The Longitudinal Polarimeter at HERA

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Precision Electron Polarimetry at Jlab
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• Electron Polarization at HERA
• Laser System & Calorimeter
• Statistical and Systematic Precision
• Laser Cavity Project
• Summary and Outlook
Self polarization of electrons by Synchrotron radiation emission in curved sections: Sokolov-Ternov effect ($\tau \sim 30$ min.)

\[ P(t) = P_\infty \cdot (1 - e^{-t/\tau}) \]
Sokolov Ternov Effect

- $P_{ST} = 0.924$ for an ideal, flat machine, independent of any machine parameter
- $\tau_{ST} = 37 \text{ min}$ for HERA @ 27.5 GeV (prop. $1/\gamma^5$, $R^3$)
- Depolarization effects ($\tau_D$) in a real machine → can substantially reduce $P_{max}$:

$$P_{max} = P_{ST} \frac{\tau_D}{\tau_{ST} + \tau_D}$$

→ and effective build-up time constant $\tau$:

$$\tau = \tau_{ST} \frac{\tau_D}{\tau_{ST} + \tau_D}$$

- $P_{ST}$ and $\tau_{ST}$ calculable from first principles
  → a simultaneous measurement of $P_{max}$ and $\tau$ provides a calibration method:

$$P_{max} = \tau \left(\frac{P_{ST}}{\tau_{ST}}\right) = k \cdot P_{meas}$$
\[ \Delta \phi_{\text{spin}} = G_\gamma \Delta \phi_{\text{orbit}} \]

Spin Tune at 27.5 GeV

\[ G_\gamma = \frac{E}{0.440 \text{ GeV}} = 62.5 \]

<table>
<thead>
<tr>
<th>( \Delta \phi_{\text{spin}} ) (mrad)</th>
<th>( \Delta \phi_{\text{orbit}} ) (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>12.5</td>
</tr>
<tr>
<td>90°</td>
<td>25</td>
</tr>
<tr>
<td>180°</td>
<td>50</td>
</tr>
</tbody>
</table>
**Compton Scattering:**
\[ e^+ + \lambda \rightarrow e^++\gamma \]

**Cross Section:**
\[
\frac{d\sigma}{dE_\gamma} = \frac{d\sigma_0}{dE_\gamma}[1 + P_e P_\lambda A_z(E_\gamma)]
\]

- \( d\sigma_0, A_z \): known (QED)
- \( P_e \): longitudinal polarization of e beam
- \( P_\lambda \): circular polarization (\( \pm 1 \)) of laser beam

**Asymmetry:**
\[
A \propto E_e E_\lambda
\]

**Compton edge:**
\[
E_\gamma^{\text{max}} \propto E_e^2 E_\lambda
\]
Compton Polarimetry at HERA

Operating Modes and Principles

Laser Compton scattering off HERA electrons

TPol

LPol

CW Laser – Single Photon

Pulsed Laser – Multi Photon

Flip laser helicity and measure scattered photons

\[ P_y = 0.59 \]

Spatial Asymmetry

\[ P_z = 0.59 \]

Rate or energy Asymmetry

Statistical Error \( \Delta P = 1\% \) per minute @ HERA average currents
Experimental Setup - Calorimeter

Calorimeter position

NaBi(WO₄)₂ crystal calorimeter

segmentation → position detection of Compton photons

NaBi(WO₄)₂ crystals: 22 x 22 x 200 mm³

ρ : 7.57 g cm⁻²
Rₘ : 2.38 cm
σₜ : 12 ns

X₀ : 1.03 cm
rad. hard. : < 7 x 10⁷ rad
n : 2.15
Experimental Setup – Laser System

- M1/2 M3/4 M5/6: phase-compensated mirrors
- laser light polarization measured continuously in box #2
Experimental Setup - Details

beam expander

HERA tunnel

calorimeter position

NBW calorimeter
**Laser Control - COP**

- Synchronizing laser and electron beam
- Optimize luminosity
- Optimize \( \lambda \) polarization
- Center \( \gamma \) beam on calorimeter
- Control & readjust all parameters: ...
  - laser spots on all mirrors using CCD cameras

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**Automatic Control**
Polarimeter Operation I

Single-Photon Mode

Advantages:
- Large asymmetry: 0.60 (max)
- Easy comparison to \(d\sigma/dE\)

Disadvantage:
- \(dP/P = 0.01\) in 2.5 h (too long)

\[
A_s(E_\gamma) = \frac{\sigma_{3/2} - \sigma_{1/2}}{\sigma_{3/2} + \sigma_{1/2}} = P_e P_\lambda A_z(E_\gamma)
\]
Polarimeter Operation II

