PPS-Sim

Tools to design and optimize the polarized positron source

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DESY, Zeuthen

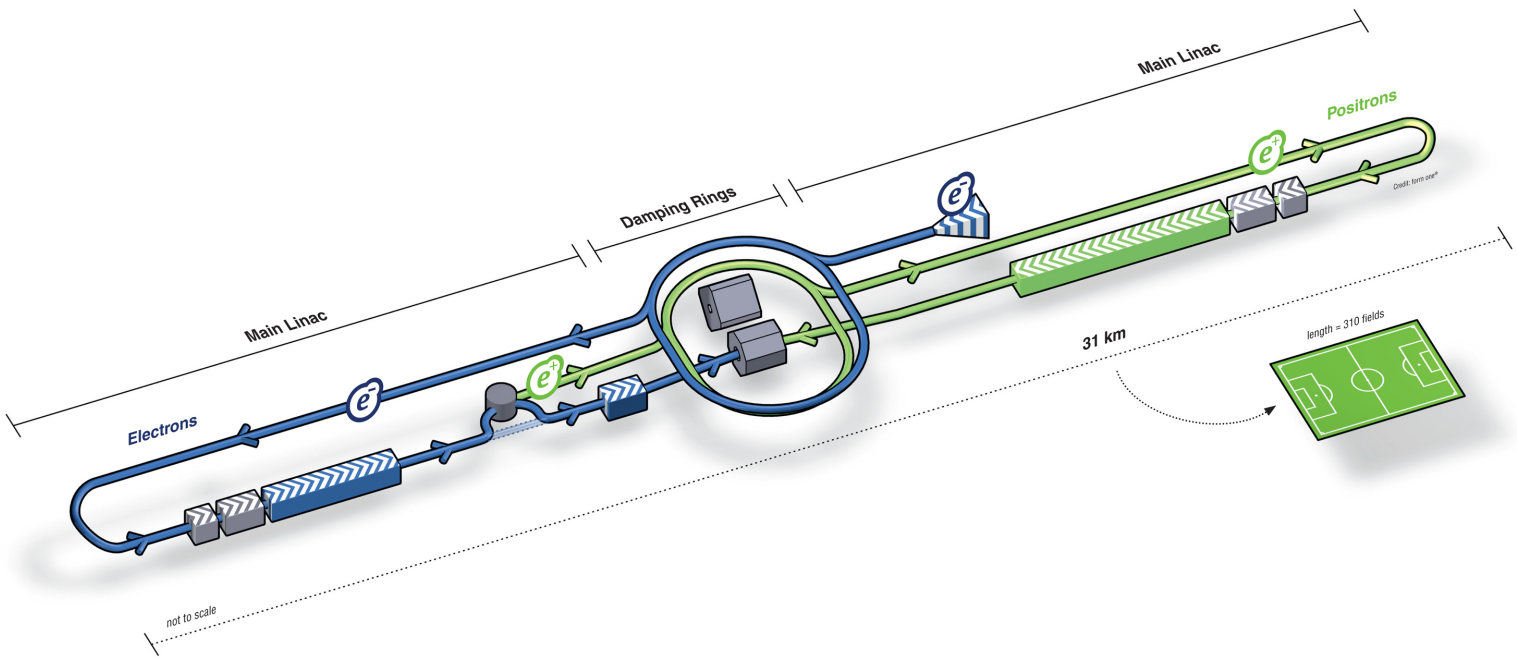
November 9, 2010

9th October, Hamburg, 2010

Outline

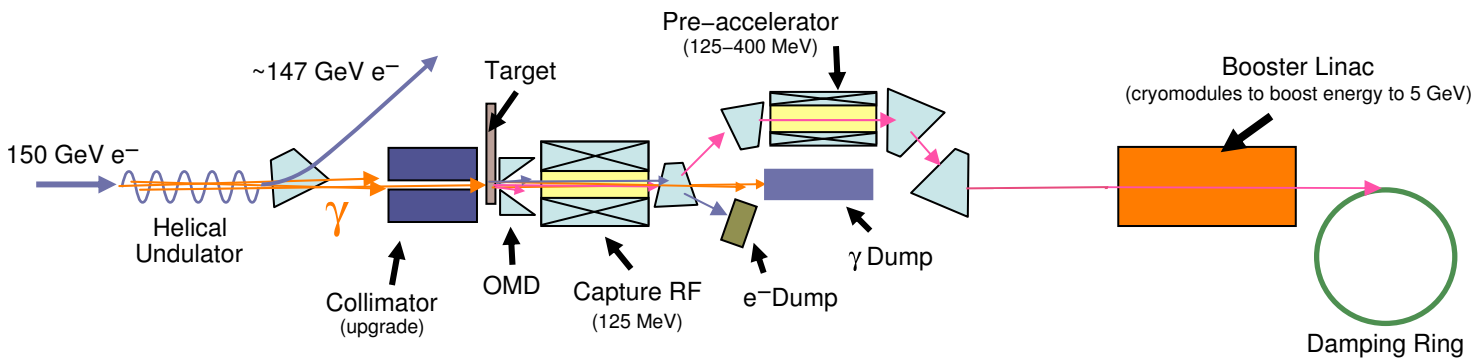
International Linear Collider

- luminosity $\mathcal{L} = 2 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $E_{\mathrm{cms}} = 500 \ldots 1000\,\mathrm{GeV}$
  (remember LEP1 $\mathcal{L} = 2.4 \cdot 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- goal integrated luminosity in first 4 years : $500\,\mathrm{fb}^{-1}$
- goal: precision machine
- polarized electron and positron beam

