



EM Polarisation library

status, progress, plans

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Outline

EM Polarisation Library

Use-cases

Physics picture

EM polarisation library – class structure

Validation

Changes since version 4.8.2

Comparison with calculation and simulation

The E166 experiment

Open questions & outlook

Stokesvector & EM fields

Photoelectric Effect & Multiple Scattering

Bremsstrahlung & Gamma conversion

Summary

Summary & Outlook

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 **longitudinal** (or circular) polarisation (extension to transverse polarisation is foreseen)
- ▶ 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.**

Physics picture

Base Stokes vectors ξ_i

- ▶ representations of arbitrary photon-lepton polarisation states
- ▶ decomposition of Spin density matrix ρ

$$\boldsymbol{\xi} = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix} \quad \rho = \frac{1}{2}(1 + \boldsymbol{\xi}\boldsymbol{\sigma})$$

Cross section is linear function of polarisation

$$\frac{d\sigma(\xi^{(1)}, \xi^{(2)}, \xi^{(3)}, \xi^{(4)})}{d\Omega} = \Phi(\xi^{(1)}, \xi^{(2)}) + \mathbf{A}(\xi^{(1)}, \xi^{(2)}) \cdot \boldsymbol{\xi}^{(3)} + \mathbf{B}(\xi^{(1)}, \xi^{(2)}) \cdot \boldsymbol{\xi}^{(4)} + \boldsymbol{\xi}^{(3)T} M(\xi^{(1)}, \xi^{(2)}) \boldsymbol{\xi}^{(4)}$$

- ▶ describes asymmetries and
- ▶ polarisation transfer
- ▶ final state correlation $M(\xi^{(1)}, \xi^{(2)})$ is neglected

$$\frac{d^2 \sigma^C}{d\epsilon d\varphi} \left(X, \epsilon; \zeta^{(\gamma)}, \zeta^{(e)}, \xi^{(\gamma)}, \xi^{(e)} \right) = \frac{r_e^2}{8X} \left(\Phi_0 \left(\zeta^{(\gamma)}, \zeta^{(e)} \right) + \Phi^{(\gamma)} \left(\zeta^{(\gamma)}, \zeta^{(e)} \right) \xi^{(\gamma)} \right. \\ \left. + \Phi^{(e)} \left(\zeta^{(\gamma)}, \zeta^{(e)} \right) \xi^{(e)} + \xi^{(\gamma)T} C \left(\zeta^{(\gamma)}, \zeta^{(e)} \right) \xi^{(2)} \right), \quad X = \frac{E_\gamma}{m_e}, \quad \epsilon = \frac{E'_\gamma}{E'_\gamma + m_e},$$

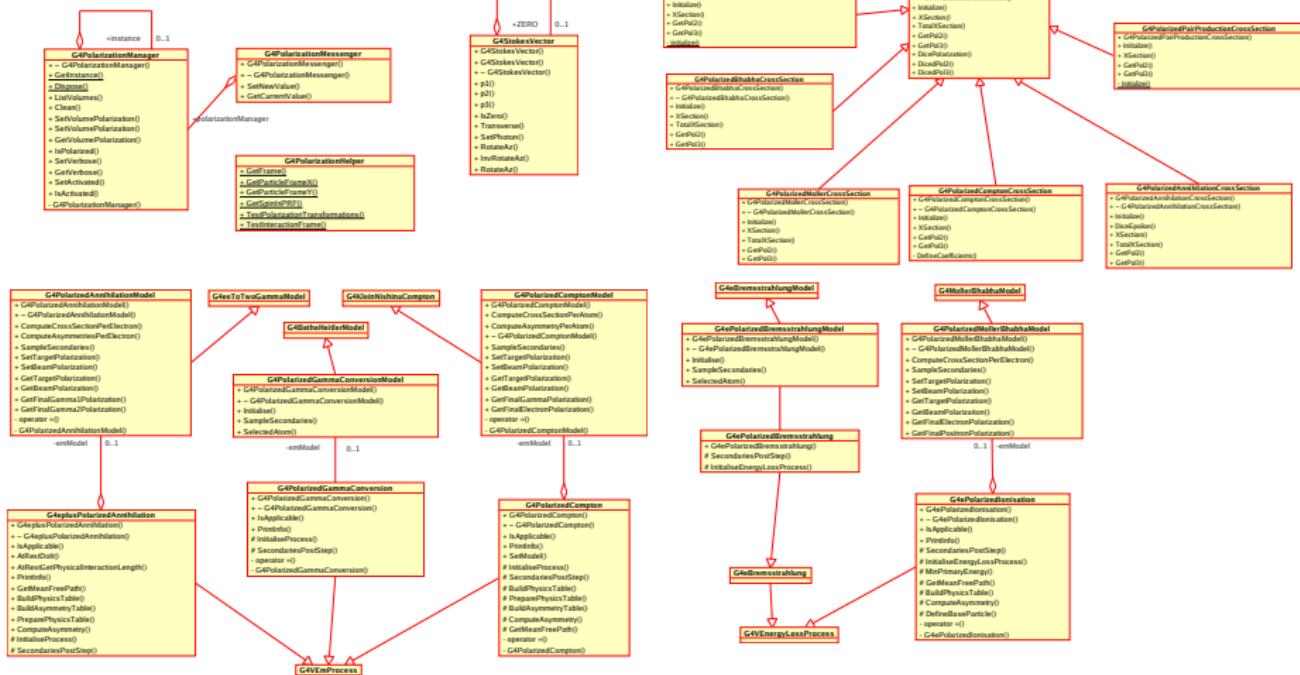
$$\Phi_0 = \frac{1}{\epsilon} + \epsilon - \sin^2 \theta (1 + \zeta_1^{(\gamma)}) - (1 - \epsilon) \sin \theta \zeta_3^{(\gamma)} \zeta_1^{(e)} - \left(\frac{1}{\epsilon} - \epsilon \right) \cos \theta \zeta_3^{(\gamma)} \zeta_3^{(e)}$$