Multi-Photon Mode

Advantages:
- eff. independent of brems. bkg and photon energy cutoff
- dP/P = 0.01 in 1 min

Disadvantage:
- no easy monitoring of calorimeter performance

\[
A_m = \frac{I_{3/2} - I_{1/2}}{I_{3/2} + I_{1/2}} = P_e P \lambda A_p
\]

\[
A_p = \frac{\Sigma_{3/2} - \Sigma_{1/2}}{\Sigma_{3/2} + \Sigma_{1/2}} = 0.184 \quad \text{(if detector is linear)}
\]
Polarization Determination

\[ A_p = \frac{\Sigma_{3/2} - \Sigma_{1/2}}{\Sigma_{3/2} + \Sigma_{1/2}} \]

\[ = 0.193 \] (for crystal calorimeter)

\[ \Sigma_i = \int_{E_{\text{min}}}^{E_{\text{max}}} \left( \frac{d\sigma}{dE} \right)_i E \cdot r(E) dE \]

**Question:**
Is response function **linear** over full single to multi-photon range?

**Test beam results**

- **DESY:** 0.9% syst. uncertainty
- **CERN:** 0.8% syst. uncertainty
**Polarization Performance**

**HERA:** 220 bunches separated by 96 ns

- 174 colliding + 15 non-colliding = 189 filled bunches

- 20 min measurement
  - $dP/P = 0.03$ in each bunch

- **Time dependence:**
  - helpful tool for tuning

![Graph showing polarization versus bunch number and electron polarization over time](image)
"Non-Invasive" Method

Possible to 'empty' an electron bunch with a powerful laser beam at HERA
A large Systematic Effect - Solved

In multi-photon mode:
1000 γ’s → 6.8 TeV in detector

Protect PMT’s from saturation
→ insert Ni foil in 3mm air gap

Problem:
NBW crystals are 19 X₀
→ small shower leakage
  with large analyzing power

\[ A_p(\text{w/ foil}) = 1.25 \times A_p(\text{w/o foil}) \]

No light attenuators are used since early 1999
### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta P_e/P_e$ (%) (2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analyzing Power $A_p$</strong></td>
<td>$\pm 1.2^\alpha$</td>
</tr>
<tr>
<td>- response function</td>
<td>($\pm 0.9$)</td>
</tr>
<tr>
<td>- single to multi photon transition</td>
<td>($\pm 0.8$)</td>
</tr>
<tr>
<td><strong>$A_p$ long-term instability</strong></td>
<td>$\pm 0.5^\beta$</td>
</tr>
<tr>
<td>- PMT linearity (GMS system checked)</td>
<td>($\pm 0.4$)</td>
</tr>
<tr>
<td><strong>Gain mismatching</strong></td>
<td>$\pm 0.3^\gamma$</td>
</tr>
<tr>
<td><strong>Laser light polarization</strong></td>
<td>$\pm 0.2$</td>
</tr>
<tr>
<td><strong>Pockels cell misalignment</strong></td>
<td>$\pm 0.4^\gamma$</td>
</tr>
<tr>
<td>- $\lambda/2$ plate (helicity dep. beam shifts)</td>
<td>($\pm 0.3)^\gamma$</td>
</tr>
<tr>
<td>- laser-electron beam overlap</td>
<td>($\pm 0.3)^\gamma$</td>
</tr>
<tr>
<td><strong>Electron beam instability</strong></td>
<td>$\pm 0.8^\gamma$</td>
</tr>
<tr>
<td>- electron beam position changes</td>
<td>($\pm 0.6)^\gamma$</td>
</tr>
<tr>
<td>- electron beam slope changes</td>
<td>($\pm 0.5)^\gamma$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\pm 1.6^\delta$</td>
</tr>
</tbody>
</table>

$^\alpha$ new sampling calorimeter built and tested at DESY and CERN

$^\beta$ from comparison with prototype sampling calorimeter

$^\gamma$ statistics limited

$^\delta$ published in NIM A 479, 334 (2002)
**New Sampling Calorimeter**

- PMT's
- Wave length shifters
- Scintillator plates
- Tungsten plates

**Test beam results**

- DESY
- CERN

better energy resolution & linearity than NBW calorimeter
New Sampling Calorimeter - Details

