HERA TRANSVERSE POLARIMETER ABSOLUTE SCALE AND ERROR BY RISE-TIME CALIBRATION

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Abstract.

We give the results of an analysis of some 18 rise-time calibrations which are based on data collected in 1996/97. Such measurements are used to determine the absolute polarization scale of the transverse electron beam polarimeter (TPOL) at HERA. The results of the 1996/97 calibrations are found to be in good agreement with earlier calibrations of the TPOL performed in 1994 with errors of 1.2% and 1.1%. Based on these calibrations and a comparison with measurements from the longitudinal polarimeter (LPOL) at HERA carried out over a two-months period in 2000, we obtain a mean LPOL/TPOL ratio of 1.018. Both polarimeters are found to agree with each other within their overall errors of about 2% each.

1. Introduction

Two polarimeters are employed at the HERA ep storage ring to measure the polarization of its 27.5 GeV electron or positron beam. Both instruments are laser backscattering Compton devices. The TPOL polarimeter measures the transverse beam polarization by detecting the associated angular anisotropy of the backscattered Compton photons. The original configuration of this instrument has been covered in considerable detail [1, 2, 3, 4, 5] and recent upgrades are described in [6]. The LPOL polarimeter measures the longitudinal beam polarization between the spin rotators at the HER-

MES experiment by detecting an asymmetry in the energy spectra of the Compton photons [7].

In this paper, we will present the results of an analysis of rise-time calibration data which were collected in 1996/97. Such measurements are used to determine the absolute polarization scale of the TPOL polarimeter. These results will be compared with earlier TPOL calibrations obtained in 1994 and with recent cross calibrations with the LPOL polarimeter.

2. The rise-time calibration method

Electrons or positrons are injected unpolarized at 12 GeV into the HERA storage ring and are subsequently ramped to the nominal beam energy of 27.5 GeV. Transverse polarization evolves then naturally through the spin flip driven by synchrotron radiation (the Sokolov-Ternov effect [8]) with an exponential time dependence

$$P(t) \;=\; P^{\infty}\,(1-\exp\,(-t/\tau)) \tag{1}$$

For a circular machine with a perfectly flat orbit the spin vector of the positrons (electrons) will be exactly parallel (antiparallel) to the direction of the guide field and the theoretical maximum of the polarization has been calculated to be $P^{\infty}_{ST} = 8/(5\sqrt{3}) = 92.4\%$, with an associated rise-time constant

$$\tau_{ST} \;=\; P^{\infty}_{ST}\,\frac{m_e|\rho|^3}{r_e\hbar\gamma^5} \tag{2}$$

where γ is the Lorentz factor, ρ is the radius of curvature of the orbit and the other symbols have the usual meaning.

For rings such as HERA with the spin rotators needed to get longitudinal polarization at experiments and/or reversed horizontal bends, P^{∞}_{ST} can be reduced substantially below 92.4% and τ_{ST} can be modified too, see Table 1. Synchrotron radiation also causes depolarization which competes with the Sokolov-Ternov effect with the result that the equilibrium polarization is reduced even further. Moreover the depolarization is strongly enhanced by the presence of the small but non-vanishing misalignments of the magnetic elements and the resulting vertical orbit distortions which are typically 1 mm rms.

These effects are treated in the formalism of Derbenev and Kondratenko [9] which has been summarized in [10]. Then the equilibrium polarization and the time constant can be written as

$$P^{\infty} \;=\; -\frac{8}{5\sqrt{3}}\,\frac{\oint ds\,\langle\,|\rho(s)|^{-3}\,\hat{b}\cdot(\hat{n}-\partial\hat{n}/\partial\delta)\,\rangle_s}{\oint ds\,\langle\,|\rho(s)|^{-3}\,[1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}(\partial\hat{n}/\partial\delta)^2]\,\rangle_s} \tag{3}$$

$$\tau \;=\; \frac{8}{5\sqrt{3}}\,\frac{m_e}{r_e\hbar\gamma^5}\,C\,\frac{1}{\oint ds\,\langle\,|\rho(s)|^{-3}\,[1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}(\partial\hat{n}/\partial\delta)^2]\,\rangle_s} \tag{4}$$