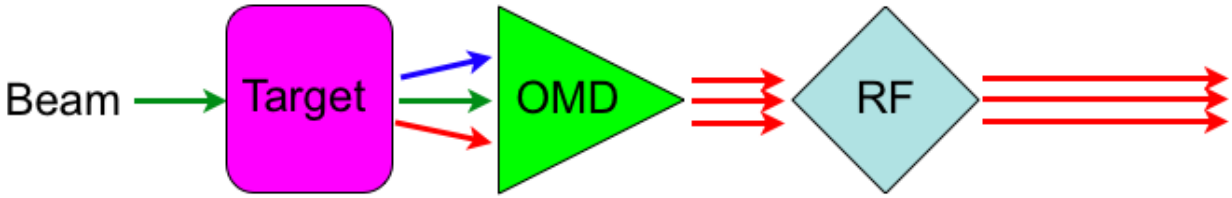


Positron source

- Parameters
  - 1ms bunch trains with 2820 bunches, 5Hz repetition
  - $3 \cdot 10^{10}$ positrons per bunch
- Challenge:
  - high intensity (target damage)
  - high polarisation



Polarized Positron Source Simulation



Primary beam

- Photons from Undulator
- Electrons (conventional source)
- Input file (e.g. Compton photons, Hybrid target)

Target

- e.g. Ti wheel, Liquid lead

Positron Capture Optic (OMD)

- AMD, QWT, Li-Lens
- Soleonid B-field, RF E-field

PPS-Sim – Foundation

Geant4 toolkit

a toolkit for the simulation of the passage of particles through matter

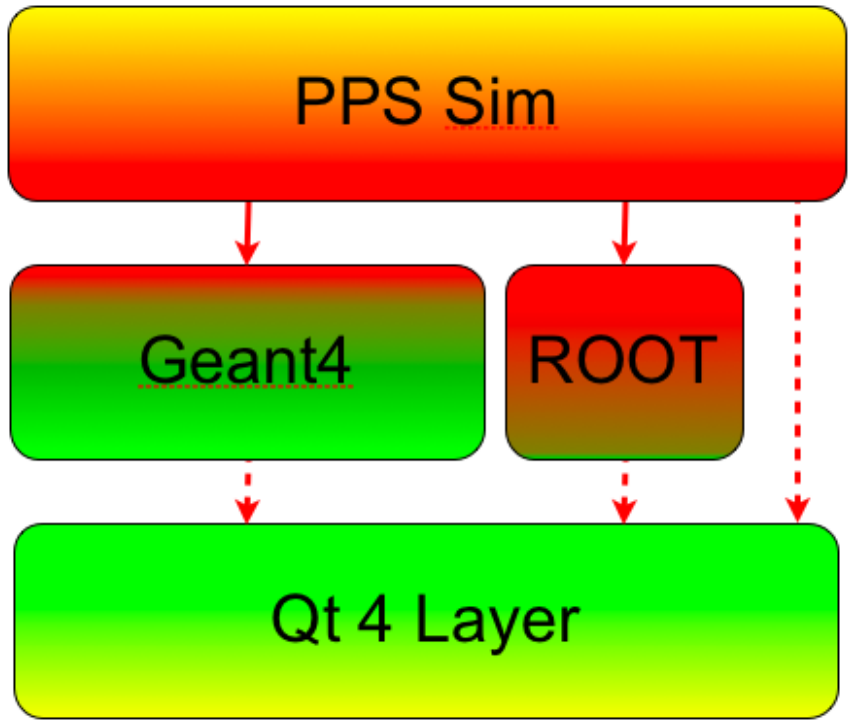
Features include

- powerful geometry package
- elecromagnetic and hadronic shower simulation
- polarization transfer in physics processes
- particle and spin tracking in electromagnetic fields (T-BMT)
- visualization (geometry, particls, energy deposition, ...)
- GUI (XM, Qt, . . .)
- . . .

PPS-Sim – Foundation

Layout

- use Geant4 for: geometry, physics, UI
- use ROOT for: data analysis, persistency



Prerequisites

- Geant4 (incl. Qt4 binding)
- ROOT (incl. Qt4 binding)
- Qt 4.2 or above

PPS-Sim – Features

Input

- Beam, Target & OMD (free configurable geometry)

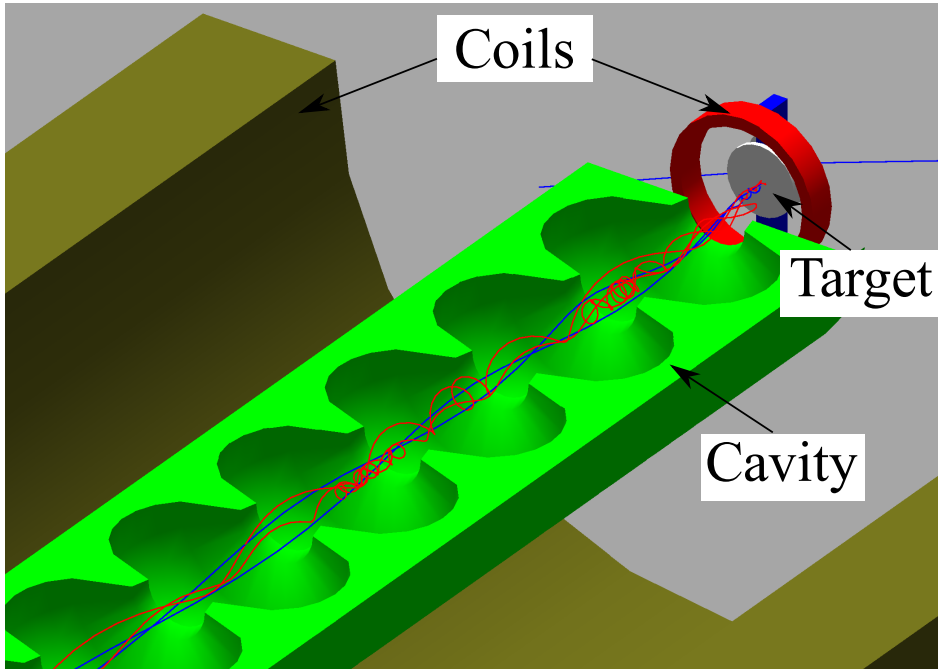
Output

- positron yield & polarisation (incl. DR acceptance)
- beam properties (width, emittance, energy, . . .)
- total energy deposition in components
- PEDD in target, LiLens or Windows

User interface

- GUI allows for setting of simulation parameter
- visualisation of geometry & tracks
- semi-automatic parameter scans (e.g. RF phase)
- output as .root, .eps, . . .