$$\Phi_1^{(\gamma)} = - \sin^2 \theta + \frac{1}{2} (\cos 2\theta + 3) \zeta_1^{(\gamma)} + \left(\frac{1}{\epsilon} - 1 \right) \sin \theta \zeta_3^{(\gamma)} \zeta_1^{(e)}$$

$$\Phi_2^{(\gamma)} = 2 \cos \theta \zeta_2^{(\gamma)} - \left(1 - \frac{1}{\epsilon} \right) \sin \theta \zeta_3^{(\gamma)} \zeta_2^{(e)}$$

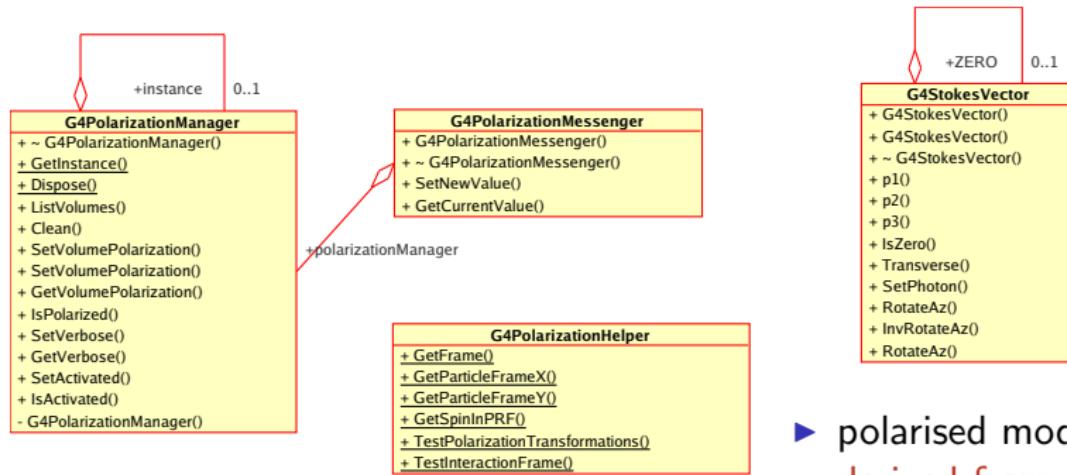
$$\Phi_3^{(\gamma)} = - (1 - \epsilon) \cos^2 \theta \zeta_3^{(e)} + \left(\frac{1}{\epsilon} + \epsilon \right) \cos \theta \zeta_3^{(\gamma)} - \left(\frac{1}{\epsilon} - 1 \right) \zeta_3^{(e)} \\ - (1 - \epsilon) \sin \theta \left(\cos \theta (1 + \zeta_1^{(\gamma)}) \zeta_1^{(e)} - \zeta_2^{(\gamma)} \zeta_2^{(e)} - \sin \theta \zeta_1^{(\gamma)} \zeta_3^{(e)} \right)$$

EM Polarisation Library



- ▶ provides (almost all) polarised QED processes

EM Polarisation Library – helper classes



- ▶ polarisation library based on standard EM physics
- ▶ provides polarised QED processes
- ▶ helper to **assign polarisation to any logical volume**

- ▶ polarised models are derived from standard EM models
- ▶ avoids duplication of code
- ▶ guarantees equivalence of unpolarised results

Developments since introduction of EM polarisation library

(Sept. 2006)

Before release 8.2

- ▶ number of physics bug fixes

Changes for release 8.3 / 9.0

- ▶ corrections in PRM
- ▶ small bug fix (uninitialized variable)
- ▶ improvement inter-platform compatibility (compiler warnings)
- ▶ adjustments due to design changes in underlying EM physics
(`SampleSecondary` , `PostStepGetPhysicsalInteractionLength`)