where the unit vector $\hat{n}$ describes the polarization direction which is a function of the machine azimuth s and the phase space coordinate $\vec{u} = (x, p_x, y, p_y, z, \delta)$, the unit vectors $\hat{b}$ and $\hat{s}$ describe the magnetic field orientation and the direction of motion, and C is the circumference of the machine. The angular brackets $\langle\,\rangle_s$ denote an average over phase space at azimuth s. The term with $(\partial\hat{n}/\partial\delta)^2$ accounts for the radiative depolarization due to photon-induced longitudinal recoils and the term with $\partial\hat{n}/\partial\delta$ in the numerator of 3 arises from the dependence of the radiation power on the spin orientation.

These expressions can be summarized in the scaling relation

$$\frac{P^{\infty}}{(P^{\infty}_{ST}+\Delta)} \;=\; \frac{\tau}{\tau_{ST}} \tag{5}$$

between the actually observed parameters P^{∞} and τ of equation 1 and the theoretical values P^{∞}_{ST} and τ_{ST} which are obtained by ignoring terms with $\partial\hat{n}/\partial\delta$ in equations 3 and 4. For the HERA machine at 27.5 GeV they take the values in Table 1 [11]:

HERA status	year	P^{∞}_{ST}	τ_{ST} (min)
flat	1994	0.915	36.7
non-flat	1996/97	0.891	36.0

TABLE 1. Input parameters for rise-time calibrations

The correction Δ in equation 5 results from the term $\partial\hat{n}/\partial\delta$ in the numerator of equation 3. In the case of a flat ring, Δ is negligible compared to P^{∞}_{ST}. However, for a non-flat HERA, namely with spin rotators activated at HERMES, Δ/P^{∞}_{ST} remains small but can still be significant. Since the magnitude of Δ depends on the distortions of the machine, it is very difficult to calculate reliably [11].

The scaling relationship of equation 5 can be exploited to predict the expected equilibrium polarization P^{∞} when we know the remaining quantities P^{∞}_{ST}, τ_{ST}, τ and Δ. Through comparison of the actually measured value of P^{∞} with the predicted value from equation 5 we can therefore calibrate the polarimeter.

This is the essence of the rise-time method. It requires knowledge of the theoretical maximum values for the machine in the absence of depolarizing spin diffusion effects, i.e. P_{ST}^{∞} and τ_{ST} from equations 3 and 4, and a measurement of the actual rise-time τ from a fit of data to the functional form of equation 1. For a non-flat ring we also need to know Δ. However, by comparison with rise-time calibrations obtained earlier with a flat machine, we will be able to examine this term experimentally.

3. Experimental Procedure

In order to take rise-time calibration data which are free from major systematic effects it is essential that the build-up of polarization proceeds under conditions of an extremely stable machine performance since even minor operator adjustments in the course of a measurement may change the parameters of the functional form that describes the time dependence. For this reason rise-time calibrations require dedicated HERA operation, where the machine is brought to a very stable condition and is then only monitored without further operator invention. The beam polarization is then destroyed by the resonant depolarization technique by applying an rf field to a weak kicker magnet [12]. When the baseline polarization P_0 has been established the depolarizing rf is turned off at time $t = 0$ and the subsequent exponential rise is measured under completely quiet machine conditions. After one or two hours, the polarization can be destroyed again for another rise-time measurement and so forth.

In order to retain only data of high quality, we applied the following selection criteria: (a) stable machine and polarimeter conditions; (b) depolarizing rf frequency shifts by no more than 100 Hz (corresponding to a change in beam energy of about 1 MeV); in order to apply this test the beam needs to be depolarized before and after each rise-time measurement; (c) the depolarizer should be activated for about 10 minutes prior to $t = 0$ to establish a reliable baseline P_0. Of the rise-time data collected in 1996/97, altogether 18 curves out of a total of 25 survived these cuts. For the older measurements taken in 1994, 8 curves out of 14 could be retained [13].

