Overview on Compton Polarimetry

General Issues
- spin motion & alignment tolerances
- beam-beam effects & upstream vs. Downstream

Compton Polarimetry Basics
- beam parameters & Compton detection methods
- kinematics, cross sections & asymmetries
- laser choices and parameters

Specific Polarimeter Studies
- upstream polarimeter study (DESY)
- downstream polarimeter study (SLAC)
Spin Motion

\[ \frac{g-2}{2} = 1.16 \times 10^{-3} \]

\[ \theta_{\text{spin}} = \gamma \frac{g-2}{2} \theta_{\text{orbit}} = \frac{E_0}{0.44065 \text{ GeV}} \theta_{\text{orbit}} \]

\[ \phi_{\text{spin}} = \left[ 1 - \frac{g-2}{2} \right] \int \frac{B_z}{B_0} \frac{dl}{\rho} \approx \int \frac{B_z}{B_0} \frac{dl}{\rho} = 2 \phi_{\text{orbit}} \]

- Spin vector must be vertical in the damping ring
- Spin Rotator in the transfer line to the linac:
  manipulates spin direction for any desired orientation at the experiment
  must compensate all technical spin rotation effects along the machine
  requires fast polarimeter at the high-energy end for efficient tune-up
- Spin orientation is extremely sensitive to orbit deflections, at 250 GeV:
  \[ \theta_{\text{spin}} = 567 \theta_{\text{orbit}} \]
Spin motion along the accelerator

(e.g. for TESLA TDR topology)

<table>
<thead>
<tr>
<th></th>
<th>$z$ (km)</th>
<th>$\Delta \theta_x^{\text{orbit}}$ (mrad)</th>
<th>$\Delta \theta_y^{\text{orbit}}$ (mrad)</th>
<th>$\Delta \theta_x^{\text{spin}}$ (deg)</th>
<th>$\Delta \theta_y^{\text{spin}}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$ linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>front of linac</td>
<td>-16.5</td>
<td>0.0</td>
<td>-5.6</td>
<td>0º</td>
<td>-3.6º</td>
</tr>
<tr>
<td>end of vert. slope</td>
<td>-13.5</td>
<td>0.0</td>
<td>2.0</td>
<td>14º</td>
<td></td>
</tr>
<tr>
<td>end of linac</td>
<td>-1.65</td>
<td>0.0</td>
<td>0.1</td>
<td>0º</td>
<td>3.3º</td>
</tr>
<tr>
<td>HDS 5.3 mrad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>front of straigt section</td>
<td>-1.042</td>
<td>0.000</td>
<td>0.000</td>
<td>0º</td>
<td>0º</td>
</tr>
<tr>
<td>end of straigt section</td>
<td>-0.624</td>
<td>0.000</td>
<td>0.000</td>
<td>0º</td>
<td>0º</td>
</tr>
<tr>
<td>3 mrad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dump hall</td>
<td>-0.258</td>
<td>0.000</td>
<td>0.000</td>
<td>0º</td>
<td>0º</td>
</tr>
<tr>
<td>detector region</td>
<td>$e^+e^-$ IP</td>
<td>0.000</td>
<td>0.000</td>
<td>0º</td>
<td>0º</td>
</tr>
<tr>
<td>beam extraction region</td>
<td>FSEP, MSSEP, BV</td>
<td>0.110</td>
<td>0.0</td>
<td>-15º</td>
<td>-500º</td>
</tr>
</tbody>
</table>