PPS-Sim – Physics

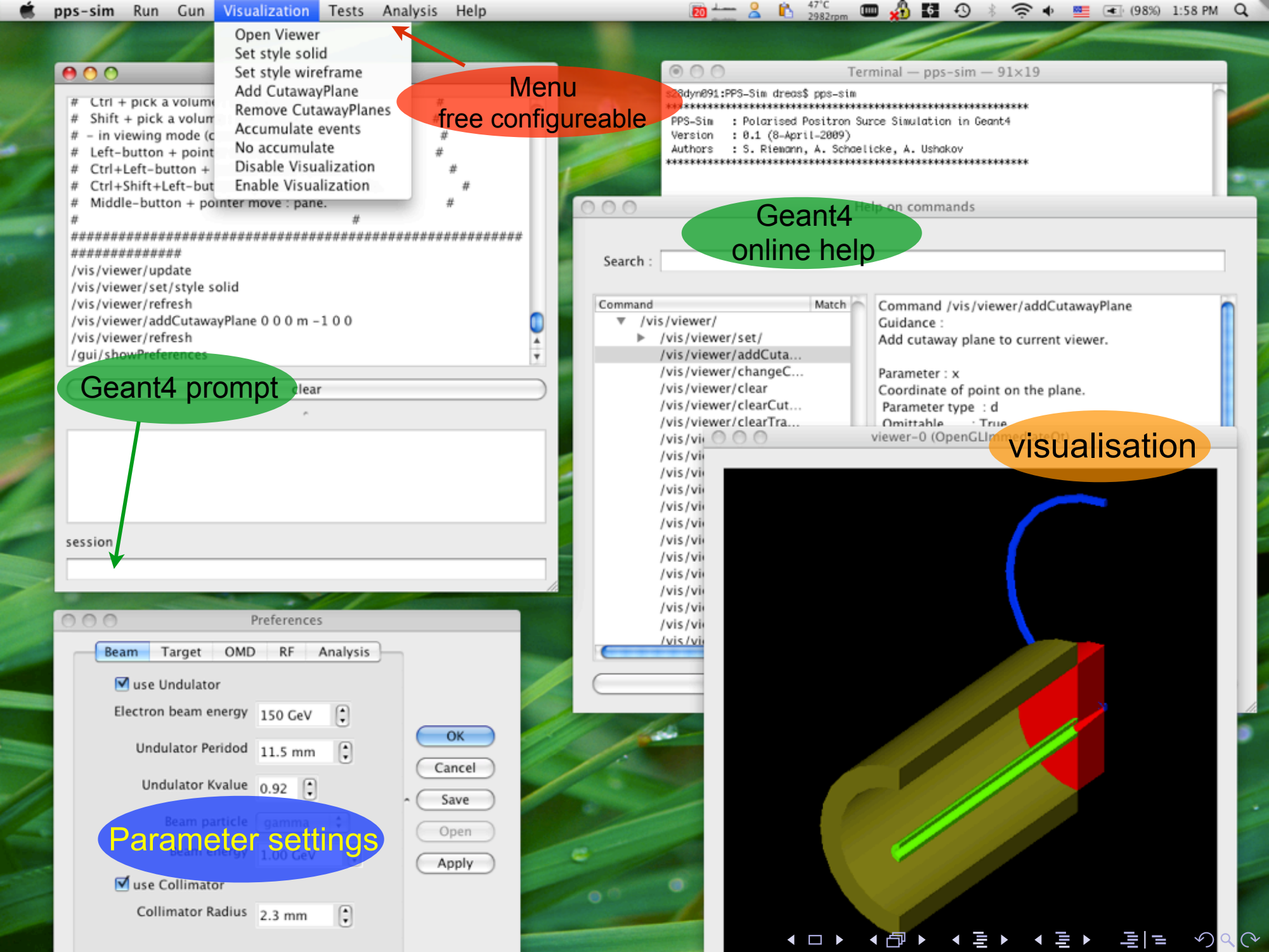


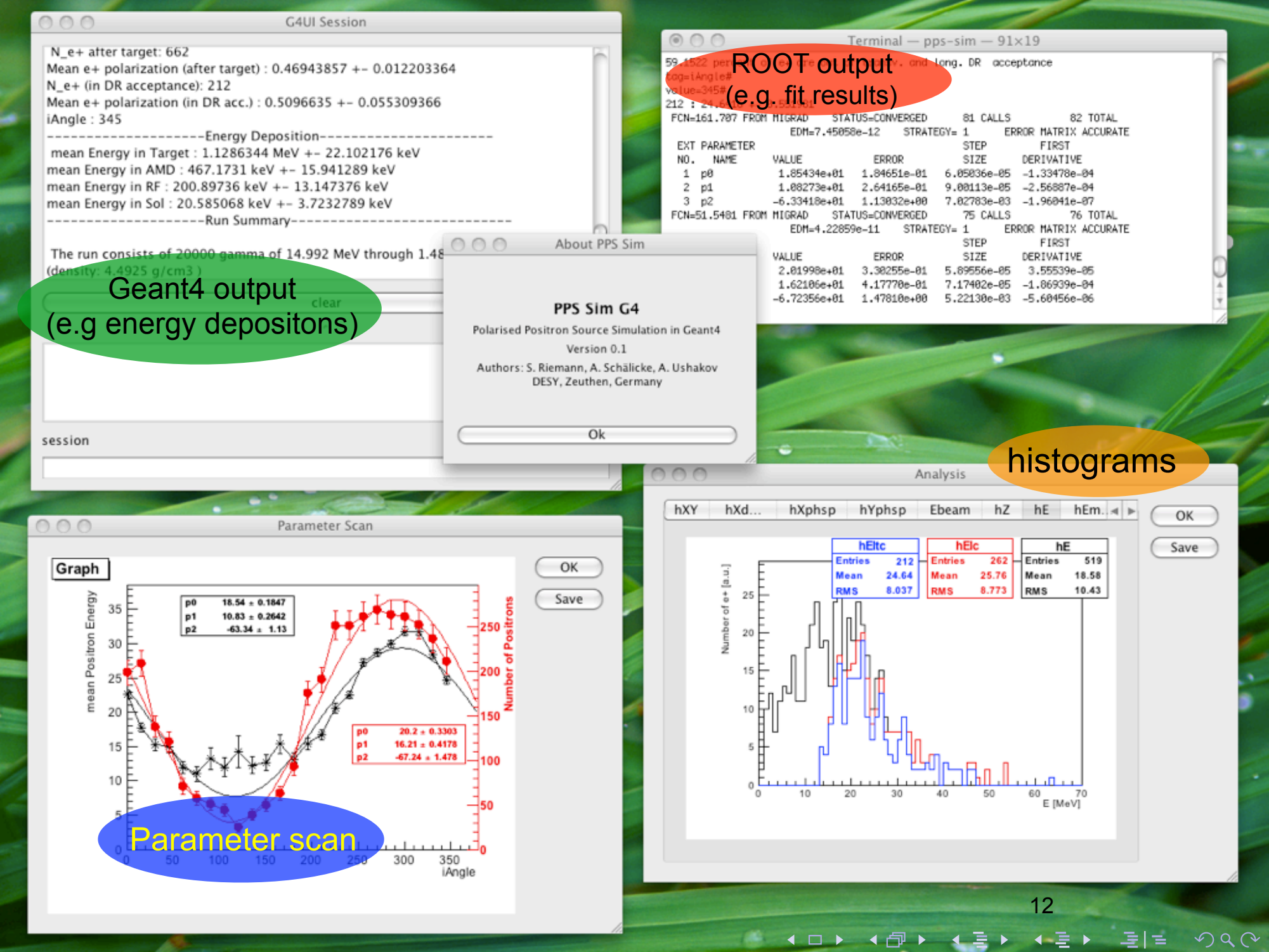
Polarized processes

- Compton
- Bhabha / Møller
- photo effect
- pair production
- bremsstrahlung
- positron-electron annihilation

Spin Tracking: T-BMT equation

$$\frac{d\mathbf{S}}{dt} = -\frac{e}{m\gamma}\left[(\gamma a+1)\mathbf{B}_T + (a+1)\mathbf{B}_L - \gamma\left(a+\frac{1}{\gamma+1}\right)\beta\mathbf{e}_v \times \frac{\mathbf{E}}{c}\right] \times \mathbf{S}$$

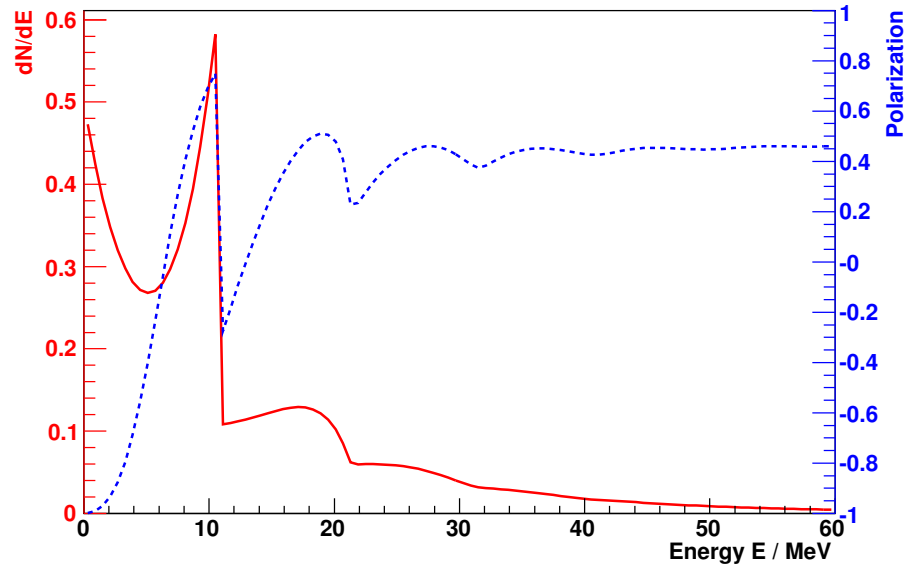

pps-sim Run Gun Visualization Tests Analysis Help
Open Viewer
Set style solid
Set style wireframe
Add CutawayPlane
Remove CutawayPlanes
Accumulate events
No accumulate
Disable Visualization
Enable Visualization
Menu
free configureable
Terminal — pps-sim — 91×19
PPS-Sim : Polarised Positron Surce Simulation in Geant4
Version : 0.1 (8-April-2009)
Authors : S. Riemann, A. Schaelicke, A. Ushakov
Geant4
online help
Help on commands
Search :
Command
Match
/vis/viewer/
/vis/viewer/set/
/vis/viewer/addCuta...
/vis/viewer/changeC...
/vis/viewer/clear
/vis/viewer/clearCut...
/vis/viewer/clearTra...
Command /vis/viewer/addCutawayPlane
Guidance :
Add cutaway plane to current viewer.
Parameter : x
Coordinate of point on the plane.
Parameter type : d
/vis/viewer/update
/vis/viewer/set/style solid
/vis/viewer/refresh
/vis/viewer/addCutawayPlane 0 0 0 m -1 0 0
/vis/viewer/refresh
/gui/showPreferences
Geant4 prompt
session
visualisation
Preferences
Beam
Target
OMD
RF
Analysis
use Undulator
Electron beam energy
150 GeV
Undulator Peridod
11.5 mm
Undulator Kvalue
0.92
Parameter settings
use Collimator
Collimator Radius
2.3 mm
OK
Cancel
Save
Open
Apply


