Polarisation and Polarimetry at HERA

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Abstract

Longitudinal polarisation of the lepton beam is a key ingredient to the success of the world’s unique \(e^\pm p\) ring collider HERA. This article aims at providing a brief introduction to the physics motivation for deep-inelastic scattering of polarised electrons or positrons off protons, the basic mechanisms to establish lepton polarisation in the high-energy storage ring and to describe briefly the three different polarimeters, which measured both the transverse and the longitudinal polarisation.

Keywords: polarised electron storage ring, polarisation, polarimetry, high-energy beams, HERA, Compton scattering

1 Introduction

The unique HERA facility in Hamburg, Germany collided leptons with protons at centre-of-mass energies of 300 and 318 GeV between 1991 and 2007, incorporating radiative polarisation of the lepton beam. Spin rotators installed around the interaction points of the experiments HERMES, H1 and ZEUS transformed the natural transverse polarisation of the lepton beam to longitudinal polarisation, which is in deep-inelastic scattering a powerful tool to study the internal structure of the nucleus.

The polarisation was measured routinely with two polarimeters. Using polarisation dependent Compton scattering, the transverse polarimeter TPOL detected the tiny up–down asymmetries associated with vertical polarisation, while the longitudinal polarimeter LPOL utilised the energy asymmetry caused by longitudinal polarisation. The third polarimeter, employing a Fabry–Perot cavity to provide a
high laser photon density to measure longitudinal polarisation, started to collect
significant amounts of data towards the end of 2006 and in 2007.

2 The HERA Collider

The *Hadron Elektron Ring Anlage* HERA is the first and only electron–proton
or positron–proton storage ring, located at the *Deutsches Elektronen–Synchrotron*
DESY laboratory in Hamburg, Germany. First $e^\pm p$ collisions were achieved in Oc-
tober 1991, with the colliding beams experiments ZEUS and H1 taking first physics
data shortly afterwards.[1] The fixed target experiments HERMES and HERA–B
went into operation in 1995 and 2000 respectively, the latter taking data till March
2003. The collider went through an ambitious luminosity upgrade in 2000/01 and
has been shut down finally after a successful second running period on 1 July 2007.
A schematic of the HERA accelerator complex is shown in Fig. 1 (left).

![HERA accelerator complex](image)

Figure 1: The HERA accelerator complex (left) and the integrated luminosity at
HERA I and HERA II (right).[2] Labels LER and MER: Low and Middle (proton)
Energy Runs, black marks: approximate change of year.

At HERA electron or positron beams were accelerated to the energy of 27.5 GeV
and the counter-rotating proton beams to energies of 820 GeV or 920 GeV. Colliding
at the interaction points of ZEUS and H1 the beams yielded a centre-of-mass energy
an order of magnitude larger than conventional fixed target experiments. From the
beginning HERA was designed to incorporate a polarised lepton beam and the estab-
ishment of transverse polarisation in the storage ring was an important prerequisite
for the HERMES experiment. Longitudinal polarisation was delivered to HERMES
from its beginning and since the upgrade also to H1 and ZEUS. Till the final shut-
down each of the colliding beams experiments collected an integrated luminosity of \( \approx 0.5 \text{ fb}^{-1} \) as can be taken from Fig. 1 (right).

### 2.1 Physics Case for longitudinal Polarisation

At HERMES, the longitudinal polarised lepton beams scattered off gas targets to study the nucleon spin structure by determining the spin-dependent structure functions of various nuclei. The helicity distributions of individual quark flavours inside the nucleon could be determined and further information on the spin structure of the nucleon has been obtained by investigating whether the gluons inside of the nucleon are also polarised.[3]

Being delivered with a longitudinally polarised lepton beam, the physics programs of H1 and ZEUS were extended by a large electroweak program, allowing to study for instance the chirality of charged current (CC) interactions. The CC deep-inelastic scattering (DIS) cross section depends on the polarisation of the lepton colliding with the proton.[4, 5] According to the Standard Model only left handed fermions couple to the \( W^- \)-boson, the cross section should therefore vanish for fully right-handed polarised electrons and fully left-handed positrons. By setting an upper limit on a non-vanishing cross section a lower limit on the mass of a hypothetical right-handed \( W^- \)-boson can be set.