In the moment

- ▶ concentrate on **validation** and
- ▶ **publications** (G4 implementation/validation & E166 experiment)

Validation

Comparison 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 low-energy **Compton transmission polarimetry**

Comparison with calculation

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

Comparison with Whizard/O'mega

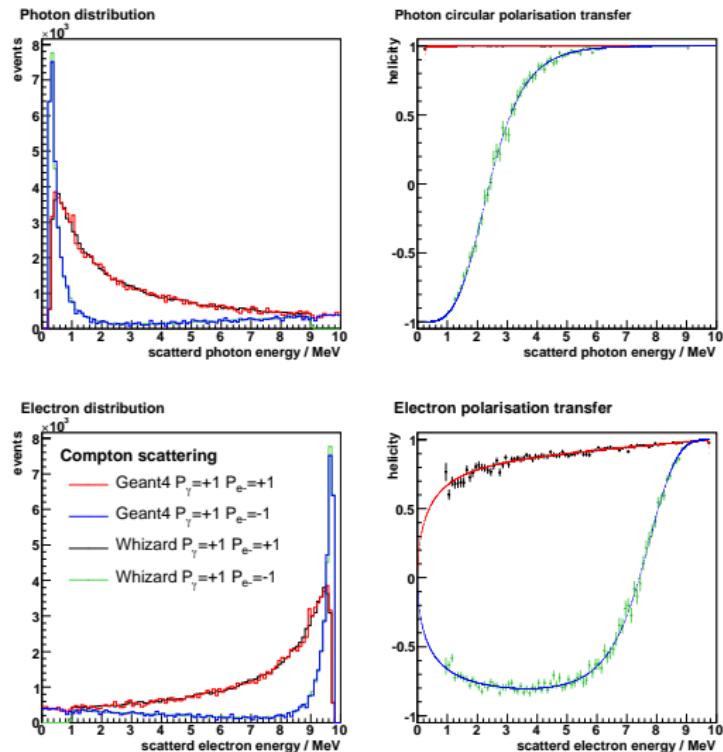
- ▶ arbitrary initial polarisation
- ▶ final state helicity
- ▶ simple $2 \rightarrow 2$ processes
 - ▶ Compton
 - ▶ Møller/Bhabha
 - ▶ e^+e^- -annihilation

Checks:

- ▶ Polarisation transfer
- ▶ Asymmetries

Missing:

- ▶ Interactions with nuclei
e.g. Pair-Production
- ▶ linear polarised photons



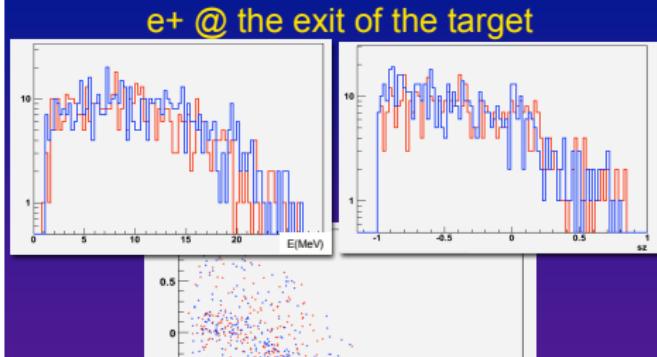
Comparison with EGS

EGS:

- ▶ polarisation implementation by K.Föttmann
- ▶ describes polarisation transfer
- ▶ no depolarisation via ionisation
- ▶ no target polarisation

Checks:

- ▶ good agreement for polarisation transfer to high energetic positrons
- ▶ context of Compton based source (O.Dadoun)



Geant4/EGS results using higher energy of incoming photon
(from 1.8GeV e- beam, with diaphragm)

		Geant4	EGS
γ	$\langle E(\text{MeV}) \rangle (\text{RMS})$	37.10(12.33)	37.08 (12.40)
γ	$S_z (\text{RMS})$	-0.40 (0.60)	-0.40 (0.60)
e^-	$\langle E(\text{MeV}) \rangle (\text{RMS})$	26.32 (8.48)	26.79 (8.55)
e^-	$S_z (\text{RMS})$	-0.50(0.37)	-0.45 (0.37) ?
e^+	$\langle E(\text{MeV}) \rangle (\text{RMS})$	26.62 (8.73)	26.21 (8.30)
e^+	$S_z (\text{RMS})$	-0.54 (0.32)	-0.53 (0.32)

