Polarisation in Geant4

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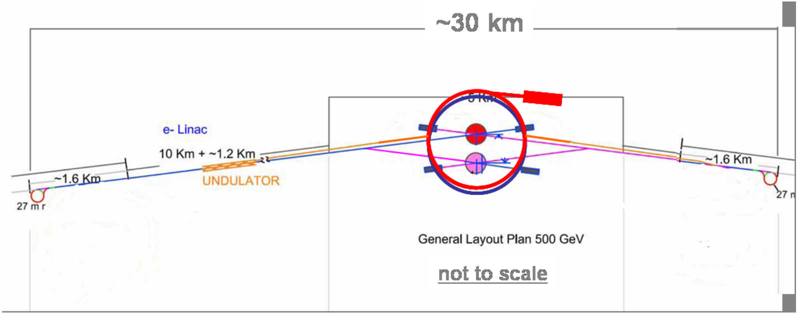
Outline

Motivation – The International Linear Collider

- luminosity $\mathcal{L} = 2 \cdot 10^{34}\, cm^{-2} s^{-1}$, $E_{\text{cms}} = 500 \ldots 1000\, GeV$ (remember LEP1 $\mathcal{L} = 2.4 \cdot 10^{31}\, cm^{-2} s^{-1}$)
- goal integrated luminosity in first 4 years : $500\, fb^{-1}$
- nominal operation: 1ms bunch trains with 2820 bunches, 5Hz repetition rate (bunch interval 308 ns)
- option to have both, positron and electron beam, polarised



Use-cases

1. Polarisation-Transfer

   e.g. a circularly polarised photon beam hits a thin target:
   What is the degree of polarisation of

   - the outgoing photon beam
   - the produced electron/positrons

   needed for Target studies for the ILC positron source optimisation and especially the E166 experiment

2. Polarimetry

   if a polarised beam hits a polarised target,

   - asymmetries in total cross sections
     (example E166 Compton transmission polarimeter), and
   - asymmetries in distribution
     (low–energy Polarimeter for the ILC)

   can be observed.

Use-cases

Interactions of polarised Electrons, Positrons and Photons

- main focus on logitudinal (or circular) polarisation (extension to transverse polarisation is forseen)
- envisaged energy domain is 1MeV . . . 10 MeV (E166 experiment, positron source) or up to 5GeV (ILC low-energy polarimeter)

Polarisation needed in

- Pair–production
- Bremsstrahlung
- Compton scattering
- Møller/Bhabha scattering
- Positron annihilation into two photons

Good news: Everything described by QED.

G. Stokes, Trans. Cambridge Phil. Soc. **9** (1852) 399

Stokes parameter

Wave function :

$$\Psi(\boldsymbol{x}, t) = a_1 \Psi_1 + a_2 \Psi_2$$

Jones vector :

$$|a_1|^2 + |a_2|^2 = 1 \qquad \boldsymbol{a} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$\sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Spin density matrix :

$$\rho = \boldsymbol{a} \otimes \boldsymbol{a}^* = \begin{pmatrix} a_1 a_1^* & a_1 a_2^* \\ a_2 a_1^* & a_2 a_2^* \end{pmatrix} = \frac{1}{2}(1 + \boldsymbol{\xi}\boldsymbol{\sigma})$$

Stokes parameter :

$$\boldsymbol{\xi} = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix} = \boldsymbol{a}^\dagger \boldsymbol{\sigma}\, \boldsymbol{a}$$

