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

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Abstract. A Fabry-Perot cavity polarimeter installed in 2003 at HERA was designed to measure the longitudinal polarisation of the electron beam with high precision for each electron bunch spaced with a time interval of 96 ns. By interacting a high intensity laser (enhanced up to a few kW within the cavity) with the HERA electron beam it is possible to measure its polarisation with a relative statistical precision of 2% per bunch per minute. Detailed systematic studies have been performed and in particular a complete theoretical model has been developed in order to control at the per mill level the degree of circular polarisation of the laser beam. The result is a total systematic uncertainty of 1%. This is the first time that such a precision is achieved in the difficult, hostile and noisy environment of a particle collider.

1. Introduction
A fast and high precision longitudinal Compton polarimeter using a continuous wave laser resonating in a Fabry-Perot cavity (LPOL cavity) was proposed, constructed and installed in the electron-proton collider HERA near the existing longitudinal Compton polarimeter (LPOL) [1]. In addition to the LPOL, the transverse polarisation of the electron beam is also measured by another polarimeter (TPOL) [2].

With respect to the prior HERA LPOL and TPOL polarimeters, the higher statistical precision of the LPOL cavity is achieved by increasing firstly the power of the continuous wave laser by more than two orders of magnitude compared to the TPOL and secondly the frequency of the electron-photon(laser) interaction to 10 MHz compared to 0.1 kHz of the pulsed laser of the LPOL. A new Data Acquisition System (DAQ), synchronised to the HERA beam clock, has been developed accordingly which operates without any trigger at 10 MHz.

Among all the source of systematic errors, the knowledge of the degree of circular polarisation $S_3$ of the laser beam at the electron-laser interaction point (IP) is of particular interest. Indeed, this quantity is directly involved in the following Compton scattering cross section:

$$\frac{d\sigma}{dE_\gamma} = \sigma_0 \frac{dE_\gamma}{dE_\gamma} - P_2 S_3 \frac{d\sigma_L}{dE_\gamma}$$

(1)

(where $E_\gamma$ is the energy of the scattered photon and $\sigma_0$ and $\sigma_L$ are respectively the non-polarised and the longitudinal Compton cross sections), and as shown in Eq.(1) only the product $S_3 P_2$ is determined in Compton polarimetry. $S_3$ has therefore to be measured precisely in order to achieve the same level of precision for $P_2$.

The main purpose of the present article is to report about the electron polarisation measurement with the LPOL cavity experiment, and describe the experimental setup and methods that we have used to reach a few per mill level of systematic uncertainty on $S_3$. 
2. LPOL cavity principle and electron polarisation extraction

The HERA Fabry-Perot cavity is similar to a device that has been used successfully to measure the polarisation of the CEBAF LINAC electron beam [3, 4, 5]. One major difference between the HERA and CEBAF LPOL cavities is the dynamical regime. Whereas the luminosity of Compton scattering is relatively low at CEBAF, it reaches much higher values at HERA. That is, the average number of back-scattered Compton photons (hereafter named BCP) is close to one per bunch in the latter case and much smaller in the former. The HERA dynamical regime, denoted as ‘few photon mode’ in this article, has been used successfully for the first time by the LPOL cavity to measure the electron beam polarisation. The advantage of the few photon mode is that one can calibrate the calorimeter in an absolute way using two reference points of the photon energy spectrum independently of the electron beam polarisation: firstly the Compton kinematic edge, located at 10 GeV at HERA for our 1.064 nm laser beam wavelength, and secondly the bremsstrahlung kinematic edge, located around 27.5 GeV which corresponds to photons radiated from the scattering of the electron beam with the residual gas of the vacuum beam pipe (hereafter named BGP).

The LPOL cavity overall system is shown in figure 1. Each of the 220 electron bunches crosses the laser beam and the BCPs reach a calorimeter at about 60 m from the electron-laser IP. A precise description of the cavity, the calorimeter, electronics and DAQ can be found in [6, 7]. The available data for the polarisation measurement of an individual bunch consists of a pair of photon energy histograms. These are successively recorded by the calorimeter DAQ for each bunch during one DAQ period (≈ 10 s) for the two polarisation states of the laser beam $S_3 = +1$ and $S_3 = -1$. These spectra come from a sum of genuine BCPs from electron-laser interactions, and three main backgrounds: the already mentioned BGP, the electron beam scattering off Black Body Photons (hereafter named BBP) emitted by the hot beam pipe, and the Synchrotron Radiation Photons (hereafter named SRP). Since the DAQ operates without trigger, the total number of entries of the histograms are fixed to 400,000 (corresponding to the number of HERA turns accumulated during one DAQ period).