4. Results and Errors

Figure 1 shows two examples of rise-time data obtained in 1997. The curves are fits to the following functional form, with τ, P_0 and K as free fitting parameters

$$K \cdot \Big[P(t) - P_0 \Big] \;=\; \frac{P_{ST}^{\infty}}{\tau_{ST}}\, \tau \Big[1 \,-\, \exp\left(-t/\tau\right) \Big] \tag{6}$$

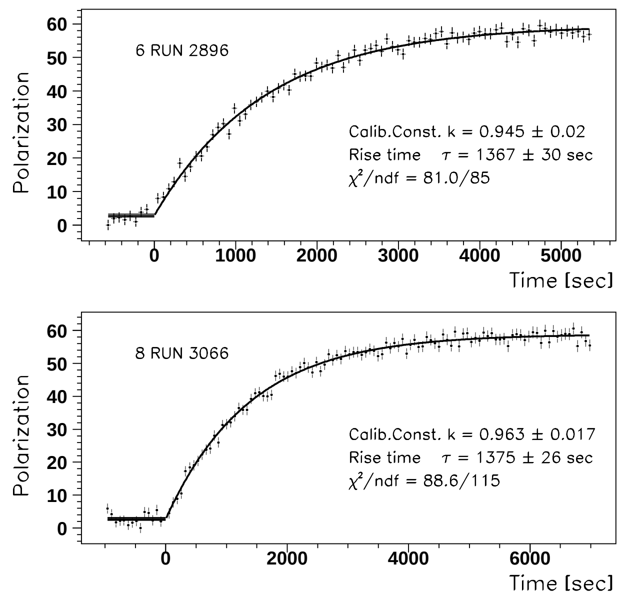

Figure 1. Examples of rise-time calibration measurements

The appropriate input values for P_{ST}^{∞} and τ_{ST} were listed in table 1. The parameter K is the calibration factor for the polarization measurement of the polarimeter. The results of the 1996/97 rise-time fits are listed in table 2, together with the older calibration data from 1994 which had been reported earlier [13].

In table 3 we give the weighted mean value of K, $\bar{K} = \sum w_i K_i / \sum w_i$ with $w_i = (\Delta K_i)^{-2}$, the error of the mean value $\Delta\bar{K} = (\sum w_i)^{-1/2}$, and the associated $\chi^2/ndf = \sum w_i\,(K_i - \bar{K})^2/(N-1)$. Furthermore we give a rescaled error $\langle\Delta\bar{K}\rangle_{scaled} = (\chi^2/ndf)^{1/2} \cdot \Delta\bar{K}$ to account for the underestimation of the original errors indicated by $\chi^2/ndf > 1$. The scaling is equivalent to adding a common systematic error of size $(\Delta\bar{K})_{syst} = \Delta\bar{K} \cdot (\chi^2/ndf - 1)^{1/2}$ in quadrature, see [14] for an explanation of these procedures.

For a proper interpretation of the calibration results shown in table 3, it is important to understand that all TPOL polarization values have been scaled by a factor 0.946 since 1996 [13] in good agreement with the value of 0.951 given here. The subsequent 1996/97 relative re-calibration factor of 0.999 is therefore equivalent to an overall absolute factor of $0.999 \cdot 0.946 = 0.945$ in relation to the original polarization scale used prior to 1996.

The analysis of the 1994 rise-time data reported in [13] assigned an error of 0.032 to the determination of K. The error quoted is the rms σ of the nearly gaussian distribution of K-measurements. This rms σ value