- describes arbitrary lepton or photon polarisation states

W. H. McMaster, Rev. Mod. Phys. **33** (1961) 8

Matrix formalism

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

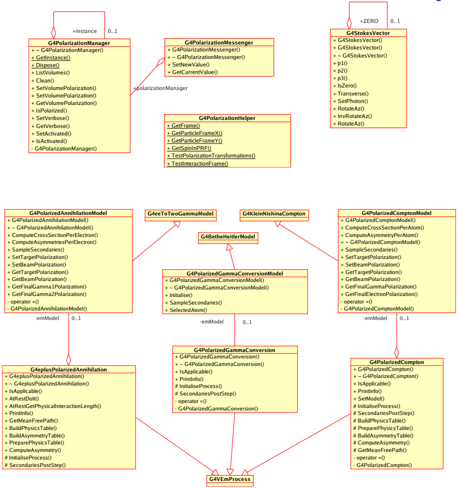
- relates incoming Stokes vector(s) $\boldsymbol{\xi}_0$ to outgoing Stokes vector(s) $\boldsymbol{\xi}$
- I gives differential distribution (intensity)

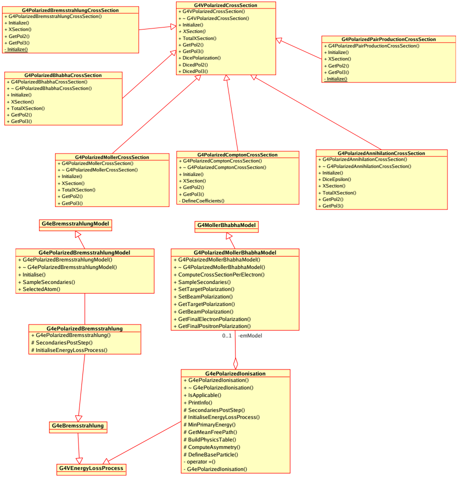
Transformation Matrix :

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

- Differential cross section
- Asymmetry
- Polarisation
- Depolarisation and polarisation transfer

New Geant4 Polarisation Library





- provides (almost all) polarised QED processes

Validation

Comparision with other simulation

- EGS, *polarisation extension by K. Flöttmann*
  - considers polarisation transfer only
  - simulates Pair production, Bremsstrahlung, Compton
  - suitable for target studies
- Geant3, *polarisation extension by V. Gharibyan/P. Schüler*
  - concentrates on asymmetries
  - simulates Bremsstrahlung, Compton (polarised target)
  - suitable for Compton transmission polarimetry

Comparision with calculation

- based on ref. from '60s, recalculation of processes by P. Starovoitov
  - Bhabha/Møller cross section
  - Compton cross section
  - positron annihilation cross section

Application to the E166 Experiment

Proposal:

- Demonstration of polarised positron production with a helical undulator

Status:

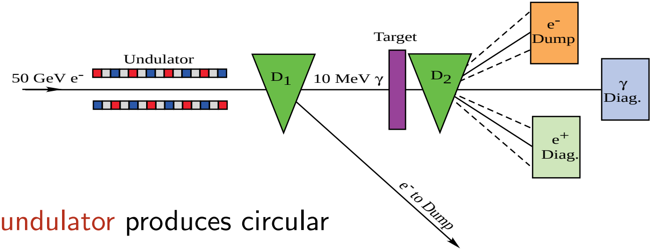
- approved in June 2003
- two runs, June and September 2005
- $\approx$ 8.5 million events on tape
- analysis is ongoing

Collaboration:

- about 50 people
- 15 institutes
- from 3 continents

G. Alexander *et al.*, 2003, SLAC-PROPOSAL-E-166.

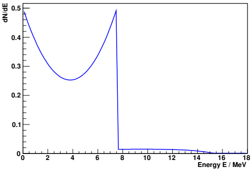
Schematic layout



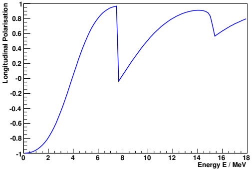
- 1 meter helical undulator produces circular polarised photons
- utilising 50 GeV electron final focus test beam (FFTB) at SLAC
- photons are converted to positrons in thin W-target
- measurement of photon and positron polarisation by Compton transmission polarimetry