G4UI Session
N_e+ after target: 662
Mean e+ polarization (after target) : 0.46943857 +- 0.012203364
N_e+ (in DR acceptance): 212
Mean e+ polarization (in DR acc.) : 0.5096635 +- 0.055309366
iAngle : 345
--------------------Energy Deposition----------------------
mean Energy in Target : 1.1286344 MeV +- 22.102176 keV
mean Energy in AMD : 467.1731 keV +- 15.941289 keV
mean Energy in RF : 200.89736 keV +- 13.147376 keV
mean Energy in Sol : 20.585068 keV +- 3.7232789 keV
--------------------Run Summary----------------------------
The run consists of 20000 gamma of 14.992 MeV through 1.48
(density: 4.4925 g/cm3)
clear
session
Geant4 output
(e.g energy depositons)
Terminal — pps-sim — 91×19
ROOT output
(e.g. fit results)
FCN=161.787 FROM MIGRAD STATUS=CONVERGED 81 CALLS 82 TOTAL
EDM=7.45058e-12 STRATEGY= 1 ERROR MATRIX ACCURATE
EXT PARAMETER STEP FIRST
NO. NAME VALUE ERROR SIZE DERIVATIVE
1 p0 1.85434e+01 1.84651e-01 6.05036e-05 -1.33478e-04
2 p1 1.88273e+01 2.64165e-01 9.00113e-05 -2.56887e-04
3 p2 -6.33418e+01 1.13032e+00 7.02783e-03 -1.96041e-07
FCN=51.5481 FROM MIGRAD STATUS=CONVERGED 75 CALLS 76 TOTAL
EDM=4.22859e-11 STRATEGY= 1 ERROR MATRIX ACCURATE
STEP FIRST
VALUE ERROR SIZE DERIVATIVE
2.01998e+01 3.30255e-01 5.89556e-05 3.55539e-05
1.62106e+01 4.17770e-01 7.17402e-05 -1.86939e-04
-6.72356e+01 1.47810e+00 5.22130e-03 -5.60456e-06
About PPS Sim
PPS Sim G4
Polarised Positron Source Simulation in Geant4
Version 0.1
Authors: S. Riemann, A. Schälicke, A. Ushakov
DESY, Zeuthen, Germany
Ok
Parameter Scan
Graph
OK
Save
mean Positron Energy
Number of Positrons
iAngle
p0 18.54 ± 0.1847
p1 10.83 ± 0.2642
p2 -63.34 ± 1.13
p0 20.2 ± 0.3303
p1 16.21 ± 0.4178
p2 -67.24 ± 1.478
Parameter scan
Analysis
histograms
hXY hXd... hXphsp hYphsp Ebeam hZ hE hEm...
OK
Save
hEltc
Entries 212
Mean 24.64
RMS 8.037
hElc
Entries 262
Mean 25.76
RMS 8.773
hE
Entries 519
Mean 18.58
RMS 10.43
Number of e+ [a.u.]
E [MeV]

Yield & Polarization

Yield & Polarization

- Input: photon spectrum (from helical Undulator)
- interaction with target
- tracking of particle
- apply damping ring acceptence
- derive yield & polarization



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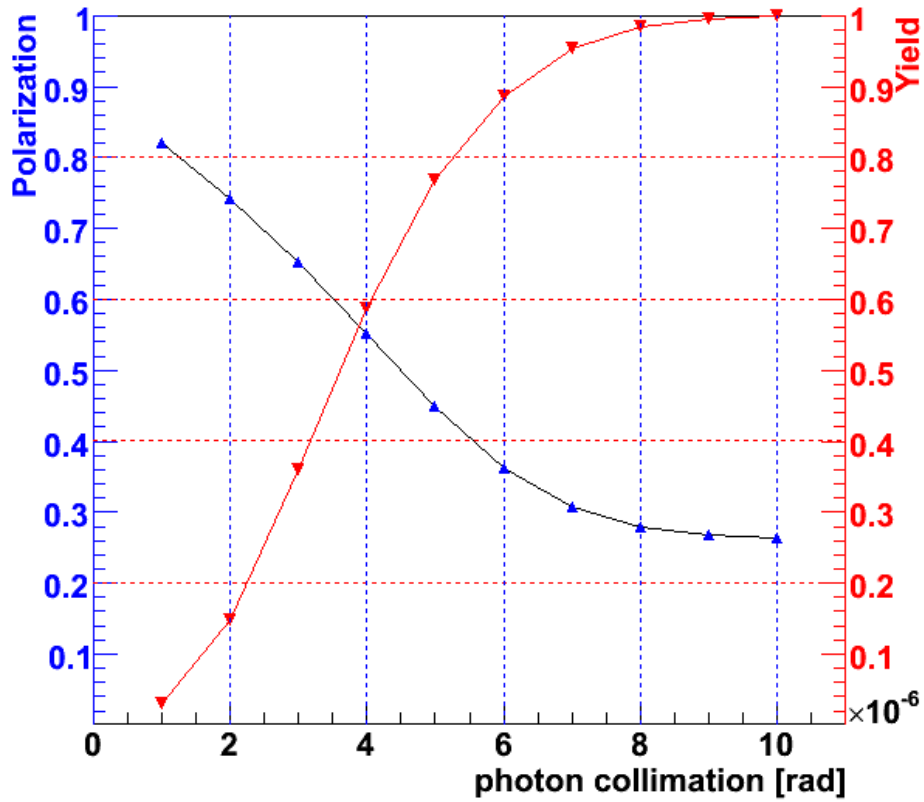