Table 1: Orbit and spin rotation angles at 250 GeV. All angles are relative to the $e^+e^-$ detector axis. For 400 GeV multiply all spin rotation angles of this table by 1.6.
Alignment Tolerances

\[ \frac{\Delta P}{P} \leq 0.1\% \rightarrow \Delta \theta_{\text{spin}} \leq 45 \text{ mrad} \rightarrow \Delta \theta_{\text{orbit}} \leq 80 \mu\text{rad} \ (250 \text{ GeV}) \rightarrow \Delta \theta_{\text{orbit}} \leq 50 \mu\text{rad} \ (400 \text{ GeV}) \]

\[ \Rightarrow \ i.e. \ beam \ orbit \ directions \ at \ the \ polarimeter \ & \ e+e- \ detector \ must \ be \ extremely \ well \ aligned \ to \ each \ other \]

\[ \Rightarrow \ very \ tight, \ but \ not \ impossible \]

\[ \Rightarrow \ will \ require \ high-precision \ BPM\text{‘}s \ & \ surveying \ techniques \]

\[ \Rightarrow \ applies \ to \ any \ kind \ of \ polarimetry \ method \ & \ location \]
Beam-Beam Effects I: depolarization estimates for TESLA

angular spread of disrupted beam leads to corresponding spread of spin vector distribution

⇒ estimated depolarization*
  of disrupted beam: ≈ 1% (extracted beam)
  of beam at e+e- IP: ≈ 0.25% (lumi-weighted)

* only Thomas-BMT spin rotations effects considered

Table 2: Disrupted beam rms angular spreads of orbit and spin angles.

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\Delta \theta_x^{rms}$ (mrad)</th>
<th>$\Delta \theta_y^{rms}$ (mrad)</th>
<th>$\Delta \theta_x^{pol}$ (mrad)</th>
<th>$\Delta \theta_y^{pol}$ (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 GeV</td>
<td>245</td>
<td>27</td>
<td>130</td>
<td>15</td>
</tr>
<tr>
<td>400 GeV</td>
<td>153</td>
<td>17</td>
<td>130</td>
<td>15</td>
</tr>
</tbody>
</table>

SLAC – Jan. 6-8, 2005
ILC MDI - Workshop

K. Peter Schüler
Overview on Compton Polarimetry
### Beam-Beam Effects II: depolarization studies for NLC

Kathleen Thompson: SLAC-PUB-8761 (Jan. 2001)
(see also Yokoya & Chen: SLAC-PUB-4692)

#### NLC-500: outgoing e- depolarization:

<table>
<thead>
<tr>
<th></th>
<th>BMT</th>
<th>ST</th>
<th>TOTAL</th>
<th>BMT</th>
<th>ST</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(analytic results)</td>
<td>(simulation results)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLC-A</td>
<td>0.6%</td>
<td>0.4%</td>
<td>1.1%</td>
<td>0.4%</td>
<td>0.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>NLC-B</td>
<td>0.8%</td>
<td>0.4%</td>
<td>1.1%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.9%</td>
</tr>
<tr>
<td>NLC-C</td>
<td>0.9%</td>
<td>0.3%</td>
<td>1.1%</td>
<td>0.5%</td>
<td>0.3%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

#### NLC-500: luminosity-weighted e- beam depolarization:

<table>
<thead>
<tr>
<th></th>
<th>BMT</th>
<th>ST</th>
<th>TOTAL</th>
<th>BMT</th>
<th>ST</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(analytic results)</td>
<td>(simulation results)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLC-A</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>NLC-B</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>NLC-C</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

\[ \Delta P \text{ (downstream)} \approx 4 \times \Delta P \text{ (lumi-weighted)} \]

⇒ upstream value is much closer to lumi-weighted polarization!
### beam parameters & Compton detection methods

- **typical e+/e- beam parameters**
  - beam energies (GeV):
    - HERA: 27.5
    - SLC: 45.6
    - ILC: 45.6; 250; 400; 500
  - bunch population:
    - HERA: $4 \cdot 10^{10}$
    - SLC: $4 \cdot 10^{10}$
    - ILC: $2 \cdot 10^{10}$
  - no. of bunches per pulse:
    - HERA: $10.4 \cdot 10^6$
    - SLC: 120
    - ILC: 14 100
  - no. of pulses per sec:
    - HERA: 96 ns
    - SLC: 8.3 ms
    - ILC: 337 ns
  - no. of bunches per sec:
    - HERA: $10.4 \cdot 10^6$
    - SLC: 120
    - ILC: 14 100
  - bunch separation:
    - HERA: 96 ns
    - SLC: 8.3 ms
    - ILC: 337 ns
  - average beam current:
    - HERA: $\sim 50 \, \text{mA}$
    - SLC: $\sim 0.8 \, \mu\text{A}$
    - ILC: $\sim 45 \, \mu\text{A}$