Oliver Dadoun EGS/Geant4 Benchmark

For $\gamma e^+ S_z$: EGS = Geant4

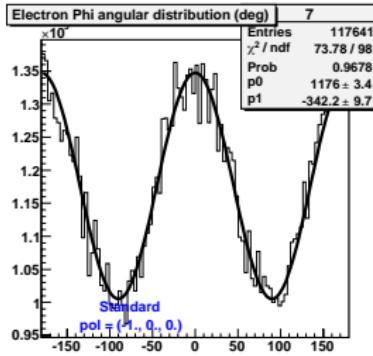
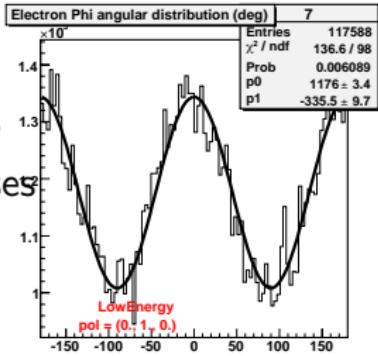
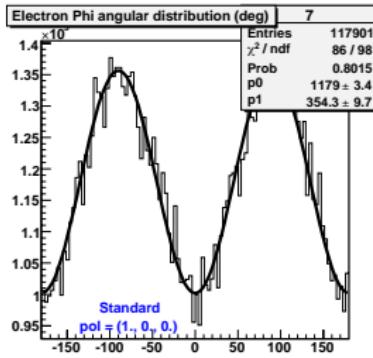
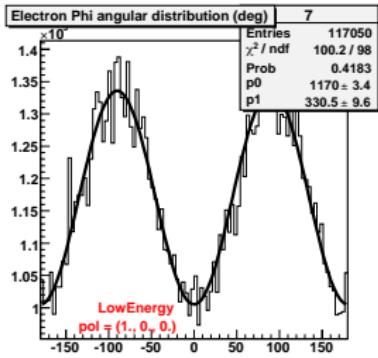
Polarised EM standard vs. LowEnergy

Existing in LowEnergy:

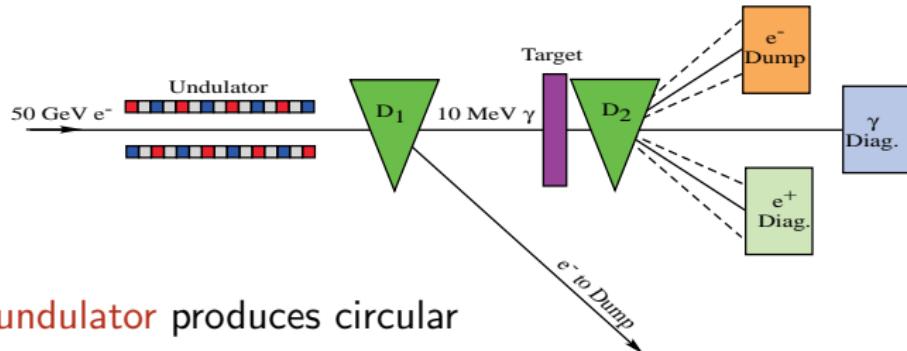
- ▶ Rayleigh scattering
- ▶ Compton scattering
- ▶ Photo electric effect

Problems:

- ▶ linearly polarised photons
- ▶ limited overlap in processes
- ▶ (different models)



E166 Schematic layout

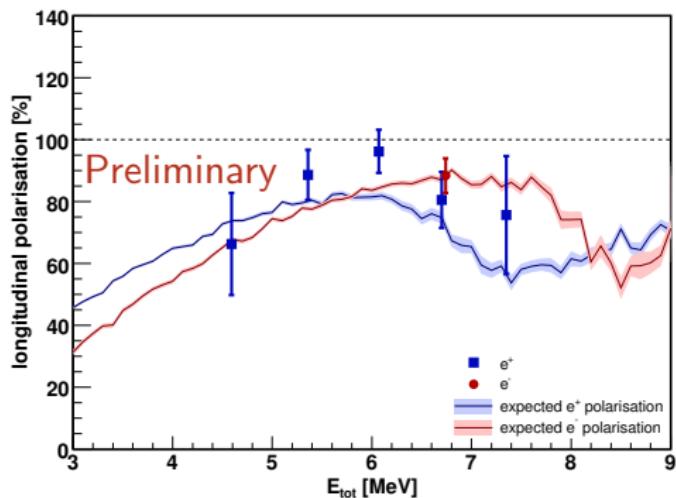


- ▶ 1 meter **helical undulator** produces circular polarised photons
 - ▶ utilizing 46.6 GeV electron final focus test beam (FFTB) at SLAC
 - ▶ polarised photons are converted to polarised positrons in thin W-target
 - ▶ measurement of photon and positron polarisation by Compton transmission polarimetry

E166 Results

Gamma asymmetry

Positron/Electron polarisation



	measured Asym.	Geant3 simulation
Aerogel	3.50 %	3.54 %
SiW-Cal	3.52 %	3.22 %

- ▶ polarisation compatible with expectation
- ▶ positron, electron and photon data analysed
- ▶ publication in preparation