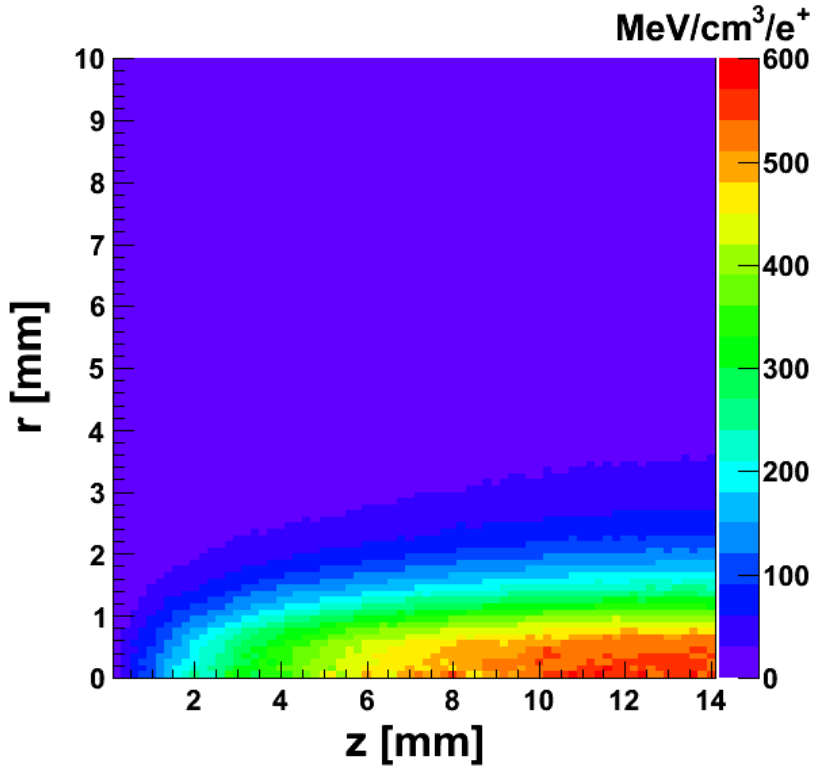
Peak Energy Deposition Density (PEDD)

PEDD

- in target (or windows)
- currently only in absence of magnetic field

Example

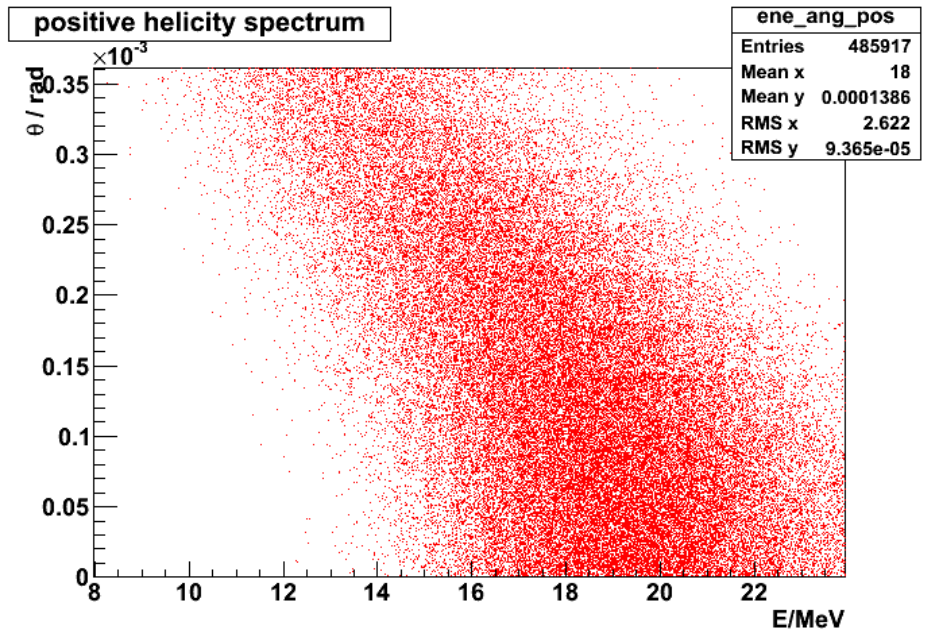
- Undulator based source
- 150 GeV drive beam
- 14 mm, Ti target



Compton source

Compton

- input spectrum from external file (by E. Bulyak)
- vary thickness and material
- derive yield and polarization



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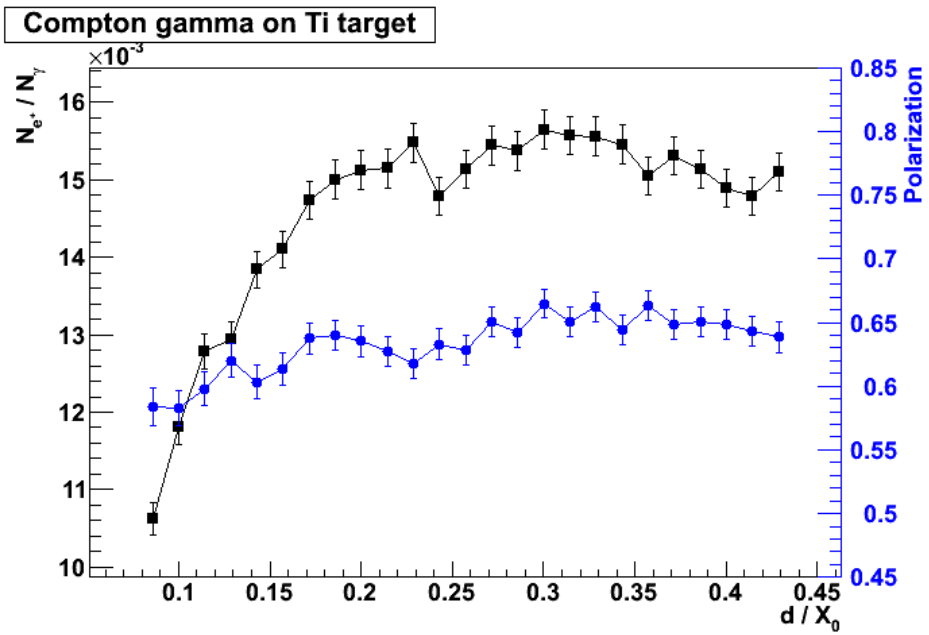