- **Compton detection methods**
  - HERA
    - TPOL
    - LPOL
    - Cavity
  - SLD
  - ILC

<table>
<thead>
<tr>
<th>long/trans</th>
<th>HERA</th>
<th>HERA</th>
<th>HERA</th>
<th>SLD</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>e vs. $\gamma$ detection</td>
<td>$\gamma$</td>
<td>$\gamma$</td>
<td>$\gamma$</td>
<td>e ($\gamma$)</td>
<td>e ($\gamma$)</td>
</tr>
<tr>
<td>single event counting</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>(no)</td>
</tr>
<tr>
<td>multi event detection</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>laser pulse rate (Hz)</td>
<td>cw</td>
<td>100</td>
<td>cw</td>
<td>17</td>
<td>5 (*)</td>
</tr>
<tr>
<td>* downstream / ** upstream polarimeter proposals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14 100 (**)</td>
</tr>
</tbody>
</table>
Compton Kinematics

\[ \omega + E = \omega_0 + E_0 \simeq E_0 \]

\[ x = \frac{4E_0\omega_0}{m^2} \cos^2(\theta_0/2) \simeq \frac{4E_0\omega_0}{m^2} \]

\[ y = 1 - \frac{E}{E_0} = \frac{\omega}{E_0} \]

\[ r = \frac{y}{x(1-y)} \]

\[ \theta_\gamma = \frac{m}{E_0} \sqrt{\frac{x}{y} - (x + 1)} \]

\[ \theta_e = \frac{y}{1 - y} \theta_\gamma \]

\[ \omega_{max} = \frac{E_0 x}{1 + x} \]

\[ E_{min} = \frac{E_0}{1 + x} \]

\[ \begin{array}{cccccc}
E_0 & \lambda & \omega_0 & x & \omega_{max} & E_{min} \\
(\text{GeV}) & (\text{nm}) & (\text{eV}) & & (\text{GeV}) & (\text{GeV}) \\
45.6 & 1064 & 1.165 & 0.813 & 20.4 & 25.2 \\
 & 532 & 2.33 & 1.63 & 28.3 & 17.3 \\
 & 266 & 4.66 & 3.25 & 34.9 & 10.7 \\
250 & 1064 & 1.165 & 4.46 & 204 & 46 \\
 & 532 & 2.33 & 8.92 & 225 & 25 \\
 & 266 & 4.66 & 17.8 & 237 & 13 \\
400 & 1064 & 1.165 & 7.14 & 351 & 49 \\
 & 532 & 2.33 & 14.3 & 374 & 26 \\
 & 266 & 4.66 & 28.6 & 386 & 14 \\
\end{array} \]
Compton Polarimetry

cross sections, 
spin asymmetry, 
scattering angles

- $1 < P < +1$
- $1 < \lambda < +1$

$$A = \frac{d\sigma^- - d\sigma^+}{d\sigma^- + d\sigma^+}$$

$$\frac{d\sigma}{dy} = \frac{2\sigma_0}{x} \left[ \frac{1}{1-y} + 1 - y - 4r(1-r) + P\lambda r x(1-2r)(2-y) \right]$$
standard detection method: scattered electron detection with suitable magnetic spectrometer

\( E_0 = 45.6 \text{ GeV} \)
\( \omega_o = 4.66 \text{ eV (UV)} \)

\( E_0 = 250 \text{ GeV} \)
\( \omega_o = 2.33 \text{ eV (green)} \)

\( E_0 = 400 \text{ GeV} \)
\( \omega_o = 1.165 \text{ eV (IR)} \)

may need to adjust wavelength of laser to obtain acceptable coverage of Compton edge region for all beam energies
Photon Detection Option (with suitable calorimeter)

analyzing power = asymmetry of energy-weighted cross section integrals

\[ A_p = \frac{I^- - I^+}{I^- + I^+} \]

\[ I^\pm = \int y \frac{d\sigma^\pm}{dy} dy \]