There is also sensitivity to some electroweak parameters of the Standard Model like the \( W^- \)-boson mass \( M_W \). The ratio of neutral current (NC) to CC cross sections constrains the \( W^- \)-boson mass in the \((M_W, M_t)\) plane. The sensitivity to the \( W^- \)-boson mass and the electroweak mixing angle \( \sin^2 \theta_W = 1 - M_W^2/M_Z^2 \) provides also a test for electroweak universality.[6]

Other examples are given by the measurement of the light quark \((u, d)\) neutral current couplings and the \( \gamma Z^0 \) interference structure functions \( F_2 \) and \( xF_3 \) by detailed comparison of polarised NC and CC cross sections[7] and potential for new physics in e.g. searches for leptoquarks or \( R^- \)-parity violating supersymmetry.

### 2.2 Radiative Polarisation

Acceleration in a circular machine like HERA implies crossing of many depolarising resonances, making it difficult to sustain an initial polarisation at a high degree.[8] Instead, the inevitable emission of synchrotron radiation is used to polarise the stored beam after acceleration has finished. By means of spin-flips caused by a small fraction of synchrotron emissions in the magnetic field of bending dipoles, the spin of emitting particles align parallel or anti-parallel with the transverse magnetic field, leading to a gradual build-up of polarisation. This radiative polarisation has been first described by Sokolov and Ternov in 1964.[9]
In an ideal machine the build-up of radiative polarisation $P$ proceeds exponentially with

$$P(t) = P_{ST}(1 - e^{-t/\tau_{ST}})$$

(1)

with the asymptotic polarisation limit and build-up time given by $P_{ST} = 8/(5\sqrt{3}) \approx 0.924$ and $\tau_{ST} \approx 100 s \cdot \rho^3/E^5 \cdot \text{GeV}^5/m^3$.

In a real storage ring the polarisation build-up is counteracted by several depolarising effects, causing the maximal achievable polarisation $P$ and build-up time $\tau$ to be smaller than given by the Sokolov–Ternov effect alone. Spin diffusion in the presence of misalignments, field errors and horizontal magnetic fields along the ring weaken the polarisation build-up and careful alignment and organisation of the quadrupole strengths, known as spin matching, along with harmonic orbit corrections are needed to minimise the influence. In addition, depolarising resonances are avoided by choosing a half-integer spin-tune, i.e. the number of precessions a spin performs per turn in the ring $\nu := a\gamma$ with $a = (g - 2)/2$ being the electron gyromagnetic anomaly. HERA operated at $E = 27.5 \text{GeV}$ had a spin-tune of $\nu = 62.5$.

### 2.3 Spin Rotators

In order to obtain longitudinal polarisation at the interaction points of the experiments, pairs of spin rotators were installed around each interaction region, exploiting spin precession arising from deflection in transverse magnetic fields. As the spin-tune $\nu$ is large, small commuting orbit deflections $\phi$ can be used to generate large non-commuting spin precessions $\psi = \nu\phi$.

At HERA the so-called mini–rotator design of Steffen and Buon has been adopted, consisting of a series of six alternating vertical and horizontal bends without any focussing quadrupoles within due to its relatively small length of 56 m. These dipole spin rotators allow to have either sign of electron helicity in the longitudinal spin state, though with a maximum orbit distortion of $\pm 22 \text{cm}$ the bends had to be moved vertically upon a helicity change. The first rotator pair has been installed in 1993/94 for the HERMES experiment, followed by further pairs for H1 and ZEUS during the HERA upgrade in 2000/01.