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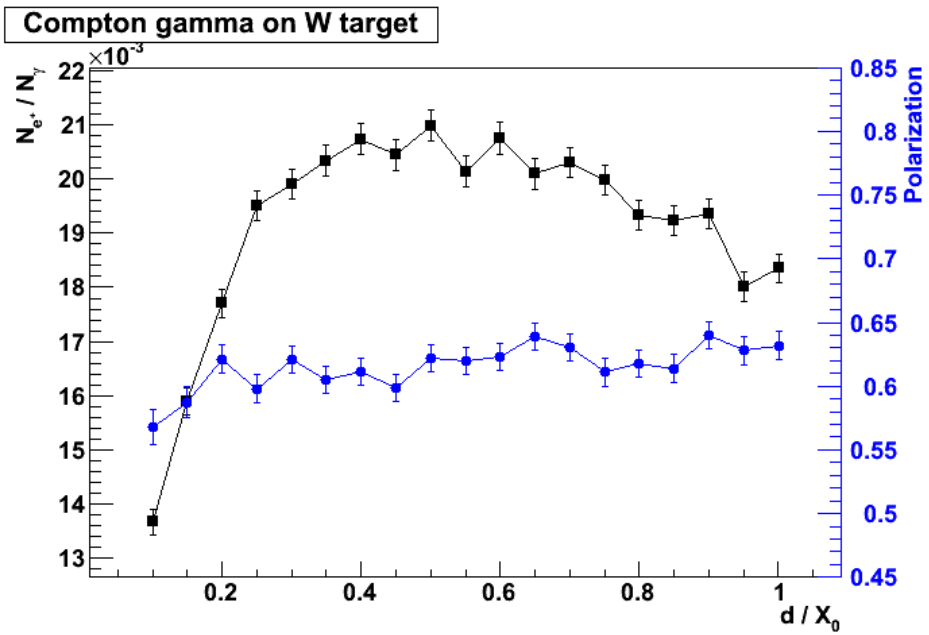


Summary

- PPS-Sim
  - exploitation of the Geant4 toolkit
  - provides Qt GUI for easy usage
  - allows batch runs for high statistics accumulation
  - uses ROOT for data analysis and persistency
- Features
  - e+ production: Undulator, Conventional
  - capture: AMD, QWT, Li-Lens
  - acceleration: RF & solenoid incl. spin tracking
- Available
  - source code available from pps-sim.desy.de or from author
  - documentation on LCpositrons Wiki
  - repository on DESY SVN Server

Appendix

Polarization in Geant4

- Stokes parameter
- Matrix formalism
- Examples
- Frames
- Spin representation problem

Spin Tool Workshop

- Working Session

Stokes parameter

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

Wave function :

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

Jones vector :

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

Spin density matrix :

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

Stokes parameter :

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

$$\sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_3 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Matrix formalism

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

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

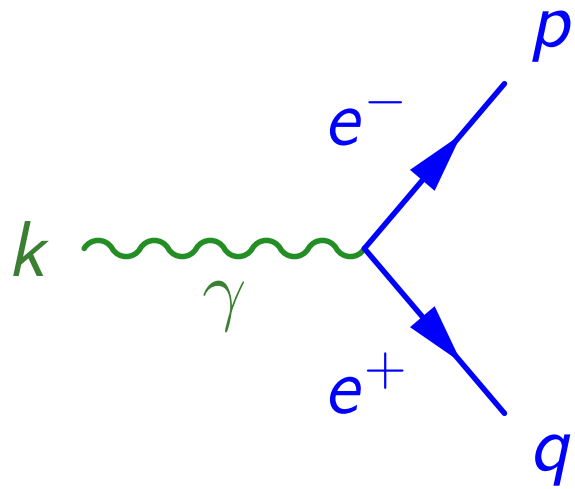
Transformation Matrix :

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

- Differential cross section
- Asymmetry
- Polarization
- Depolarization and polarization transfer

Pair production in field of nucleus

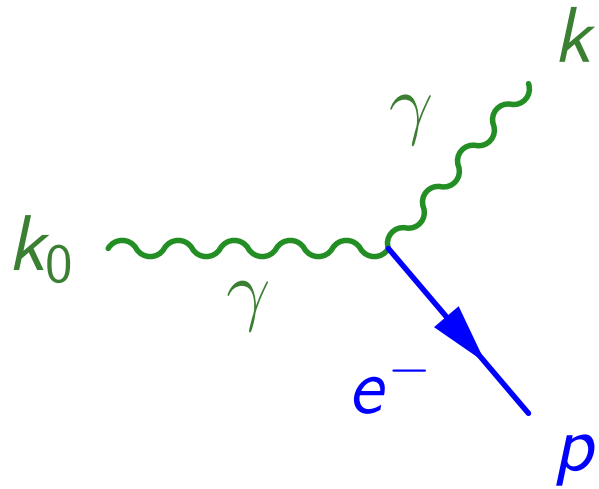
$$T = \begin{pmatrix} I & -D & 0 & 0 \\ 0 & 0 & 0 & -L \\ 0 & 0 & 0 & -T \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



$$I = [p^2 + (p-k)^2](3 + F(p,k;Z)) - 2p(p-k)(1 + G(p,k;Z))$$
$$D = 8p(p-k)\, G(p,k;Z)$$
$$L = k\{(2p-k)[3 + F(p,k;Z)] + 2(p-k)[1 + G(p,k;Z)]\}$$
$$T = 4k(p-k)\, H(p,k;Z)$$

Compton scattering on electron at rest

$$T = \begin{pmatrix} I & A & 0 & E \\ A & B & 0 & H_1 \\ 0 & 0 & C & H_2 \\ F & G_1 & G_2 & D \end{pmatrix}$$