Stokesvector & EM fields

Problem

- ▶ Polarised physics processes (standard EM) rely on *Stokes vector*
- ▶ Polarisation of electrons/positrons affected by electromagnetic fields
- ▶ G4Mag_SpinEqRhs assumes *Spins*

Possible solution

- ▶ if material and magnetic fields are separated translate Stokes vectors to spins on boundary
 - ▶ loss of information
 - ▶ does not work if material and magnetic field overlap
- ▶ abandon Stokes vectors for leptons and use Spins
 - ▶ loss of information from the beginning
 - ▶ (possible) performance degradation

Photoelectric Effect & Multiple Scattering

currently in preparation: Polarised Photoelectric Effect

- ▶ concentrates on polarisation transfer from circularly polarised photons
- ▶ high probability of polarisation transfer (important in some small edges of the phase space)

missing piece: Polarised Multiple scattering

- ▶ currently polarisation effects are ignored
- ▶ complicated situation in literature
- ▶ hints are welcome!
- ▶ possible path via new G4CoulombScattering

Bremsstrahlung & Gamma conversion

Problem:

- ▶ polarisation implementation based on references from 60ties
[Olsen & Maximon, 1959]
- ▶ employs similarly old screening model
[Olsen, Maximon, Wergeland, 1957]
- ▶ employs *small angle approximation*

Plan:

- ▶ start with review of Bremsstahlung
(already envisaged from unpolarised physics)

Summary & Outlook

- ▶ New EM polarisation library
 - ▶ uses standard EM physics design
 - ▶ fits requirements for optimisation of ILC polarised positron source
 - ▶ general scheme based on Stokes vectors
 - ▶ focused on longitudinal and circular polarisation
 - ▶ describes polarisation transfer & asymmetry effects
- ▶ Validation
 - ▶ independent calculation of polarised processes
 - ▶ comparison with EGS, and other software tools
 - ▶ data of the E166 experiment
- ▶ Future plans
 - ▶ continue investigations of Spin interaction with EM fields
 - ▶ Photoelectric Effect (available soon)
 - ▶ Review of Bremsstrahlung

G4 polarisation group:

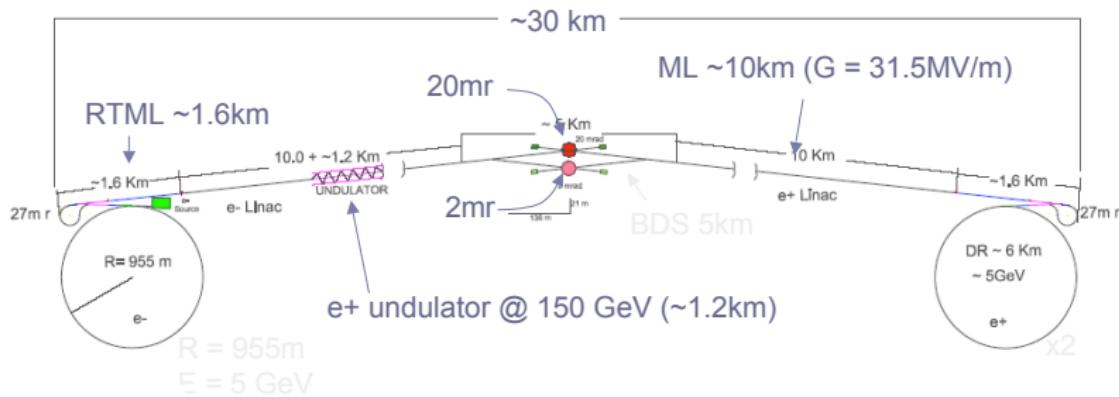
R. Dollan, K. Laihem, T. Lohse, S. Riemann, A.S., A. Stahl, P. Starovoitov
in fruitful cooperation with V. Ivantchenko and M. Maire

Thanks!

Motivation – The International Linear Collider

- ▶ luminosity $\mathcal{L} = 2 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1}$, $E_{\text{cms}} = 500 \dots 1000 \text{ GeV}$
(remember LEP1 $\mathcal{L} = 2.4 \cdot 10^{31} \text{ cm}^{-2} \text{s}^{-1}$)
- ▶ 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**

F. Asm/SLAC 11-29-2005



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

Stokes parameter

Wave function :

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

Jones vector :

$$|a_1|^2 + |a_2|^2 = 1 \quad \mathbf{a} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad \sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Spin density matrix :

$$\rho = \mathbf{a} \otimes \mathbf{a}^* = \begin{pmatrix} a_1 a_1^* & a_1 a_2^* \\ a_2 a_1^* & a_2 a_2^* \end{pmatrix} = \frac{1}{2}(1 + \xi \boldsymbol{\sigma}) \quad \sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Stokes parameter :