### 2.4 Polarisation at HERA

A typical fill of the HERA electron ring could last for more than 12 hours. Initially filled with currents of about 40 mA in 180 – 190 bunches with a spacing of 96 ns, the bunch current decreased during a fill over time due to collisions and other losses.

The polarisation at HERA was monitored independently by two fast polarimeters with a very high availability and providing realtime polarisation values to the
machine and the experiments. During the HERA II running period over 99% of all physics fills had at least one polarimeter operational. The maximum polarisation ever achieved was about 0.76 in the HERA I period before the upgrade. As spin rotators represent a source of spin diffusion, the typical equilibrium polarisation at HERA II with three spin rotator pairs was lower with \( \approx 0.4 - 0.5 \) and rise times about 40 min. The polarisation varied from fill to fill and even within a single fill, as it was subject to the tuning of the machine. In addition, colliding and non-colliding bunches had different asymptotic polarisation values due to beam tune shifts of the colliding bunches caused by beam–beam interactions with the proton bunches.

3 The HERA Polarimeters

The requirements of polarimetry at HERA were challenging. The polarimeters should measure the polarisation of the stored lepton beam continuously in a non-invasive manner, providing realtime values to the experiments and the HERA machine control with a statistical accuracy of few percent per minute measurement. In addition, the devices required the ability to handle the frequent changes in the lepton orbit. The systematical uncertainties should be small with \( \delta P/P < 2.5 \% \), if measurements relying on polarisation values shall not be dominated by polarimetry.

One polarimeter measured the transverse polarisation and two more measured the longitudinal polarisation within the HERMES straight section. The basis for all three devices is given by Compton scattering laser photons of the high-energetic lepton beam and observing the backscattered photons. The cross section for Compton scattering is sensitive to the transverse and longitudinal components \( P_y \) and \( P_z \) of the lepton beam polarisation, provided that the laser photons are circularly polarised:

\[
\frac{d^2 \sigma}{dE d\phi} = \Sigma_0(E) + S_1 \Sigma_1(E) \cos 2\phi + S_3 P_y \Sigma_2 y(E) \sin \phi + S_3 P_z \Sigma_2 z(E)
\]

with \( S_1 \) and \( S_3 \) being the linear and circular components of the laser light polarisation.\[12\] The polarisation is then measured using the asymmetry of the cross sections, when switching the laser polarisation between left and right helicity states, i.e. \( S_3 = \pm 1 \) with \( S_1 \approx 0 \):

\[
\mathcal{A}(y, E_\gamma) = \frac{\sigma_L(y, E_\gamma) - \sigma_R(y, E_\gamma)}{\sigma_L(y, E_\gamma) - \sigma_R(y, E_\gamma)}
\]

3.1 Transverse Polarimeter TPOL

The transverse polarimeter (TPOL) operated throughout the complete HERA I and II periods in the straight section West near the HERA–B experiment. It measured
the tiny spatial asymmetry between the left and right laser helicity states caused by
the transverse polarisation.\textsuperscript{13, 10}

A green Argon–Ion laser, operated at 10 W in cw mode, was made circularly
polarised by means of a Pockels cell, switching the helicity at a frequency of $\approx 80$ Hz.
The laser beam was transported by an optical system over more than $300$ m into the
HERA tunnel and was brought into collision with the lepton beam under a vertical
angle of $3.1\text{ mrad}$. The degree of light polarisation was regularly monitored behind
the Compton interaction point using a rotating Glan prism, with typical polarisation
values $S_3 > 0.99$.