To extract the electron polarisation from a pair of bunch energy histograms, the theoretical energy spectra of one BCP (see Eq.(1)), BGP [8, 9] and BBP [10] are computed numerically. The SRP background [11] is considered as a pedestal and it is treated separately. All these spectra are mixed and the convolution of all the processes is performed to provide an energy histogram. The detector effects (calorimeter, ADC/energy conversion and electronic noise) are applied to the energy histograms. A comparison between the experimental and calculated energy histograms is performed using a likelihood fit. The unknown parameters of this fit are the luminosities of the BCP, BGP and BBP processes integrated over one DAQ period, the electron beam polarisation and the parameters describing the detector effects. A detailed derivation of the formula used in our fits can be found in [7, 12]. In figure 2, such a calculated energy histogram is shown together with the experimental one. An excellent agreement is seen between the data and the red curve representing the sum of all processes. In figure 3, the two spectra for laser polarisation $S_3 = 1$ and $S_3 = -1$ are shown in the ‘Compton energy range’ together with the measured values. The difference allows the electron polarisation measurement.
**Figure 2.** Measured energy spectrum (black) accumulated during 10 s of acquisition time and fitted result (red).

The total LPOL cavity data taking amounts to about 500 hours (from 6 October 2006 to the end of the HERA running in June 2007). The LPOL cavity provides a bunch dependent polarisation measurement every 20 s. The relative statistical precision is about 2% per bunch per minute as shown in figure 4 for a typical example. All LPOL cavity data have been analysed with the polarisation results available to be compared with the corresponding measurements from the TPOL. Figure 5 shows an example of polarisation measurements of one HERA luminosity fill provided by the LPOL cavity and TPOL polarimeters for the colliding electron bunches. The better statistical precision from the LPOL cavity polarimeter can be clearly appreciated.

**Figure 3.** Compton edges of two energy spectra where the laser helicity was $S_3 = 1$ (right) and $S_3 = -1$ (left).

**Figure 4.** Bunch dependent polarisation measurement from the LPOL cavity averaged over 3 independent measurements corresponding to about one minute duration. The error bars represent the statistical precision of the measurement with the solid (dashed) histograms showing the colliding (pilot) bunch structure.

**Figure 5.** Polarisation measurement from the LPOL cavity (blue points) and the TPOL (red points) for the colliding bunches as a function of time for about ten hours.

Detailed systematic studies have been performed to determine the total error on $P_z$. Most of them can be estimated from the data themselves by using the full LPOL cavity data set and
including also dedicated data taking periods with non-standard setups [7]. An overall relative systematic error of 0.9% is quoted on $P_2$, this number including all the systematics except the knowledge of $S_3$ which cannot be determined from the data themselves.

3. Control of $S_3$

The uncertainty on the $S_3$ determination comes mainly from two sources: (1) the measurement of $S_3$ itself performed with an optical system usually located close to, but outside, the electron beam pipe and, (2) the transport of the measured $S_3$ value through optical elements and vacuum window up to the electron-laser IP. The method to measure $S_3$ and the transport of the measured value are described in this section.

A schematic overview of the Fabry-Perot cavity optical setup is presented in figure 6. The laser beam passes first through a Glan-Thomson prism in order to provide a purely linearly polarised state and then through a quarter wave plate (labeled $QWP_{\text{ent}}$) to provide an elliptical polarised state. The beam then passes through the entrance optics which is composed of a glass plate (used to pick up a fraction of the beam for the locking procedure exploiting the “Pound-Drever” technique [13]) and two lenses (used to match the laser beam to the cavity fundamental mode). The beam is then precisely aligned with four mirrors (of which two are motorised) before entering the two meter long Fabry-Perot cavity.