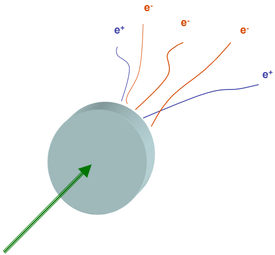
Target – Expected positron polarisation

γ energy



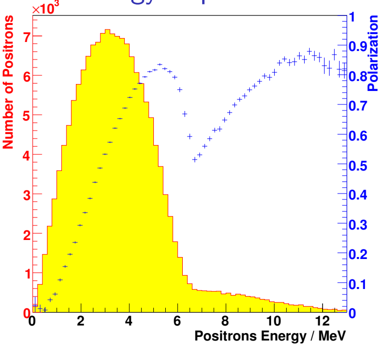
γ polarisation



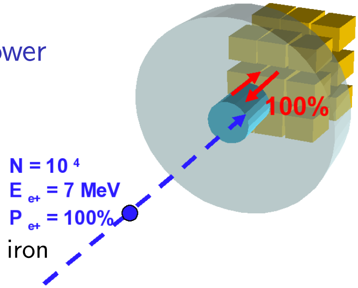


- input photon energy & polarisation generated by helical undulator
- conversion into electron–positron pairs in a thin W-target
- polarisation transfer to high energetic leptons
- simulation: expected energies and polarisation of produced positrons

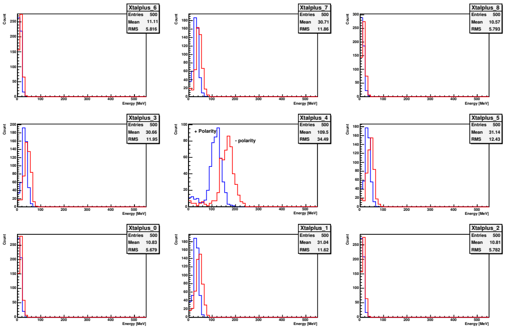
e^+ energy & polarisation



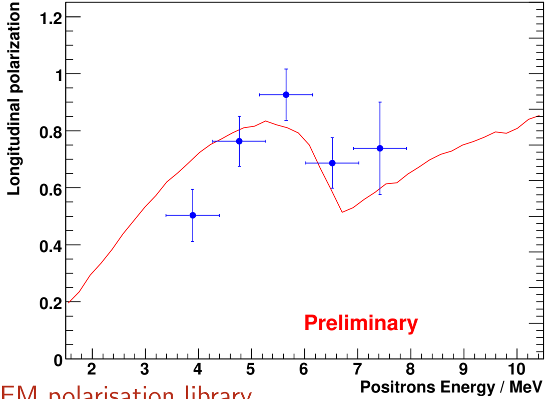
Polarimeter – Simulation of Analysing Power



- reconversion of positrons into photons via Bremsstrahlung and annihilation
- transmission of photons through magnetised iron (magnetisation parallel or anti-parallel)
- measurement of transmission in a 9-crystal CsI calorimeter
- polarisation dependence of Compton cross section results in an asymmetry
- simulation gives analysing power (conversion factor between measured asymmetry and polarisation of positrons)



Positron polarisation – Preliminary results



- measurements of small asymmetries ($\mathcal{O}(1\%)$) was a challenge
- measured positron polarisation at 5 energies
- simulations based on new EM polarisation library
- results consistent with expectation
- analysis ongoing
- final results expected ...soon!

Summary & Outlook

- New EM polarisation library
  - fits requirements for optimisation of ILC polarised positron source
  - general scheme based on Stokes vectors
  - focused on logitudinal and circular polarisation (in the moment)
  - describes polarisation transfer & asymmetry effects
  - included in Geant4 8.2 released in December
- Validation onging
  - independent calculation of polarised processes
  - comparison with EGS, and other software tools
  - data of the E166 experiment
- Future plans
  - continue in validation
  - work on efficiency optimisation
  - improve software framework (in cooparation with M.G.Pia)

G4 polarisation group:
R. Dollan, K. Laihem, T. Lohse, S. Riemann, A.S., A. Stahl, P. Starovoitov
in fruitful cooparation with V. Ivantchenko and M. Maire

Thanks!