Independent of electron spin **S** : (I, A, B, C, D)

$$I = 1 + \cos^2\theta + (k_0 - k)(1 - \cos\theta)$$

$$A = \sin^2\theta$$

$$D = 2\cos\theta + (k_0 - k)(1 - \cos\theta)\cos\theta$$

Dependent on electron spin **S** : (E, F, G_i, H_i)

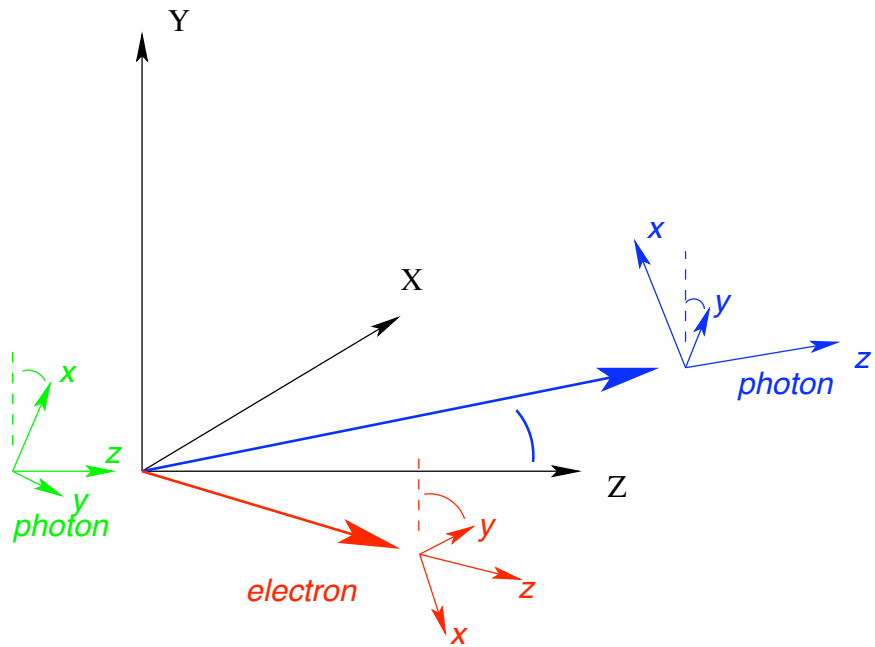
$$E = -(1 - \cos\theta)(\mathbf{k}_0\cos\theta + \mathbf{k}) \cdot \mathbf{S}$$

$$F = -(1 - \cos\theta)(\mathbf{k}\cos\theta + \mathbf{k}_0) \cdot \mathbf{S}$$

Frames

Interaction frame

- all participating particle define the x-z-plane
- incoming photon gives the z direction
- *particle 1* and gives the x-direction
- y-axis is then perpendicular to the scattering plane



Particle frame

- defined by the Geant4 routine `G4ThreeMomemtum::rotateUz()`

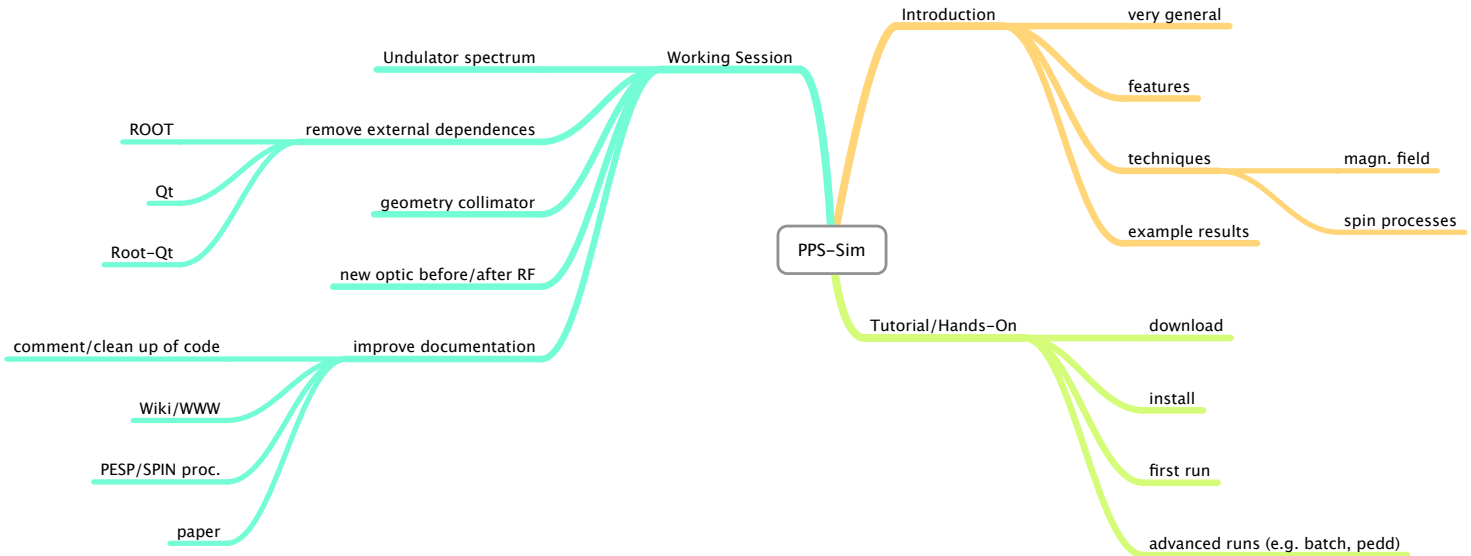
Global frame

- defined by the Geant4 geometry

Problem Spin representation

- Physics processes
  - polarization transfer/destruction in interaction with matter
  - three component Stokes vector
  - probabilistic interpretation
  - magnitude ≤ 1
  - Problem 1: no correlation effects
- Spin transport
  - governed by T-BMT
  - calculated using Runge-Cutta algorithms
  - Spin magnitude $= 1$
  - Problem 2: ambiguous transformation from Stokes vector to Spin (quantisation axis)

Working Session



Working Session