The backscattered Compton photons were detected $65$ m downstream of the
Compton interaction point in a compact, $19X_0$ deep electromagnetic scintillator–
tungsten sampling calorimeter, read out using wavelength shifter bars from all four
transverse sides. To achieve sensitivity to the vertical position of the incident photon,
the scintillator plates were optically decoupled along the central horizontal plane,
thus dividing the calorimeter effectively into independent upper and lower halves.
Information about the energy and the vertical impact position $y$ of an incident pho-
ton is then obtained from the sum of the two halves $E = E_{\text{up}} + E_{\text{down}}$ and the energy
asymmetry $\eta$ between them:

$$\eta := \frac{E_{\text{up}} - E_{\text{down}}}{E_{\text{up}} + E_{\text{down}}} \quad (4)$$

The operation of the transverse polarimeter relied on the single–photon mode
with on average $\bar{n} = 0.01$ backscattered photons per bunch crossing, so that, if at all,
only one photon will be detected. While this requires relatively low photon rates of $< 100$ kHz,
it allows to use the known kinematical endpoint of the Compton scattering
process, called Compton edge, for the absolute calibration of the detector. The main
background is bremsstrahlung generated along the $7.3$ m short straight section which
is in the line of sight of the detector. The measurement of the backscattered photon
distributions separately for the two laser helicity states was interspersed regularly
with measurements where the laser was blocked off. This allowed to measure the
background and to subtract it from the Compton data on a statistical basis.

The polarisation of colliding and non-colliding bunches is measured separately
and since the upgrade in 2000/01 also a bunchwise measurement is made possible by
means of a new faster DAQ. During this upgrade also a position sensitive detector
in the form of crossed silicon strip detectors including the necessary preradiator of
$1X_0$ thickness have been added in front of the calorimeter. These detectors should
allow for an in situ measurement of the intrinsic calorimeter response, the non-
linear transformation between the spatial impact point $y$ and the energy asymmetry
$\eta$ called $\eta(y)$–transformation.
The polarisation is then calculated from the shift of the mean energy asymmetry distributions for left and right laser helicity states using an analysing power $\Pi$:

$$\eta_L - \eta_R := \Delta S_3 P_y \Pi \quad (5)$$

as illustrated in Fig. 2 (left). At HERA I the analysing power was determined from simulations and from rise time measurements in a flat machine, where the intrinsic relation between the asymptotic polarisation value and the rise time constant as given by the Sokolov–Ternov effect is exploited for the calibration of the absolute polarisation scale. At HERA II the beam conditions as well as the detector have changed. Both the lepton beam size and divergence as well as the longitudinal position of the Compton interaction point became more variable, influencing the photon distribution at the calorimeter surface and thus the analysing power. Also the exchange of the calorimeter and the added dead material in front are likely to change the analysing power with respect to the HERA I running period.

The statistical uncertainty of the polarisation measurement amounts to about 2 – 3% per minute of data, for single bunches to about 10% per 10 minutes of measurement. The current, preliminary estimation of systematic uncertainties amounts to 2.9% as is shown in the table in Fig. 2 (right).

| Systematic uncertainty          | $\Delta P/P$ |
|-------------------------------|-------------|
| Electronic noise              | $< \pm 0.1\%$ |
| Calorimeter calibration       | $< \pm 0.1\%$ |
| Background subtraction        | $< \pm 0.1\%$ |
| Laser light polarisation       | $\pm 0.1\%$ |
| Compton beam centering        | $\pm 0.4\%$ |
| Focus correction              | $\pm 1.0\%$ |
| Interaction point region      | $\pm 0.3\%$ |
| Interaction point distance    | $\pm 2.1\%$ |
| Absolute scale                | $\pm 1.7\%$ |
| **Total syst. uncertainty**   | $\pm 2.9\%$ |

Figure 2: Illustration of the polarisation dependent shift of the mean energy asymmetry distributions (left) and the preliminary list of contributions to the fractional systematic uncertainty of the TPOL measurement (right).
the first of the three has been corrected for since 2004\cite{15}, for the second only an upper limit from geometrical acceptances is known. The three mentioned dominant contributions are correlated and have to be evaluated thus in a correlated fashion using a detailed realistic simulation of the magnetic beam line and a precise modelling of the calorimeter response including $\eta(y)$-transformation and energy resolution.

