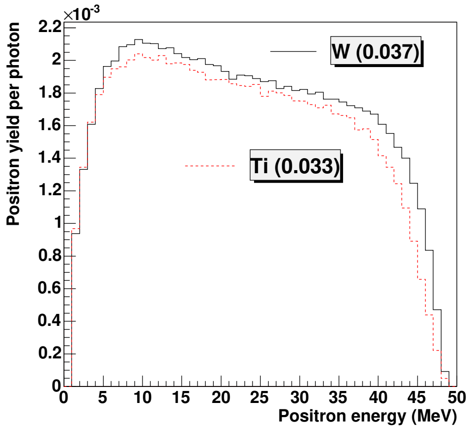

Fig. 3: *The positron energy spectrum from a 50 MeV photon beam hitting the W and Ti 0.2 r.l. target, with high energy positron yield.*

The positron energy spectrum from a 50 MeV photon beam hitting the W and Ti target, with high energy positron yield is shown in Fig. 3. Although two materials have different atomic number and radiation length (Ti Z=22, 1 r.l. =3.562cm ; W Z=74, 1 r.l. = 3.4mm) they have similar energy distribution for created positrons. Because of the cutoff energy one can see significant decrease of yield for low energy positrons.

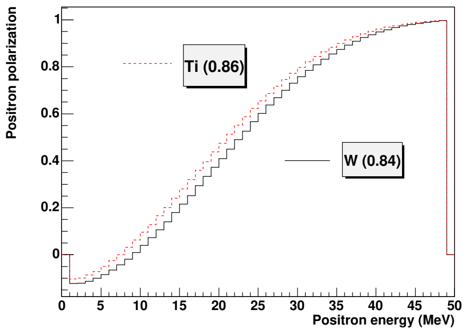

Fig. 4: *Longitudinal polarization of positrons as a function of positron energy, that escape W and Ti targets, hit by a polarized photon beam, with mean polarization for positrons above 25 MeV.*

In Fig. 4 longitudinal polarization of positrons as a function of positron energy, hit by a polarized photon beam, with mean polarization for positrons above 25 MeV, shows us that the higher the positron energy, the higher the polarization. Again, two materials have the similar polarization curve, and also mean polarization for positrons with energy >25 MeV. The Ti target gives a slightly higher polarization, but that's not too important, more important is the fact that the high energy positrons have the high polarization.

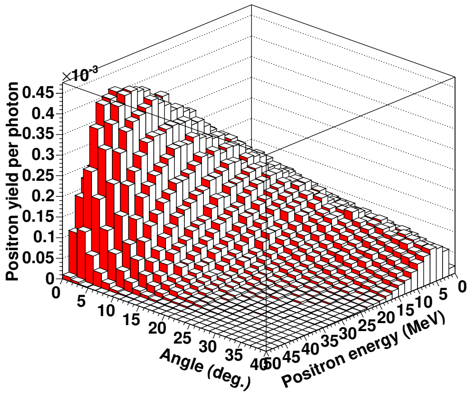

Fig. 5: *The 3D energy-angle distribution of positrons escaping 0.2 r.l. Ti target.*

The 3D energy-angle distribution of positrons escaping the 0.2 r.l. Ti target hit by a 50 MeV photon beam, see Figure 5, shows that most of positrons above 25 MeV are produced at small angles, less then 20 degrees.

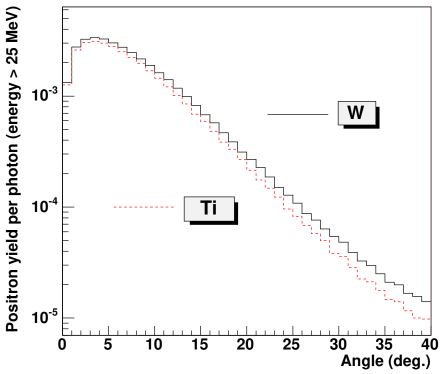

Fig. 6: *Yield of high energy positrons (> 25 MeV) as a function of polar angle.*

High energy positrons (>25 MeV) in Figure 6, which have high polarization are concentrated in the forward direction. Therefore it's possible to build the capture system for the positrons that are interesting for our purpose.

3.3 Comparison of different radiation length

In Table 2 we compared the positron yield, integrated over all angles, for 0.2, 0.5 and 1.0 radiation length Ti target. In the first column yield for positrons of all energies is given, in the second yield for high energy positrons (>25 MeV) and in the last column mean polarization for the high energy positrons.

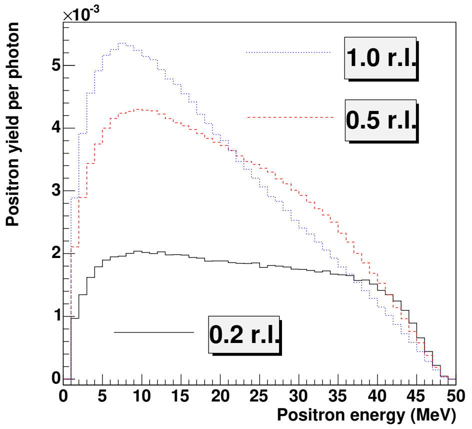

Fig. 7: *Comparison of positron yield for 50 MeV photon beam hitting different r.l. Ti target.*

Positron yields for three different radiation lengths for titanium is shown in Fig 7. Photons hitting the thickest target (1.0 r.l.) produce more positrons, but a thin target (0.2 r.l.) is the best if you look at the positrons we want to get, the high energy ones. For positrons above 40 MeV the thinest target gives best yield.