- sampling & NBW calorimeters sit on movable table (x-y)
  → fast switching possible
- one calorimeter is always protected from synchrotron and bremsstrahlung radiation
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta P_e/P_e (%)$ (2000)</th>
<th>$\Delta P_e/P_e (%)$ (&gt;2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzing Power $A_p$</td>
<td>$\pm 1.2^\alpha$</td>
<td>$\pm 0.8$</td>
</tr>
<tr>
<td>- response function</td>
<td>$(0.9)$</td>
<td>$(+0.2)^\alpha$</td>
</tr>
<tr>
<td>- single to multi photon transition</td>
<td>$(0.8)$</td>
<td>$(+0.8)$</td>
</tr>
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<td>$A_p$ long-term instability</td>
<td>$\pm 0.5$</td>
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<td>$\pm 0.4$</td>
</tr>
<tr>
<td>Total</td>
<td>$\pm 1.6$</td>
<td>$\pm 1.1$</td>
</tr>
</tbody>
</table>

$^\alpha$ new sampling calorimeter built and tested at DESY and CERN

$^\beta$ statistics limited

expected precision: (multi-photon mode)
Systematic Uncertainties - II

Longitudinal polarization with unpolarized electron beam (27.6 GeV)
measure false asymmetries (IP not optimal, HERA clock unstable)

\[ \langle P_e \rangle = -0.38\% \pm 0.14\% \]
\[ \langle I_e \rangle = 14 \text{ mA} \]
\[ \chi^2/df = 55.3/78 \]

Gain mismatching (± 0.2%)
Pockels cell misalignment (± 0.2%)
Electron beam instability (± 0.4%)

estimate consistent with data

estimated (2002)
**Polarization-2000**

**HERMES, H1, ZEUS and Machine Group**

**Goal:** Fast and precise polarization measurements of each electron bunch

**Task:** major upgrade to Transverse Polarimeter *(done)*

upgrade laser system for Longitudinal Polarimeter *(in progress)*

Fabry-Perot laser cavity

\[ (\delta p_e)_{\text{stat}} = 1\% / \text{min/bunch} \]

Final Cavity

Mount for travel

(courtesy F. Zomer)
# A Comparison of Different Polarimeters

<table>
<thead>
<tr>
<th>Polarimeter</th>
<th>Laser Power</th>
<th>Laser Frequency</th>
<th>Gamma Rate</th>
<th>Gamma Rate (n_{\gamma})</th>
<th>(\delta P_e)_{stat}</th>
<th>(\delta P_e)_{syst}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LPOL:</strong></td>
<td>33 MW</td>
<td>0.1 kHz</td>
<td>1000 \gamma/pulse</td>
<td>1%/min (all bunches)</td>
<td>~2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pulse laser</td>
<td>multi-\gamma mode</td>
<td>1%/ (&gt;30min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>i.e. 0.01 \gamma/bc</td>
<td>(single bunch)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(bc=bunch crossing)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TPOL:</strong></td>
<td>10 W</td>
<td>10 MHz</td>
<td>0.01 \gamma/bc</td>
<td>1-2%/min (all bunches)</td>
<td>~4% → &lt;2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>cw laser</td>
<td>single-\gamma mode</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(cw=continuous wave)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>New LPOL:</strong></td>
<td>5 kW</td>
<td>10 MHz</td>
<td>1 \gamma/bc</td>
<td>0.1%/6s per mill</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>cw laser</td>
<td>few-\gamma mode</td>
<td>(all bunches)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(all bunches)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(single bunch)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Fabry-Perot Cavity**
  - 0.7 W
  - Expected precision

(courtesy F. Zomer)
Photon Detection and Systematic Uncertainty of $P_e$

**New LPOL (few-photon mode):**
- Compton and Bremsstrahlung edges clearly visible
- Background determination and Calibration easy
- $(\delta P_e)_{syst}$: per mill level expected

**Existing LPOL (multi-photon mode):**
- Up to 1000 $\gamma$ produced per pulse
- Signal/background ratio improved
- > 5TeV measured in the detector!
- Calibration difficult
- Non-linearity $\rightarrow$ main syst. error

(courtesy F. Zomer)
Polarization after Lumi Upgrade

All three spin rotators turned on

$P_e > 50\%$
TPOL/LPOL Ratio

Still under investigation

LPOL:

TPOL:

various analysis codes give different answers!

Strategy:
investigate ratio for good and bad fills and look for any dependencies
Conclusions

• Longitudinal Polarization is currently measured with
  - 1% statistical uncertainty per minute (for all bunches)
  - 1.6% systematic uncertainty (with NBW calorimeter)
  - ~1% systematic uncertainty (with new Sampling calorimeter)

• After upgrade to optical cavity is finished,
  - systematic uncertainty: 1% or less.
  - statistical uncertainty: 1-2% for each individual bunch

• Longitudinal Polarimeter measures rate (energy) differences

• Compton Scattering is possible for $E_{\text{beam}} \gtrsim 1 \text{ GeV}$
  - large asymmetries: $A \sim E_e E_\lambda$
  - polarization measured/monitored continuously