3.2 Longitudinal Polarimeter LPOL

The second polarimeter (LPOL) measured the longitudinal lepton beam polarisation within the HERMES spin rotator pair, downstream of the HERMES gas target.\cite{16} It went into operation in 1997 and used the sizable asymmetries in the energy distributions of the backscattered Compton photons when switching between the left and right laser helicity states.

The polarimeter operated in \textit{multi–photon mode}, where on average $\bar{n} \approx 10^3$ photons are backscattered per bunch crossing. In this mode background like bremsstrahlung becomes less important. With most of the long straight section East in the line of sight of the calorimeter, bremsstrahlung background would be too high to operate in single–photon mode.

The key ingredient to such high backscattering probabilities are high power laser pulses. Generated by a frequency-doubled green Nd:YAG laser, pulsed at 100 Hz, each laser pulse had a fixed power of 100 mJ and a length of 3 ns. The laser was synchronized with the lepton bunches and a trigger for readout at twice the laser pulse frequency allowed to measure background every second event. The circular polarisation, achieved by a Pockels cell flipping helicity for every pulse, was measured using a Glan–Thompson prism regularly with $S_3 > 0.99$.

The laser was transported with an optical system over 70 m into the HERA tunnel and collided with the lepton beam at a vertical crossing angle of 8.7 mrad. The backscattered Compton photons were detected 54 m downstream by a compact electromagnetic Čerenkov calorimeter, consisting of four 19 $X_0$ deep NaBi(WO$_4$)$_2$ crystals (NBW), read out separately. The crystals were optically decoupled and arranged in a rectangular $2 \times 2$ array to allow for a positioning of the calorimeter in the photon beam.

In the multi–photon mode, the detector signal is proportional to the integral of the energy-weighted Compton cross section:

$$I_{S_3 P_z} := \int_{E_{\gamma}^\text{min}}^{E_{\gamma}^\text{max}} r(E_\gamma) E_\gamma \frac{d\sigma_C}{dE_\gamma} dE_\gamma$$

with $r(E_\gamma)$ being the single–photon relative response function, a constant for a perfectly linear detector. The energy-weighted Compton cross section is shown in
Fig. 3 (left). The energy dependent asymmetry then becomes

\[ A := \frac{I_{S_3 P_z < 0} - I_{S_3 P_z > 0}}{I_{S_3 P_z < 0} + I_{S_3 P_z > 0}} = \Delta S_3 P_z \Pi_z \tag{7} \]

The statistical uncertainty of the measurement is about 1 – 2 % per minute and about 6 % per 5 minutes measurement, clearly limited by the repetition rate of the laser.

| Systematic uncertainty                     | \( \Delta P/P \) |
|--------------------------------------------|------------------|
| Analysing power                            | ±1.2 %           |
| long-term stability                        | ±0.5 %           |
| Gain matching                              | ±0.3 %           |
| Laser light polarisation                    | ±0.2 %           |
| Helicity dep. luminosity                   | ±0.4 %           |
| Interaction region stability               | ±0.8 %           |
| Total (HERA I)                             | ±1.6 %           |
| Extra (new calorimeter)                    | \( \leq \pm 1.2 \% \) |
| Total (HERA II)                            | ±2.0 %           |

Figure 3: The energy-weighted single differential Compton cross section \( E_\gamma d\sigma_C/dE_\gamma \) (left) and the list of contributions to the fractional systematic uncertainty of the LPOL measurement (right).

