Precision Polarimetry for Future $e^+e^-$ Linear Colliders

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on behalf of the Linear Collider Physics & Detector Study

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Two Linear Collider Concepts

**CLIC**
- $\sqrt{s} = 0.5, 1.4, 3$ TeV
- technology under development
- $P(e^-) = 80\%$, $P(e^+) = 0$ ($x\%$)
- beam energy spread: 0.3%
- energy loss (Beamstrahlung): 28%

**ILC**
- $\sqrt{s} = 90, 200...500$ GeV ($...1$ TeV)
- technology proven (FLASH, ...)
- $P(e^-) \geq 80\%$, $P(e^+) \approx 30\%(60\%)$
- beam energy spread: 0.1%
- energy loss (BS): 4.5%
Introduction

Compton Polarimeters

Spin Tracking

At the IP

Conclusions

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Polarimetry Concept

**Wanted:**
- long-term luminosity weighted polarisation average

\[
\langle P \rangle = \frac{\int P \cdot \mathcal{L} dt}{\int \mathcal{L} dt}
\]  

(1)

- for each data set, to per mille level precision!

**Tool Kit:**
- Compton polarimeters upstream (& downstream) of $e^+e^-$ IP
- Spin tracking between polarimeters and IP
- Cross-check with $e^+e^-$ collision data
**Working Principle**

**Laser Compton scattering:**

- $\mathcal{O}(10^3)$ events / bunch
- $\frac{d\sigma}{dE}$ depends on $P_z$
- $\frac{d^2\sigma}{dE d\phi}$ depends on $P_{x,y}$
- asymmetry w.r.t. to laser helicity $\sim P_z (P_{x,y})$

**Magnetic Chicane:**

- deflects scattered $e^\pm$ away from beam
- transforms $E \rightarrow x \Rightarrow$ measure $dN/dx$
- 4 magnet design:
  - restores unscattered beam
  - renders position on detector independent of $E_{\text{beam}}$
Polarimeter Uncertainties & Detector Requirements

Polarimeter Uncertainties

- laser polarisation: \( \leq 0.1\% \)
- alignment w.r.t. beam: 0.1...0.2%
  - lateral position ("Compton edge"): need \( \mathcal{O}(0.1 \text{ mm}) \) for \( \leq 0.1\% \)
  - tilts: typ. 0.05%/ mrad
- detector linearity: aim for 0.1...0.2%

⇒ detector design with excellent possibilities to monitor alignment and linearity mandatory!

Detector Requirements

- alignment & linearity
- excellent monitoring, if possible online
- homogeneous response
- robustness against backgrounds (beam gas, beam halo, \( e^+ e^- \) pairs, muons, synchrotron rad.) esp. at downstream location
- dynamic range: factor \( \mathcal{O}(10^2) \) near Compton edge
Gas Cherenkov Detector \cite{JINST 7, P01019 (2012)}

- used in so far most precise Compton polarimeter (0.5..1% at SLD)
- robust against background via high Cherenkov threshold (10 MeV for $e^{-}$ in C$_4$F$_{10}$)
- in-situ monitoring improvements:
  - non-linearity to few per mille level $\rightarrow$ use LED between trains
  - angular alignment based on multi-anode photon detectors
- testbeam operation of 2-channel prototype $\rightarrow$ achieved tilt alignment of 0.1°
Alternative Detectors

Quartz Cherenkov Detector

[A. Vauth]

- high photon yield: $\sim 10^3$ photo $e^-$ per Compton $e^-$
- can resolve Compton $e^-$ peaks in photoelectron (QDC) spectrum
- $\rightarrow$ “self-calibrating”
- optimised geometry based on Geant4 simulation

Silicon Pixel Detector

[G. Alexander, I. Ben Mordechai]

- option for transverse polarimetry
- standard LHC style pixel detector ok in terms of rad. hardness and occupancy (ILC upstream)
- simulation result based on ILC upstream chicane: can get $dP_y/P_y = 0.2\%$
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Spin Tracking