⇒ May be attractive for Giga-Z (\(E_0 = 45.6\) GeV), to avoid need for UV-lasers
Luminosity for pulsed lasers

\[ \mathcal{L} = f_b N_e N_\gamma g \]

- \( f_b \) = bunch crossings per sec
- \( N_e, N_\gamma \) = no. of e, \( \gamma \) per bunch
- \( g \) = geometry factor
- \( \sigma_{xy}, \sigma_{y\gamma} \) = transverse laser beam size
- \( \sigma_{z\gamma} = c \sigma_{t\gamma} \) = laser pulse length
- \( \theta_o \) = laser crossing angle

\[ g = \frac{1}{2\pi \sigma_{z\gamma} \sigma_{y\gamma} \sqrt{1 + (0.5 \theta_o \sigma_{z\gamma} / \sigma_{y\gamma})^2}} \]

\[ \mathcal{L} = \frac{\mathcal{L}_{max}}{\sqrt{1 + (0.5 \theta_o \sigma_{z\gamma} / \sigma_{y\gamma})^2}} \]

\[ \mathcal{L}_{max} = \frac{f_b N_e N_\gamma}{2\pi \sigma_{z\gamma} \sigma_{y\gamma}} \]

\[ \Rightarrow \text{effectiveness of laser degrades with increasing pulse length \& crossing angle} \]
laser choices & parameters

1. **Q-switched Nd:YAG laser**
   - **pro** ⇒ very high pulse energy (up to several 100 mJ),
     robust commercial systems, relatively low cost
   - **con** ⇒ very low rep-rate (~5 Hz), i.e. only a small sampling fraction (1/2820) of all ILC bunches can be measured;
     inefficient due to long pulse length (ns’s)

2. **TESLA TTF rf-gun type Nd:YLF laser**
   - **pro** ⇒ pulse pattern matched to ILC bunch & pulse structure;
     100% of all ILC bunches will be measured;
     high efficiency due to short pulse length (10 ps);
     sufficient pulse energy (10-100 µJ) to achieve negligible stat. errors in 1 sec!
   - **con** ⇒ non-commercial system, ~ 400 k€ per laser

3. **Pulsed Fabry-Perot Cavity (R&D project at Orsay)**
   - **pro** ⇒ aims for similar performance as (2)
   - **con** ⇒ must operate complex laser system remotely in ILC tunnel (reliability!);
     feasibility must still be demonstrated (note: HERA Fabry-Perot is not pulsed!)
Nd:YLF laser parameters I

<table>
<thead>
<tr>
<th>configuration</th>
<th>( \lambda ) (nm)</th>
<th>( \epsilon_\gamma ) (eV)</th>
<th>( \langle P_L \rangle ) (W)</th>
<th>( j_\gamma ) (( \mu )J)</th>
<th>( \sigma_{\gamma \gamma} ) (ps)</th>
<th>( f_b ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESLA - 500</td>
<td>524</td>
<td>2.37</td>
<td>0.5</td>
<td>35</td>
<td>10</td>
<td>14100 = 5 \cdot 2820</td>
</tr>
<tr>
<td>TESLA - 800</td>
<td>1047</td>
<td>1.18</td>
<td>1.0</td>
<td>71</td>
<td>10</td>
<td>19544 = 4 \cdot 4886</td>
</tr>
<tr>
<td>Giga - Z</td>
<td>262</td>
<td>4.74</td>
<td>0.2</td>
<td>14</td>
<td>10</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 8: Tentative polarimeter laser specifications for TESLA-500, TESLA-800, and Giga-Z. \( P_L \) is the average laser power, \( j_\gamma \) the pulse energy, \( \sigma_{\gamma \gamma} \) the pulse length, and \( f_b \) is the total number of laser pulses per second.

laser schematic of TTF injector gun:
regen. multi-stage Nd:YLF ampl.
(built by Max-Born-Inst.)
operates at nominal pulse & bunch pattern of TESLA