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

- ▶ describes arbitrary lepton or photon polarisation states

Matrix formalism

$$\begin{pmatrix} I \\ \xi \end{pmatrix} = T \begin{pmatrix} I_0 \\ \xi_0 \end{pmatrix}$$

► relates incoming Stokes vector(s) ξ_0
 to outgoing Stokes vector(s) ξ
 ► 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

The E166 Experiment Proposal:

- ▶ Demonstration of polarised positron production with a helical undulator

Status:

- ▶ approved in June 2003
- ▶ two runs, June and September 2005
- ▶ ≈ 8.5 million events on tape
- ▶ analysis is ongoing



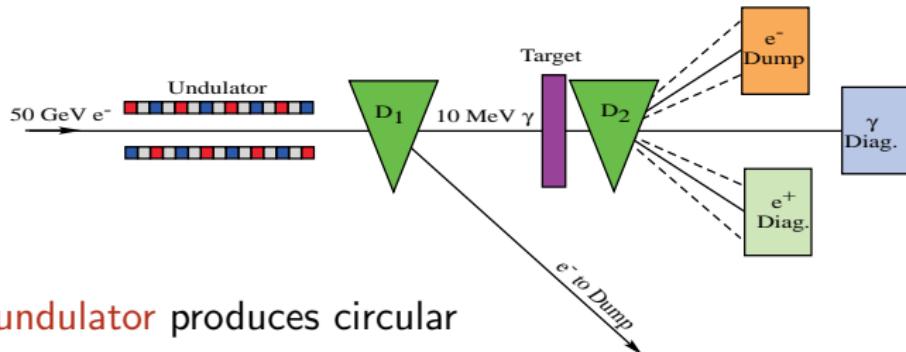
Collaboration:

- ▶ about 50 people
- ▶ 15 institutes
- ▶ from 3 continents



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

Schematic layout

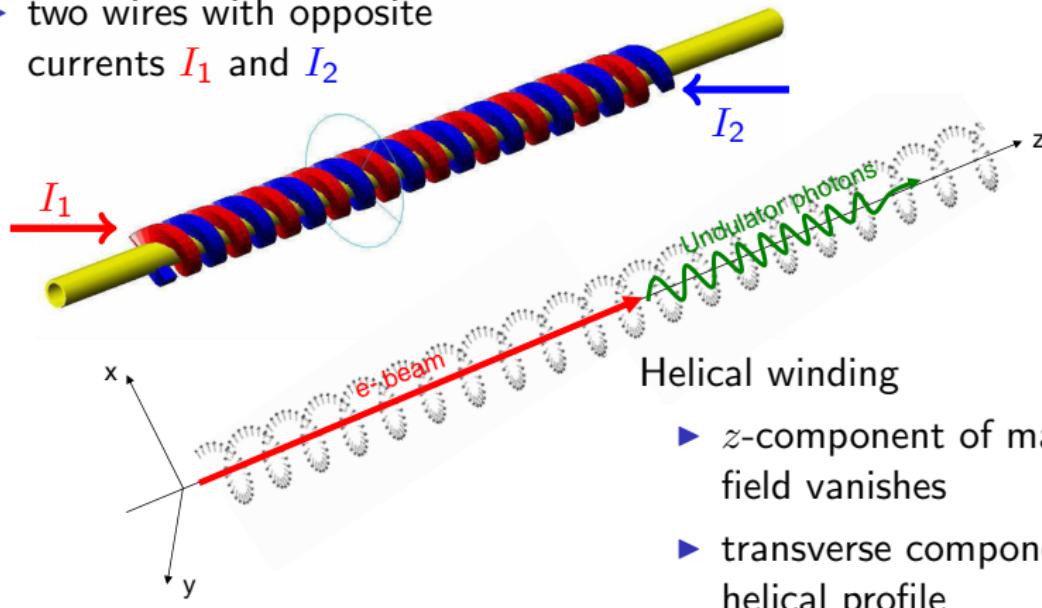


- ▶ 1 meter **helical undulator** produces circular polarised photons
- ▶ utilizing 50 GeV electron final focus test beam (FFTB) at SLAC
- ▶ photons are converted to positrons in thin W-target
- ▶ measurement of photon and positron polarisation by Compton transmission polarimetry

Balakin and Mikhailichenko, BINP 79-85 (1979).