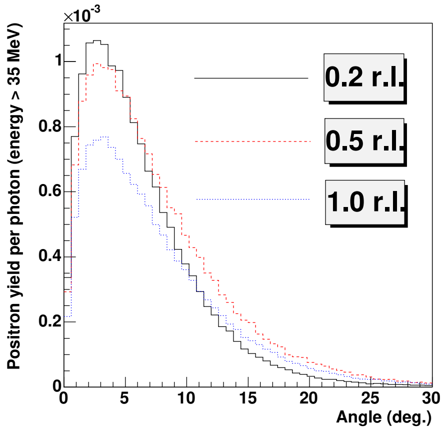

Fig. 8: *Positron yield as a function of polar angle emitted from Ti target at three thicknesses hit by 50 MeV photon beam.*

Tab. 2: *Yield for all and high energy positrons and mean polarization for >25 MeV given for diff. r.l.*

r.l.	All	High	mean pol.
0.2 r.l.	0.079	0.033	0.86
0.5 r.l.	0.143	0.048	0.87
1.0 r.l.	0.160	0.039	0.87

Also, if you look at the angular distribution of produced positrons above 35 MeV in Fig. 8, you can see that the 0.2 r.l. target has the highest peak, which means that most high energy positrons are produced in angles less then 10 degrees; the 0.5 r.l. target has a wider distribution, and lower peak, which means that positrons and particles which were their ancestors underwent more interactions, so the positron beam is less focused. After passing 1 r.l. positrons lose energy, so the number with energy greater then 35 MeV is significantly reduced.

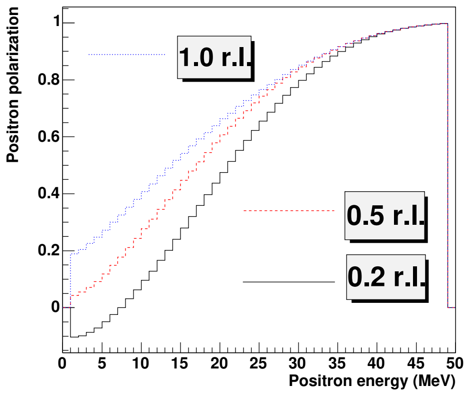

Fig. 9: *Influence of the target thickness on the polarization of positrons emerging from a Ti target.*

An advantage of having a thick target is a high degree of polarization, higher than for thin targets, see Fig. 9, because positrons which are produced with small energy get absorbed in the ticker target. These energy bands are filled with positrons created with higher energy and higher polarization, as stated in [2]. The mean polarization of all positrons is higher for thicker target, but we should keep in mind the previous figures and the fact that a thin target have more high energy positrons moving in small angles.

4 Conclusions

We used EGS4 to simulate a positron production after hitting a thin target by a 50 MeV photon and electron beam. The yield of positrons above 25 MeV for the photon beam is 0.033 for Ti, and 0.037 for W, and that's about 80 times higher than the electron beam, using the same 0.2 r.l.target. This result matched the one we got with Geant4. Almost all high energy positrons are emitted within a small angle. From target thickness analysis one can see that it's best to use thin target, $0.2 \ldots 0.5$ r.l. to get the beam within a small angle, but thick enough to have enough positrons created. High energy positrons (>25MeV) that are leaving the target have high average degree of polarization ($> 80\%$). The high polarization positrons are concentrated in the forward direction (<10 degrees), which is good for designing the capture system.

Acknowledgments

I would like to thank my supervisors Andreas Schälicke and Sabine Riemann for their help and advice and for being so approachable. A.S. and his help with computing made usage of Geant4 and ROOT a matter of minutes, not days. We appreciate K. Flötmann for giving us his polarization subroutine and his assistance in its implementation into EGS4 code, which was the most painful part of the job. We also appreciate the help of James C. Liu for letting us compare the code he used with ours, and seeing the way of implementation polarization subroutine they did at SLAC.

References

[1] H. Olsen and L.C. Maximon, *Phys. Rev.*, **114**, 887 (1959).

[2] K. Flöttmann, Ph.D thesis, DESY Hamburg (1993) DESY-93-161

[3] J. C. Liu, T. Kotseroglou, W. R. Nelson and D. C. Schultz, SLAC-PUB-8477 *Talk given at the 2nd International Workshop on EGS4, Tsukuba, Japan, 8-10 Aug 2000*

[4] W. R. Nelson, H. Hirayama and D. W. O. Rogers, SLAC-0265

[5] T. Kotseroglou *et al.*, SLAC-REPRINT-1999-151 *Prepared for IEEE Particle Accelerator Conference (PAC 99), New York, New York, 29 Mar - 2 Apr 1999*