![Figure 6. A schematic view of the Fabry-Perot cavity optical system. The location of four determination points of $S_3$ is indicated by $S_3^{\text{in}}$, $S_3^{\text{in}}$, $S_3^{\text{ext}}$, and $S_3^{\text{ell}}$. $M_E$ and $M_T$ are two transfer matrices discussed in the following.](image)

At the exit of the cavity, the beam is guided with two mirrors to enter an ellipsometer (labeled “Ellipso”) which is the key component in the determination of $S_3$. The principle of an ellipsometer is to send a light beam, of any unknown polarisation $S_3^{\text{ell}}$, through a quarter wave plate ($QWP$). By rotating the plate, the polarisation state of the light is modified and the state at the exit of the plate depends on the state at the entrance. A polariser (Wollaston prism) placed behind the plate spatially separates the beam into two orthogonal linearly polarised states. The analysis of the intensities of these two beams in the photo-detectors $pd_1$ and $pd_2$, for various azimuthal angles $\phi$ of the QWP, allows the deduction of $S_3^{\text{in}}$. Before entering the ellipsometer QWP, the beam passes first through a holographic beam sampler (HBS) in order to extract a small fraction of the entrance power (about 1% of the incident beam) measured in the photo-detector $pd_0$ and used as a reference intensity to compensate the effects due to possible laser power variations.

3.1. Ellipsometer characterisation

The measurement of $S_3$ with an uncertainty of a few per mill requires a precise control of all the ellipsometer optical components (HBS, Wollaston, photo-detectors, QWP). The birefringence of the HBS alone has been measured before its installation in the cavity system and the result
is compatible with zero [6, 14]. The extinction rate of the Wollaston prism has been measured experimentally to be less than a few $10^{-5}$. Careful studies of the detection system has shown that the photo-detector intensities $I_{1,2} = i_{p1,2}/i_{p0}$ are known at the per mill level [6, 14]. Since an optical model is needed to reconstruct $S_3$ from the photometric measurements performed after the polariser, the model accuracy has to be controlled below the per mill level. The QWP is a crucial component of the ellipsometer. It is usually anti-reflection coated with double layers and thus taken as a simple delay plate in basic optical models [15]. However, the reflectance of such coated plates is typically of the order of 0.5%, thus limiting the model accuracy to the same level. In order to decrease the model uncertainty, we followed the work of [16] by choosing an uncoated quartz QWP of high optical quality (delay and thickness tolerances of 1/300 and a few micrometers respectively). In doing so we have to account for multiple reflections inside the anisotropic uniaxial QWP, to model the plate defects and the experimental misalignments, and to perform a fine calibration of the ellipsometer and in particular of the plate thickness (a error of one micrometer on the plate thickness leads to a systematic error of 0.5% on $S_3$ [6, 14]). The ellipsometer will be first used as a calibration system to characterise precisely some of its optical components. All the details of the model describing the ellipsometer can be found in [6, 14] where the modeling and the calculations relative to the Wollaston cube, the QWP and the optical misalignments are explicitly given.

Two independent ellipsometer calibrations have been performed: one in the clean optical laboratory where the room temperature is regulated at 25$^\circ$ and the other in the HERA tunnel where the room temperature is regulated at 35$^\circ$. For each calibration, ellipsometer measurements are recorded at various incident angles $\theta_{\text{inc}}$ between the laser beam and the QWP normal direction, various azimuthal angles $\phi$ of the QWP, and various initial polarisation state $S_3^{\text{ell}}$ (see figure 6). A comparison between the experimental and calculated photo-detectors intensities is performed using a $\chi^2$ minimisation fit. The unknown parameters of this fit are the thickness of the QWP, the quartz birefringence, the light polarisation $S_3^{\text{ell}}$, and all the possible misalignment parameters of the system. The excellent agreement between experimental intensities and theoretical ones based on the fit is illustrated by a typical example in figure 7, where the quantities $I_{1,2}$ are presented for a sample as a function of the azimuthal angle $\phi$ of the ellipsometer QWP.

![Figure 7](image-url)

**Figure 7.** Experimental intensities (black bullets, for clarity only a subsample is shown) $I_1$ (a) and $I_2$ (b) compared with theoretical ones (curves) derived from the fit, as a function of the azimuthal angle $\phi$ of the ellipsometer QWP (for a angle $\theta_{\text{inc}}$ and a polarisation $S_3^{\text{ell}}$ fixed).

