Precise measurement of the longitudinal polarisation at HERA with a Fabry-Perot cavity polarimeter

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(Work conducted by the H1/LAL Orsay group, in collaboration with DESY)
Electron beam polarisation in a circular collider

Sokolov-Ternov effect

An electron turning in a magnetic field:

- Photon radiation
- with a Spin-flip probability: \( P_{\uparrow\downarrow} \neq P_{\downarrow\uparrow} \)

Electrons are polarised naturally transversally
Principle of the polarisation measurement at HERA:

Compton diffusion:

\[ E_{\gamma}, \phi_{\gamma} \sim \sigma_0 - P_L S_{\gamma} \sigma_L - P_T S_{\gamma} \cos \phi_{\gamma} \sigma_T \]

\( (\sigma_0, \sigma_L, \sigma_T: \text{known QED}) \)

- Non destructive measurement
- Pol measurement can be done simultaneously with exp. data taking

Mean position of the diffused photons for \( S_{\gamma} = \pm 1 \)

Energy spectrum of the diffused photons for \( S_{\gamma} = \pm 1 \)

\[ P_L (\text{longitudinal}) \]
• $e^\pm$ (27.6 GeV) \quad p$ (920 GeV)
• 220 bunches spaced by 96 ns
• $e^\pm$ longitudinally polarised around H1, ZEUS, HERMES

Since 1995: LPOL and TPOL

2003: beginning of the Cavity project
<table>
<thead>
<tr>
<th></th>
<th><strong>LPOL</strong></th>
<th><strong>TPOL</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>10 W pulsed (100 mJ/pulse, 100 Hz)</td>
<td>10 W CW laser</td>
</tr>
<tr>
<td>e−γ crossing</td>
<td>100 Hz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>n_γ</td>
<td>(\sim 1000) γ/pulse</td>
<td>(\sim 0.001) γ/bunch</td>
</tr>
<tr>
<td>(\Delta P_e) (stat)</td>
<td>3%/bunch/20min</td>
<td>1%–4%/allbunches/min</td>
</tr>
</tbody>
</table>

- **LPOL**: multi-photon mode, 10 W pulsed laser 100 Hz
  (i.e. \(n_γ \sim 1000\))

- **TPOL**: single photon mode, 10 W CW laser
  (i.e. \(n_γ \ll 1\))

Low statistic per bunch

- At HERA, to have:
  \((dP/P)_{stat} < 1\% / bunch / min\)

  one need  \(n_γ/bunch \sim 1\)

  \(P_{laser} \sim\) a few kW, CW
At HERA, to have:

\[(dP/P)_{stat} < 1\% / \text{bunch} / \text{min}\]

one need \(n_{\gamma} \sim 1\)

\[P_{\text{laser}} \sim \text{a few kW, CW}\]

\[\Delta P_{e}(\text{stat}) \sim 3\% / \text{bunch} / 20\text{min}\]

\[n_{\gamma} \sim 1\% - 4\% / \text{all bunches} / \text{min}\]

- **LPOL**: multi-photon mode, 10 W pulsed laser 100 Hz
  (i.e. \(n_{\gamma} \sim 1000\))

- **TPOL**: single photon mode, 10 W CW laser
  (i.e. \(n_{\gamma} \ll 1\))

Technical solution to obtain \(n_{\gamma} \sim 1\)

**Optical amplifier**

**Fabry-Perot Cavity**

Low statistic per bunch
Fabry-Perot cavity: principle

- Electrons and photons
- Pockels Cell
- Laser NdYag (~0.7W)
- Beam analysis
- ~5 kW
- ~0.7W
- ~2 m vacuum
- Beam analysis
- Linear polarization
- Circular polarization
- L ~ 2m
- 2 spherical mirrors fix one to respect to the other
- e-γ angle = 3.3°

Fabry-Perot Cavity
- cavity length L=2m
- 2 spherical mirrors fix one to respect to the other
- e-γ angle = 3.3°

Laser
- Infrared Nd:YAG (λ = 1064 nm)
- Frequency adjustable
- P = 0.7 W

Feedback system to put and keep ν_{laser} = ν_{cavity}
Ellipsometer
to control the
degree of circular
polarisation inside
the cavity

2 towers for the
4 flat 45° mirrors
2 of them are motorised
to align the laser beam
with the cavity optical axis

Vacuum pump

Bellow

Mirror support

Entrance
optical system

Laser entrance

Ellipsometer
to control the
degree of circular
polarisation inside
the cavity

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Synchrotron isolation (3 mm lead)
Thermal isolation (aluminium)
System overview

- ACQ : 400,000 acq / bunch

- Turn the laser ellipticity every 10 sec

- 220 histograms every 10 sec

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**System overview**

- 220 electron bunches $P_e$
- 96 ns
- Cavity
- ~ 60 m
- diffused $\gamma$
- Calo
- Driver
- Electron beam

- $S_\gamma = 1$
- $S_\gamma = 0$
- $d\sigma / dE_\gamma$ ~ $(d\sigma_0 / dE_\gamma) - (d\sigma_L / dE_\gamma) P_e S_\gamma$

- ACQ: 400,000 acq / bunch
- Turn the laser ellipticity every 10 sec
- 220 histograms every 10 sec

- Compton
- Bremsstrahlung (e- + residual gaz)
- Black body (beam pipe at 310 K)
- Synchrotron radiation

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Electron polarisation extraction

Theoretical spectral distributions of Compton and backgrounds

Shape of the experimental spectra for $S_\gamma = \pm 1$

For each doublet of histos (laser $S_\gamma = \pm 1$), fit for each of the 220 bunches

+ Regular determination of the calo characteristics (résolution + gain)
  
