High-precision polarimetry at the LHeC

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- Introduction
  - Why?
  - Compton back-scattering polarimetry
- State of the art
  - SLC
  - HERA
  - Preliminary conclusion
- On-going developments
  - ILC
  - Laser technology
- Conclusion: towards very high precision polarimetry
Electroweak physics sensitive to polarization
Informations on structure functions ratios

Polarisation Asymmetry and $R = \text{NC/CC}$

\[ \frac{2}{P_L - P_R} \cdot A^\pm \simeq \pm \kappa_{Ze} e \frac{F_2^Z}{F_2^Z / (F_2 + \kappa_{Ze} e Y_x P x F_3^Z)} \simeq \pm \kappa_{Ze} e \frac{F_2^Z}{F_2} \]

Classic asymmetry (Prescott et al, 1978) accesses weak interaction, $F_2^Z$ is a new, direct measure of valence quarks at high $x$

\[ \frac{2}{P_L - P_R} \cdot A^\pm \simeq \pm \kappa \frac{1 + d_u/u_v}{4 + d_u/u_v} \]

$R$ accesses weak interaction and the pure weak structure functions which are best measured at the LHeC/FCC-eh

\[ R^\pm \simeq \frac{2a_e^2}{(1 \pm P) \cos^2 \Theta} \cdot \frac{Y_+ F_2^Z - Y_- P x F_3^Z}{Y_+ W_{2}^\pm + Y_- x W_{3}^\pm} \]

Note that in experiment you would measure the cross sections and determine all correlations which is still more informative than $A$ or $R$ but contains their physics.

Precise Compton polarimetry is required to reach physics goals

LHeC Workshop, LAL, Orsay, France, 27/06/2018

Aurélien MARTENS
Compton back-scattering polarimetry

Start in '90s at HERA and SLC

\[
\left( \frac{d^2 \sigma}{dx d\phi} \right)_{\text{comp}} = \left( \frac{d^2 \sigma}{dx d\phi} \right)_{\text{unpol}} \cdot \left\{ 1 - \mathcal{P}_\gamma \left[ \mathcal{P}_z A_\gamma^z(x) + \mathcal{P}_t \cos \phi A_\gamma^t(x) \right] \right\},
\]

\[
A_\gamma^z \equiv \sigma_0^2 y [1 - x(1 + y)] \left\{ 1 - \frac{x}{[1 - x(1 - y)]^2} \right\} \cdot \left( \frac{d^2 \sigma}{dx d\phi} \right)_{\text{unpol}}^{-1}
\]

\[
A_\gamma^t \equiv \sigma_0^2 y x(1 - y) \sqrt{4y(1 - x)} \left( \frac{d^2 \sigma}{dx d\phi} \right)_{\text{unpol}}^{-1}.
\]

Measure scattered photons and/or electrons

→ Larger sensitivity expected at the threshold energy

→ e- counters (SLC/ILC)

→ γ calorimeter (HERA)
Review of the state of the art:
• Usual design ?
• Detector choice ?
• Systematics ?
SLC design: detection of electrons
SLC design: Cherenkov counters

- Channel cross-calibration and linearity is critical
- Position sensitivity of the detector
- Laser polarization can be improved → see next slides

Systematics:
- Laser Polarization: 1.0%
- Photomultiplier Linearity: 0.6%
- Detector Position Calibration (and EGS simulation): 0.4%
- Electronic Noise and crosstalk: 0.2%
- Inter-channel consistency: 0.5%

or a total of \( \delta P/P = \delta A_{LR}/A_{LR} = 1.3\% \).

About 1000 scatters per crossing
HERA T-POL

2 channel W-scintillator (up/down) w/ WLS+PMT + 2 additional readouts (left/right) for calibration

Fit of energy and vertical asymmetries → Longitudinal and transverse polarisations → % level precision

Small number (<<1) of scatters per crossing

Barber et al., NIMA329 (1993) 79

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Low sensitivity to threshold & backgrounds

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>$\Delta P_e / P_e$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzing power</td>
<td>$\pm 1.2$</td>
</tr>
<tr>
<td>Analyzing power long-term instability</td>
<td>$\pm 0.5$</td>
</tr>
<tr>
<td>Gain mismatching</td>
<td>$\pm 0.3$</td>
</tr>
<tr>
<td>Laser light polarization</td>
<td>$\pm 0.2$</td>
</tr>
<tr>
<td>Pockels cell misalignment</td>
<td>$\pm 0.4$</td>
</tr>
<tr>
<td>Electron beam instability</td>
<td>$\pm 0.8$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$\pm 1.6$</strong></td>
</tr>
</tbody>
</table>

Extrapolation of calibration? Data driven control channel?

Thousand of scatters per crossing

Beckmann et al., NIM A479 (2002) 334

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Careful design of ellipsometer <0.3% systematics
Multi-parameter fit of Beam-gas contribution, synchrotron radiation, Compton scattering
Bunch per bunch measurement cumulated over 400k turns in HERA ring

intermediate number (~1) of scatters per crossing

Helicity opposite sign
Helicity same sign
HERA: bunch/bunch measurements

Bunch per bunch measurement required

- Detector knowledge and performance
- Position sensitivity of the detector (too small?)
- Synchrotron radiation treatment