Helical Undulator

- ▶ two wires with opposite currents I_1 and I_2

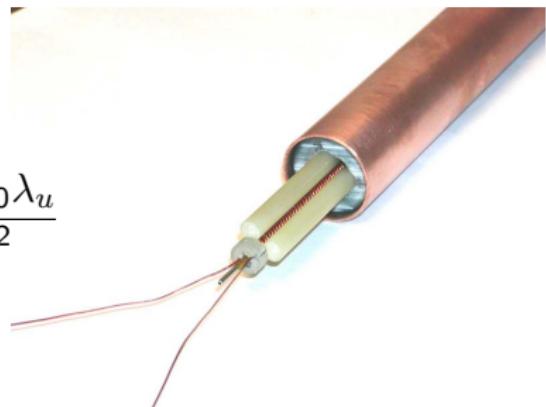


Helical winding

- ▶ z -component of magnetic field vanishes
- ▶ transverse component → helical profile

Undulator parameter

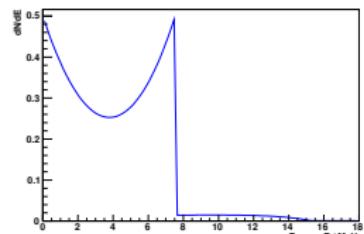
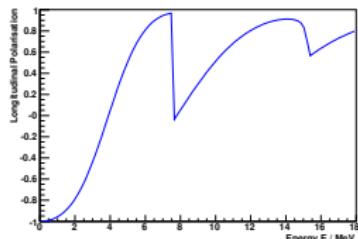
$$E_{\gamma}^{\text{cut}} \approx \frac{2\gamma^2 hc}{\lambda_u} \frac{1}{1+K^2} \quad K = \frac{2\pi e B_0 \lambda_u}{mc^2}$$



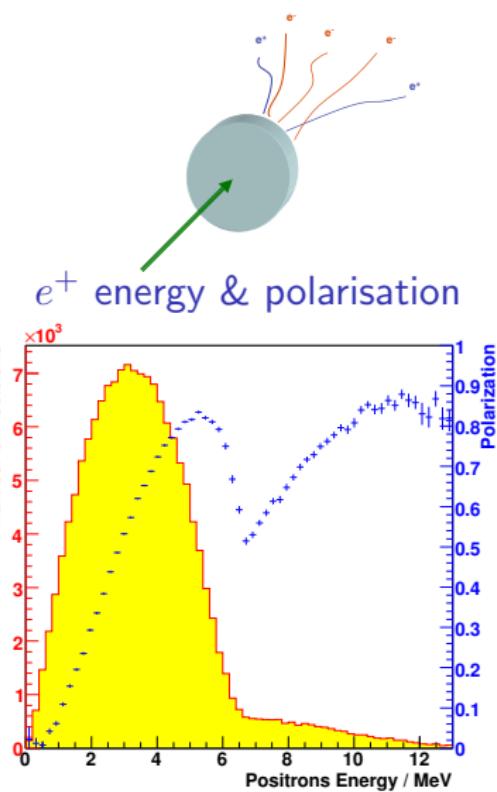
E166 Undulator

Length L	1.0 m
Period λ_u	2.54 mm
Inner radius r_u	0.9 mm
On-axis field B_0	0.75 T
Current I	2.3 kA
1st harmonic energy	7.8 MeV

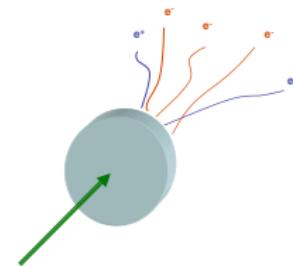
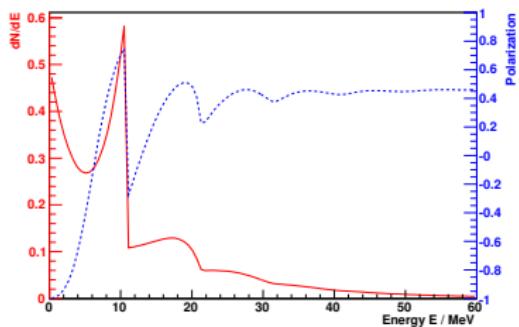
Positron Production

 γ energy γ polarisation

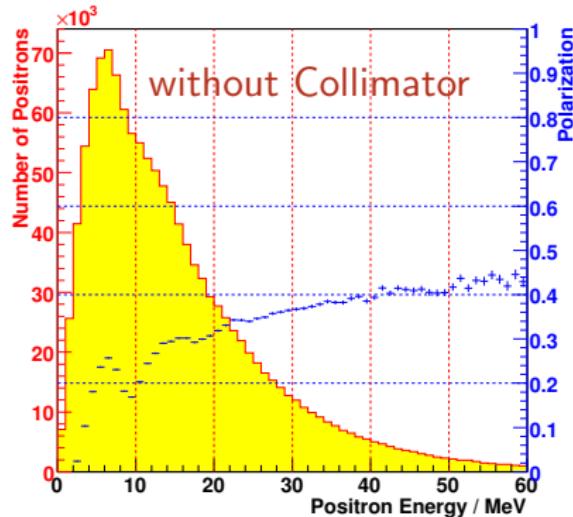
- ▶ input photon energy & polarisation generated by helical undulator
- ▶ conversion into electron–positron pairs in a thin W-target
- ▶ polarisation transfer to high energetic leptons
- ▶ simulation: expected energies and polarisation of produced positrons