Fig. 1. Schematic overview of the TTF photoinjector laser system.
**Nd:YLF laser parameters II**

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse train</td>
<td>800 pulses spaced by 1 µs</td>
<td>Achieved</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
<td>Achieved, run mode 1 Hz</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>5 µJ (262 nm)</td>
<td>50 µJ (262 nm)</td>
</tr>
<tr>
<td>Pulse length (262 nm)</td>
<td>2–10 ps (sigma)</td>
<td>7.1 ± 0.6 ps (sigma)</td>
</tr>
<tr>
<td>Transverse profile</td>
<td>Flat-top</td>
<td>Achieved</td>
</tr>
<tr>
<td>Flat-top homogeneity</td>
<td>± 10%</td>
<td>Partially achieved</td>
</tr>
<tr>
<td>Energy stability</td>
<td>Peak–peak</td>
<td></td>
</tr>
<tr>
<td>Train to train</td>
<td>≤ ± 10%</td>
<td>≤ ± 5%</td>
</tr>
<tr>
<td>Pulse to pulse</td>
<td>≤ ± 10%</td>
<td>≤ ± 5%</td>
</tr>
<tr>
<td>Synchronization</td>
<td>To reference RF signals</td>
<td>Achieved</td>
</tr>
<tr>
<td>Phase stability</td>
<td>≤ 1 ps rms</td>
<td>≤ 1 ps rms</td>
</tr>
</tbody>
</table>

Running experience with the laser system for the RF gun based injector at the TESLA Test Facility linac

S. Schreiber* a, I. Will b, D. Sertore a, b, c, A. Liero b, W. Sandner b

*Deutsches Elektronen-Synchrotron, D-22603 Hamburg, Germany
bMax-Planck-Institut, D-14476 Berlin, Germany
NIM A 445 (2000) 427

Laser for TTF injector gun
S. Schreiber et al.
NIM A 445 (2000) 427
Specific Polarimeter Studies

A. upstream polarimeter study (DESY)

For details: V. Gharibyan, N. Meyners, K.P. Schüler, www.desy.de/~lcnotes/notes.html
LC-DET-2001-047
Specific Polarimeter Studies

B. downstream polarimeter study (SLAC)

4-magnet chicane with 2nd beam focus and laser crossing at center of chicane

low-energy Compton electrons will be well-separated from disrupted beam (for 20 mrad linac crossing angle!)

Laser: 532 nm, 100 mJ, 2 ns FWHM, 5 Hz, 100 µm spot size, 11.5 mrad beam crossing angle

Summary

Upstream polarimeter study (DESY):
- assumes suitable magnetic bend (~ 1 mrad) with dog-leg or chicane geometry
- custom-built laser system (similar to existing facility at DESY) with pulse pattern matched to ILC bunch structure (14 100 per sec)
- very fast, robust facility, precision of $\Delta P/P \sim 0.25\%$

Downstream polarimeter study (SLAC):
- Assumes 20 mrad linac crossing angle with suitable magnetic chicane
- commercial laser system (similar to SLD polarimeter laser) which samples fraction of ILC bunches (5 per sec)
- Low-energy Compton electrons are well-separated from disrupted beam background, precision of $\Delta P/P \sim 0.25\%$
additional material: downstream (extraction line) studies for TESLA

Laser Beam Topology

TESLA beam extraction scheme

laser beam crossing inside the big detector!

place Compton electron detector at \( z = 65 \) m (behind MSEP magnet)
additional material: downstream (extraction line) studies for TESLA

250 GeV nominal beam energy, 40 000 disrupted beam events, simulated with „guinea pig“, distributions at e+e- IP

extrapolated background (at IP & z = 65 m) for standard 20 mm x 20 mm collimator aperture
additional material: downstream (extraction line) studies for TESLA

Compton el. detector at $z = 65$ m

green laser (same type as for upstream polarimeter)

Conclusion: large background from disrupted beam; downstream polarimetry is not possible for head-on linac configurations!