  (e beam mvtS)
each point $\leftrightarrow$ 1 minute
(measurement every 20 sec + mean on 6 doublets)

2 % / min / bunch

Statistical precision

$< 0.2$ % / min for all bunches
(error bars invisible)
each point $\leftrightarrow$ 1 minute
(measurement every 20 sec + mean on 6 doublets)

2 % / min / bunch
Statistical precision

All cavity polarimeter data taking
~ 500 hours
(Oct. 2006 to June 2007)


Systematics

Systematics determined from the full cavity data set + Dedicated data taking periods with non standard setups

- Calorimeter resolution and ADC to energy conversion
- Black body temperature
- Calorimeter position
- Synchrotron peak position
- Electronic sampling subtraction
- ...  

\[ \Delta S_\gamma \text{ transmitted unchanged to } P_e \]

Knowledge of \( S_\gamma \) (directly involved in \( \sigma \) Compton) \( \sigma = \sigma_0 - P_e S_\gamma \sigma_L \)

Not determinable from data themselves
Determination of $S_{\gamma}$

Principle:

Measurements of $I_1/I_0$, $I_2/I_0$ for different $\phi$, $\theta_{\text{inc}}$

$S_{\gamma}$ à qq %
Need a precise control of the ellipsometer optical elements
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- Performance **Wollaston** (extinction around $10^{-5}$)
- **Diode** response ($\sigma$/mean < 1 %)
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- Performance **Wollaston** (extinction around $10^{-5}$)
- **Diode response** ($\sigma$/mean < 1‰)

- **QWP**

\[ \text{error on } e_{\text{QWP}} (\mu m) \quad \text{error on } S_{\gamma} (\%) \]

\[ \Delta \varphi = \Delta n \frac{2\pi}{\lambda} e \]

- Induces a few per mill error on $S_{\gamma}$
- Manufacturer value: 91 µm ± few µm
- $n_0$ et $n_e$ known at $10^{-5}$ precision
- Necessity to determine the thickness $e$ at the per mill level
Ellipsometer calibration, how?

- measurements of $I_1/I_0, I_2/I_0$ for different $\phi, \theta_{inc}$, incident pola
- multiple internal reflexions
- all possible misalignement parameters

Fit example: $I_1/I_0$ and $I_2/I_0$ vs $\phi$

Fit with a model:

- $e$  
- $\Delta n$
- $S_\gamma$
- misal

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Two independent calibrations:

- at Orsay in laboratory (25°)
- at HERA in the tunnel (35°)

Quartz birefringence, compared with values published previously (1956 et 1999)

\[ \Delta S_\gamma < 3\% \] at the ellipsometer entrance
Transport of $S_\gamma$

- Entrance optics
- 4 mirrors
- Cavity
- 2 mirrors
- 4 mirrors
- Entrance optics
- Laser
- QWP
- Glan

- $S_\gamma$ (3‰)
- Ellipso
- Diffuser
- Wollaston
- QWP
- $\phi$
- $\theta_{inc}$
- $p_{d_0}$
- $p_{d_1}$
- $p_{d_2}$

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Transport of $S_\gamma$

- Laser
- Glan
- QWP
- Entrance optics
- Cavity
- IP
- 2 mirrors
- Ellipso
- HBS

$S_\gamma$ (3‰)

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Transport of $S_\gamma$

Biref : substrat (silice), multilayers $\text{SiO}_2/\text{Ta}_2\text{O}_5$, exit window $\sim 0$

$S_\gamma(3\%)$

$S_\gamma$ at the center of the cavity determined at $3\%$
Transport of $S_\gamma$

- $S_\gamma$ at the center of the cavity determined at 3‰.
$S_\gamma$ at the center of the cavity determined at 3‰

coherence in all the optical system: $\Delta S_\gamma \sim 5$ ‰
Conclusions & Outlook

Fabry-Perot Cavity polarimeter:

... higher **STATISTICAL** precision

- By increasing the power of the continuous wave laser at a few kW
- By increasing the frequency of the e-/laser interaction at 10MHz (every electron bunch)

\[ n_\gamma \sim 1 \text{ per bunch crossing} \]

**Statistical precision**: 2% per bunch per min

Improvement over the other two HERA polarimeters limited by
- either lower laser intensity (TPOL)
- or smaller e/photon interaction rate (LPOL)
Reach such a small systematic uncertainty was possible

1. Thanks to the few photon mode

2. Thanks to the a complete model description of the ellipsometer optical system and of the transport of $S_\gamma$ between the ellipsoid and the IP

These precise polarisation measurements

Good prospect for applications in a future linear collider

At ILC: $\Delta P_e$ syst. $\sim 2\%$

necessary for physics program achievement

Syst. uncertainty : $\sim 1\%$

(a factor 2-3 smaller than the precision quoted currently by other polarimeter at HERA)

The photon energy spectra can be described by convoluting signal and background QED processes with detector effects

( impossible for LPOL with $n_\gamma \gg 1$ )

$S_\gamma$ controlled at $3\%$

at the $e/\gamma$ IP

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These precise polarisation measurements

... tracks for decreasing the systematic error

- a larger ADC resolution (LPOL cavity 0.4%)
- a better calorimeter uniformity (LPOL cavity 0.6%)
- reduce the choice for calorimeter description (LPOL cavity 0.4%)
- still improve the control of $S_\gamma$ (LPOL cavity 0.3%)

Good prospect for applications in a future linear collider

At ILC : $\Delta P_e$ syst. $\sim 2\%$ necessary for physics program achievement

Good prospect for applications in a future linear collider

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References

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JINST 5 P06006 (2010)

... thank you