Spin Tracking in Beam Delivery System

[M. Beckmann]

From upstream via IP to downstream

- using BMAD, based on full T-BMT equation
- for \( B_\perp \) only: \( \theta_{spin} = \left( \frac{g-2}{2} \cdot \gamma + 1 \right) \cdot \theta_{orbit} \approx 568 \cdot \theta_{orbit} \)
- start with \( P_z = 80\% \), show median \( \pm 1\sigma \) band from 1000 runs

- perfect lattice
- \( 5(10) \, \mu m \) random misalignments (& corr. kickers, fast-feedback)
- + detector solenoid, anti-DID, crab cavities
- + collisions (500 GeV, w.s.)
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Measuring the Depolarisation

- Collision effect at IP $\simeq 0.2\%$
- Upstream measurement very close to $\langle P \rangle$
- $P_z$ drops another $1.2\% \pm 0.5\%$ from IP to downstream pol.
- Dominated by energy spread after collision and extraction line quad’s
- Correlation with $y$ position:
- Reduce effect by small laser spot?

⇒ Complement polarimeters with longterm $\langle P \rangle$ from collision data
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Depolarisation at CLIC [J. Esberg, D. Schulte et al]

- higher energy, smaller bunches ⇒ need strong field effects (c.f. talk by A. Hartin)!
- implemented in GuineaPig++
- studied depolarisation in collision as function of vertical offset of the beams ($\sigma_y = 1 \text{ nm}$)
- total depolarisation: $\gtrsim 6\%$
- only in 1% of nominal $\sqrt{s}$: $\lesssim 0.1\%$
- a priori don’t know actual $\sqrt{s}'$ on single event basis, e.g. for channels with missing 4-momentum
Luminosity weighted polarisation average

\[ \langle P \rangle \text{ from leptonic single } W / Z \text{ and single } \gamma \quad [G.\ Wilson] \]

- dominated by \( e^+ e^- \rightarrow W^{\pm} e^{\mp} \nu_e \) and \( e^+ e^- \rightarrow \nu_e \bar{\nu}_e Z / \gamma \)
- measure total 4 cross-sections for up to 9 possible polarisation configurations: \(+, -, ++, --, -0, +0, 0-, 0+, 00\)
- determine either \( |P^L_{e^-}| = |P^R_{e^-}| \) and \( |P^L_{e^+}| = |P^R_{e^+}| \) or additionally low small differences \( \delta_- \) and \( \delta_+ \)
- assume 2 ab\(^{-1}\) at 3 TeV, 25% +, 25% −, 50% others
- \( \delta \)'s free:
  \[ \Delta |P_{e^+}| / |P_{e^+}| = 0.3\%, \Delta |P_{e^-}| / |P_{e^-}| = 0.16\%, \delta = 0 \pm 0.27\% \]
Luminosity weighted polarisation average

\[ \langle P \rangle \text{ from } \frac{d\sigma(e^+e^- \rightarrow W^+W^-)}{d\cos\theta} \quad [I. \ Marchesini] \]

- measure for 4 sign combinations: \( P = (+, -), P = (-, +), P = (+, +), P = (-, -) \)
- fit for \( |P(e^+)|, |P(e^-)| \) (and triple gauge couplings)
- optionally unequal \( |P| \) ⇒ take differences from polarimeters
- can determine polarisations to 0.1...0.2\% level with \( \mathcal{O}(1\text{ab}^{-1}) \)
- systematically limited by polarimeters ⇒ minimize difference by fast helicity reversal or need additional runs with one \( P = 0 \)

**60\% e^+**

**30\% e^+**
Conclusions

- per mille level determination of the luminosity weighted polarisation average $\langle P \rangle$ needs
  - excellent Compton polarimetry
  - detailed understanding of spin transport between polarimeter(s) and IP
  - detailed understanding of collision effects
  - cross-check from collision data
- in all these aspects progress has been achieved
- measuring $\langle P \rangle$ to a few per mille seems achievable for ILC
- less studied so far, but probably also valid for CLIC