The current estimation of systematic uncertainties is shown in the table in Fig. 3 (right). \cite{14} The dominant systematic uncertainty is given by the analysing power \( \Pi_z = 0.1929 \pm 0.0017 \). \cite{17} Its main contributions are given by the shape of the single–photon response function as measured with test beam data and the extrapolation from single– to multi–photon mode. The latter was validated by attenuating the signal over three orders of magnitude using neutral density filters and monitoring the polarisation value in comparison with the independent measurement of the TPOL. After the replacement of the calorimeter crystals in 2004 the performance of the new calorimeter was ascertained in alternating measurements with a sampling calorimeter. From this an upper limit of 1.2 % systematic uncertainty due to the new calorimeter was estimated, increasing the formerly quoted HERA I systematic uncertainty to 2 %. \cite{14}
3.3 Cavity Longitudinal Polarimeter

A third polarimeter project has been started in the early HERA II running phase employing a Fabry–Perot cavity to stock laser photons with a very high density at the Compton interaction point. Working in continuous few–photon mode, backscattering on average $\bar{n} \approx 1$ photons per bunch crossing, it combines the virtues of both existing operational methods. While providing a very high statistics with scattering rates in the order of MHz, it can make use of the Compton and bremsstrahlung edges for the calibration of the calorimeter.

The cavity polarimeter measured the longitudinal polarisation within the HERMES spin rotator pair, located about 10 m downstream of the LPOL interaction point and utilising the same detector location for the measurement of the backscattered Compton photons. After installation of the Fabry–Perot cavity in spring 2003, first Compton events have been observed in March 2005 with a much increased operation till the end of HERA. Over 500 hours of efficient data could be collected.

The cavity is driven by an infrared Nd:YAG laser with an initial power of 0.7 W, located together with all optical components on an optical table close to the cavity. Circular polarisation of the laser light is achieved by rotating quarter wave plates, flipping the helicity every few seconds, and monitored behind the cavity.[18] The cavity mirrors are located inside the vacuum vessel at 2 m distance from each other, providing a vertical crossing angle of 3.3°. With a finesse of $\approx 3 \times 10^4$ the initial laser power is amplified by means of constructive interference with an effective gain of $\approx 5000$ to about 3 kW.[19]

The measurement of the longitudinal polarisation proceeds by an overall fit of a parametrised model to the energy distributions for the two laser helicity states collected separately. Absolute calibration is done using the known Compton and bremsstrahlung edge positions. The description of the energy spectra includes besides the Compton spectrum also contributions of background like synchrotron and Compton scattered black-body radiation, the bremsstrahlung spectrum as well as detector resolution and non-linearity parameters. Detailed simulations of the calorimeter response were needed, e.g. for a precise description of the synchrotron radiation peak. The statistical uncertainty with about 3% per bunch and 10s doublet is unprecedented at HERA.

Based on more than 500 hours of data including dedicated data samples, most of it taken during the final stage of the HERA operation, detailed systematic studies have been performed. The preliminary list of systematic uncertainties includes the modelling of the detector response and of the synchrotron radiation peak, electronic pile-up, detector parameter fitting, a varying HERA beam, the calorimeter position and the laser polarisation inside the cavity. Whereas the contributions of parameter fitting and HERA beam variations are found to be negligible, the other contributions
are of approximately the same size, adding to a total of $\delta P/P = 0.9\%$.\[20\]

4 Conclusions

The running of HERA was efficiently covered with measurements of the lepton beam polarisation. At HERA II over 99\% of all the physics fills had at least one polarimeter operational.

The preliminary estimation of the systematical uncertainties for TPOL amounts to about 2.9\% and for LPOL to 2\%. However, the agreement of the two polarimeters shows a varying behaviour over time which is not yet understood. To cover these discrepancies an additional systematical uncertainty of 3\% had been assigned, raising the uncertainty of the combined measurement to about 3.4\%.\[14\] Currently, efforts are under way to validate and improve the polarisation analyses of both polarimeters to decrease the systematical uncertainty of the combined measurement and final results are expected within the next few months.

The polarisation measurement with a high finesse Fabry–Perot cavity at HERA has been established, successfully operating with increasing data taking frequency till the end of HERA. The analysis of the systematical studies is nearly finished, indicating that the goal of a sub percent systematic precision has been achieved.

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*see also [http://www.desy.de/~pol2000](http://www.desy.de/~pol2000)