All ellipsometer parameters determined from the two independant calibrations are found to be realistic and well defined within a precision of 0.3% [6, 14]. Among them, one interesting quantity is the quartz birefringence value which can be compared with textbook values previously
determined at a temperature of 18° and 22° in [17, 18]. Based on the relation of optical index variation with temperature [19], quartz birefringence values of [17, 18] are scaled to $T = 25°$ and at $T = 35°$ and are shown in figure 8 together with the two birefringence values obtained from our fits. Our results agree at better than one per mill with the ones quoted in the references. The determination of the quartz birefringence by the ellipsometer does not aim for the same level of precision as was obtained in [17, 18] but provides a good test of the validity of the model.

**Figure 8.** Quartz birefringence values scaled to 25° and 35° from textbook values [17, 18], as a function of the wavelength. Dashed lines are straight line fits to four scaled textbook points. Birefringence values determined from the fits to our two independent data samples are indicated by an open and a solid triangle, respectively. The error bars are inclined for clarity.

### 3.2. Regular measurements of $S_3$ and systematics studies

During the data taking period of the LPOL cavity, values of $S_3^{\text{III}}$ are regularly determined. For this, the azimuthal angle of the entrance plate QWP $\text{QWP}^{\text{ent}}$ is such that the light is close to a fully right or left circularly polarised state $S_3 = \pm 1$ [7]. Each value of $S_3^{\text{III}}$ is extracted from a data sample recorded with the ellipsometer at various azimuthal angle of the ellipsometer QWP. To extract $S_3^{\text{III}}$, a fit using the model previously described is performed where the only free parameter is $S_3^{\text{III}}$, all other parameters remaining fixed to values previously determined by the characterisation of the ellipsometer in the HERA tunnel.

These values $S_3^{\text{III}}$ and their uncertainties of 0.3% quoted in section 3.1 are measurements of the degree of circular polarisation at the entrance of the ellipsometer. What we are interested in is, however, the $S_3$ value at the electron-laser IP, i.e. at the center of the Fabry-Perot cavity. A priori, these two values are the same, but because of the presence of optical components between the two (the exit mirror and the exit window of the Fabry-Perot cavity and the optical system $M_T$, see figure 6), a small difference could be induced because of a parasitic birefringence. The transport of $S_3$ have therefore to be studied.

The birefringence of the substrate, the coating and the mounting system of the exit mirror and the exit window has been estimated or measured [12, 6]: the bias induced on $S_3$ from the center to the exit of the cavity is at the utmost of the order of $3 \times 10^{-5}$. The determine the parasitic ellipticity associated to the 45° dielectric mirrors used to guide the light into the ellipsometer, the transfer matrix $M_T$ of the system has been determined and used to correct $S_3^{\text{III}}$ [6, 14]. The correction is calculable for each value of $S_3^{\text{III}}$ and therefore does not enter as a systematic error but is explicitly determined to correct each $S_3^{\text{III}}$. The corrections are all below five per mill.

Although the previous studies have provided values of $S_3$ at the electron-laser IP with an uncertainty around three per mill, we have also characterised the entrance optical elements by a matrix $M_E$ and determined the values of $S_3$ at the four different locations $S_3^{\text{ent}}$, $S_3^{\text{in}}$, $S_3^{\text{ex}}$ and $S_3^{\text{III}}$.
indicated in Fig. 6 in order to check their coherence and make sure that no additional unknown large effect could induce a bias on $S_3$ at the center of the cavity. This study has shown that $S_3$ is controlled along the whole optical path at the five per mill level [6, 14].

4. Conclusion
A new Fabry-Perot cavity polarimeter has been constructed and successfully operated at HERA. The measurement of the electron beam polarisation is reported for the first time in the few photon mode leading to a statistical precision of 2% per bunch per minute. Detailed systematic studies have been performed resulting in a total relative systematic uncertainty of about 1%, which is a factor of 2–3 smaller than the precision quoted currently by the other polarimeters at HERA. To reach such a small systematic uncertainty, on one hand we have used the possibility to describe the few photon energy spectra from first principles by convoluting the signal and background QED processes with the detector effects, and on the other hand we have determined the degree of circular polarisation $S_3$ of the laser at the electron-laser IP with an uncertainty of 0.3%. The level of accuracy presented here has, to our knowledge, never been reached in the environment of a particle collider and provides a good prospect for applications in a future linear collider [20, 21, 22].

References