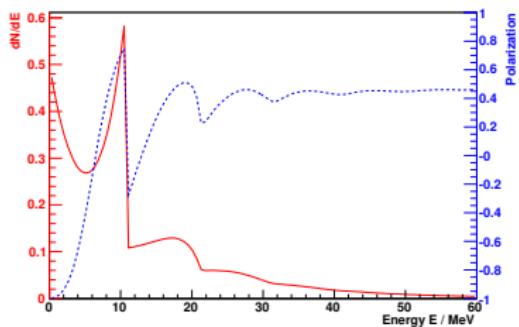
ILC Positron source



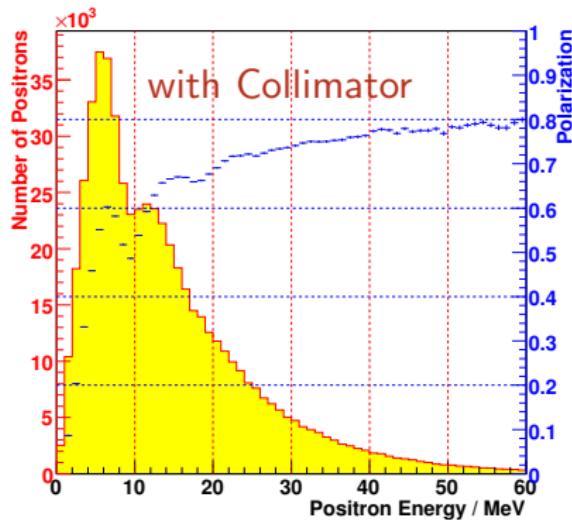
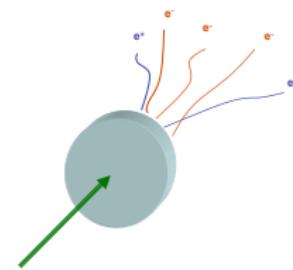
- ▶ primary beam 150 GeV
- ▶ undulator few 100 meter long
- ▶ fast rotating target (1m diameter)
- ▶ collimation of photon beam gives higher polarisation



ILC Positron source



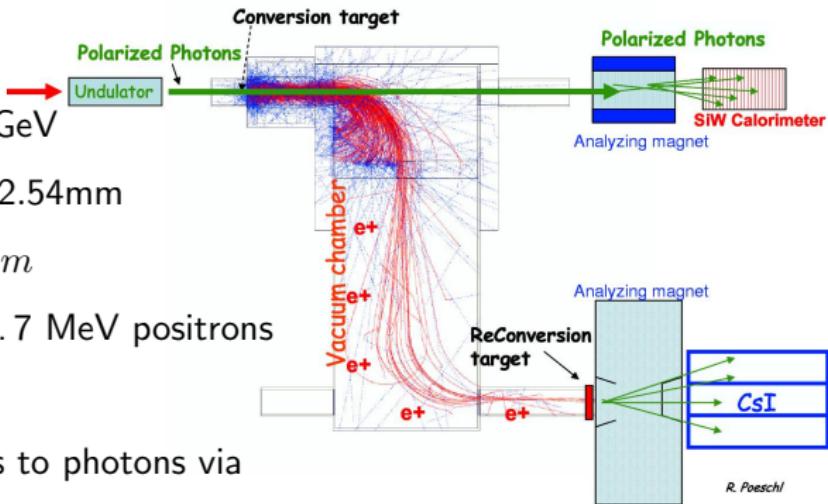
- ▶ primary beam 150 GeV
- ▶ undulator few 100 meter long
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E166 – Experimental setup

Creation of e^+

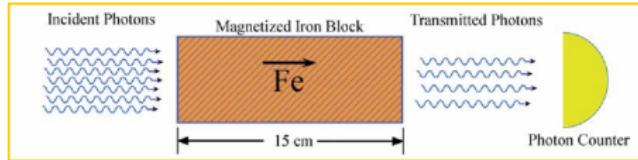
- ▶ initial e^- beam at 46.6 GeV
 - ▶ helical undulator period 2.54mm
 - ▶ W target .5 $X_0 = 1.75\text{mm}$
 - ▶ spectrometer selects 3...7 MeV positrons



Polarimeter

- ▶ reconversion of positrons to photons via Bremsstrahlung
 - ▶ flip magnetisation iron analyzer
 - ▶ asymmetry in CsI calorimeter

Compton transmission polarimetry



Setup

- ▶ reconversion of positrons to photons
- ▶ magnetised iron analyzer
- ▶ CsI calorimeter

Interactions of polarised particles with polarised matter

- ▶ Compton scattering
- ▶ Møller/Bhabha scattering
- ▶ e^+e^- -annihilation
- ▶ Bremsstrahlung