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta P/P(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrelated errors</td>
<td></td>
</tr>
<tr>
<td>HERA beam variations</td>
<td>0.4</td>
</tr>
<tr>
<td>Detector parameters</td>
<td>0.5</td>
</tr>
<tr>
<td>Correlated errors</td>
<td></td>
</tr>
<tr>
<td>BGP and BBP cross-sections</td>
<td>negligible</td>
</tr>
<tr>
<td>Calorimeter resolution and ADC to energy conversion</td>
<td>0.4</td>
</tr>
<tr>
<td>Merging of the SRP peak</td>
<td>0.4</td>
</tr>
<tr>
<td>Laser polarisation circularity</td>
<td>0.3</td>
</tr>
<tr>
<td>Electronic sampling subtraction</td>
<td>0.4</td>
</tr>
<tr>
<td>Calorimeter position scan (horizontal)</td>
<td>0.4</td>
</tr>
<tr>
<td>Calorimeter position scan (vertical)</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Preliminary conclusion

% level polarimetry achieved at SLC and HERA with Compton polarimetry, systematics limited

- Careful optical design and ellipticity control at 0.3% was obtained at HERA
- Bunch per bunch measurements are of interest to control single bunch polarization
- Two technologies have been tested:
  - electron counting
    - Direct xsec measurement
  - photon calorimetry
    - Infer polarization from energy spectra and/or energy dependent geometrical asymmetries
    - Low/medium/high yield options (driven by background level)

Systematics:
- All measurements limited, among other effects, by alignment of detectors
- Detector performance calibration also a critical contribution
  - PMT response
  - Electronic noise
  - Energy dependent efficiencies (calorimetric measurements only)

Cherenkov detector can be integrated in LHeC environment? 
Radiation hard and fast (25ns) detector?
The path towards per-mille level polarimetry @ LHeC:
- on going developments for ILC
- available laser source
ILC design in a nutshell

In situ LED calibration

Quartz cherenkov counters?
→ Data driven calibration
→ Signal collection time?

Radiation hardness to integrate it in LHeC tunnel?
Possible calorimetric detector

Relatively fast calorimeter
Different use-case: probability of 2 successive events in a given calorimeter cell is low in LHCb

R&D is required
Prefer CsI? BaF2:Y (Mu2e-II developments)
Radiation hardness level required?
Possible Laser design: industrial table-top laser

**Laser specifications**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>TANGOR</th>
<th>TANGOR HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average power</td>
<td>&gt; 50 W</td>
<td>&gt; 100 W</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>&gt; 300 µJ</td>
<td>&gt; 500 µJ</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&lt; 500 fs to 10 ps</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Single shot to 40 MHz</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>1030 nm</td>
<td></td>
</tr>
<tr>
<td>Beam quality</td>
<td>Beam $M^2 &lt; 1.3$</td>
<td></td>
</tr>
<tr>
<td>Spatial mode</td>
<td>TEM_0</td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>68 cm x 46 cm x 16 cm</td>
<td></td>
</tr>
</tbody>
</table>

Possible solution if 1-10 scatters per crossing

Ultra compact! → integrate close to Compton IP?

**Applications**

Demanding industrial sector: routinely operating systems

NB: Also TRUMPF Gmbh producing similar systems (but lower repetition rate advertised)

http://www.amplitude-systemes.com
Possible Laser design: Fabry-Perot cavity

ThomX: High gain Fabry-Perot cavity (10k)
33MHz operation with >100kW stored power under routine operations

LHeC is less demanding: about 1.2kW
→ lower cavity gain, helicity may be switched within 90μs

Possible solution if > 10 scatters per crossing
Can operate at lower power
% level polarimetry achieved at SLC and HERA with Compton polarimetry, systematics limited

Studies have been continued for ILC where precision is required to be about 0.25%

- Careful optical design and ellipticity control at 0.3% was obtained at HERA
- Bunch per bunch measurements are required to control single bunch polarization
- Two technologies have been tested: electron counting vs photon calorimetry
- Laser system can be shrinked using nowadays industrial systems or non planar FP cavity

Systematics:
- Laser ellipticity can be improved with synchronous measurement techniques?
- Alignment of detectors is critical: review detector design
- In situ/data driven detector performance calibration
- Redundant measurements? With different technologies?
- Play with laser parameters: energy, 2-color laser system?

Detailed simulations needed, use more recent technologies, keep in mind:
- Systematics
- Radiation hardness
- Time response of detectors
- Background levels
PTO laserhead
EOM
phase feedback electronics
Amplifier 2
AOM

S. Schreiber, TESLA Collaboration Meeting, WG III, 16-Sep-2003
Figure 3-9: Compton Polarimeter Laser Transport System.

M: Mirror  
MP: Compensating Mirror Pair  
GP: Glan Prism  
CP: Circularly Polarizing Pockels Cell  
PS: Compensating Phase Shift Pockels Cell  
PP: Pickoff Plate  
LTL: Laser Transport Line  
L: Lens  
PD: Photo-diode  
W: Window  
ND: Neutral Density Filter  
CIP: Compton Interaction Point  
P: Calcite Prism
Background fluctuations in between changes of laser helicity

Pile-up effects are included
HERA L-POL 2/T-POL comparison

Compatible results with more precision with L-POL

One measurement every 10s

- Detector knowledge and performance
- Position sensitivity of the detector
- Synchrotron radiation treatment
Spin (longitudinal) polarization of e- beams at LHeC is an involved subject

Ring-ring option:
- Spin tends to (anti-)align with B field due to synchrotron radiation (ST, BK)
  - Spin precess (T-BMT equation) quickly (large 'spin tune')
  \( \rightarrow \) Depolarization arise due to vertical betatron motion, skew quads, spin rotators, solenoids
  \( \rightarrow \) Depolarization increases with energy

LINAC-ring option:
  \( \rightarrow \) Depolarization can be small
  \( \rightarrow \) chromatic effects in spin rotators

Precise Compton polarimetry is required to reach physics goals