Index No.	Year	Run No.	K	ΔK	τ (sec)	$\Delta\tau$ (sec)	χ^2/ndf
1	1994	2370	0.936	0.021			
2	1994	2442	0.976	0.042			
3	1994	2444	0.900	0.038			
7	1994	2482	0.960	0.030			
8	1994	2484	0.956	0.023			
9	1994	2486	0.955	0.028			
10	1994	2488	0.994	0.021			
11	1994	2492	0.902	0.026			
1	1996	5138	0.971	0.042	1255	55	0.644
2	1996	7702	1.089	0.028	1637	42	0.788
3	1996	8382	1.006	0.023	1328	31	0.765
4	1997	2778	0.996	0.042	1392	61	0.680
5	1997	2824	0.962	0.032	1342	47	0.828
6	1997	2896	0.945	0.020	1367	30	0.953
7	1997	3030	0.998	0.031	1396	49	0.763
8	1997	3066	0.963	0.017	1374	25	0.770
9	1997	3278	0.906	0.052	1136	65	0.701
10	1997	3316	0.999	0.043	1251	57	0.597
11	1997	3318	1.030	0.070	1254	90	0.516
14	1997	3669	0.933	0.039	873	37	0.821
15	1997	6654	1.038	0.047	1172	53	0.922
16	1997	6684	1.075	0.035	1362	49	0.784
17	1997	6686	1.062	0.038	1388	53	0.838
18	1997	6688	0.977	0.035	1265	49	0.702
24	1997	9610	1.056	0.026	1391	37	0.795
25	1997	9642	1.040	0.024	1463	36	0.507

TABLE 2. Calibration results from rise-time measurements

data set	$\bar{K}_{rel}$	$\bar{K}_{abs}$	$\Delta\bar{K}$	χ^2/ndf	$(\Delta\bar{K})_{syst}$	$(\Delta\bar{K})_{scaled}$
1994	0.951	0.951	0.009	1.509	0.006	0.011
1996/97	0.999	0.945	0.007	2.744	0.009	0.012

TABLE 3. Mean calibration factors and errors

describes the typical error of a single measurement of K. The error of the mean value of K is then $\sigma/\sqrt{N}$ and thus considerably smaller than 3%.

By comparing the calibrations of 1994 and 1996/97, we find excellent agreement within the given errors of 1.1 and 1.2%. Since the 96/97-calibrations were carried out with activated spin rotators at HERMES, in contrast to 1994 when the machine was flat, we can also set an experimental upper limit of about 1.5% on the correction Δ in equation 5 which accounts for the $\partial\hat{n}/\partial\delta$ term in the numerator of equation 3.

5. LPOL/TPOL comparison

As the magnitude of the polarization at any particular point in time is an invariant around the HERA ring, a comparison between the TPOL and LPOL polarimeters will provide a cross calibration of the instruments, as long as the spin points fully upright at the TPOL and longitudinal at the LPOL. Although it is well known to the operators of the polarimeters and

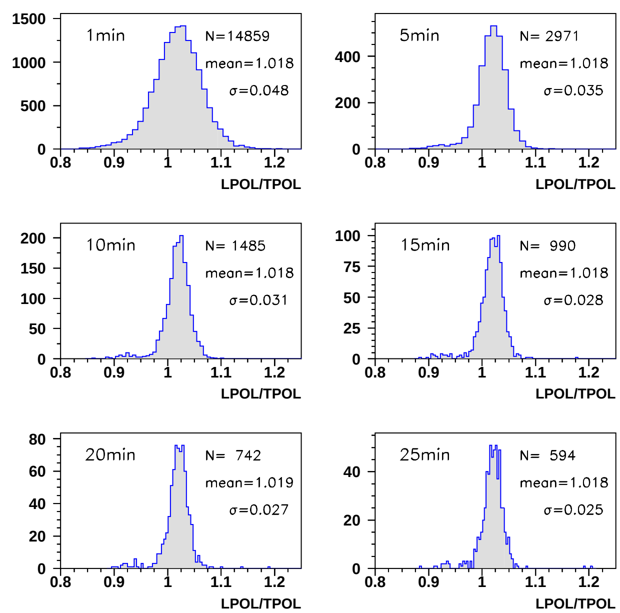

Figure 2. LPOL/TPOL ratio measurements over a two-months period in 2000

to the members of HERMES that the two instruments appeared to disagree occasionally with each other outside of their quoted errors, it is reassuring to demonstrate a large sample of measurements, covering two months of data taking in April/May of 2000, which exhibits a consistent and stable performance of both polarimeters. We have plotted the LPOL/TPOL ratio for this time period in figure 2 for six different integration times ranging from 1 to 25 minutes. We obtain a consistent mean ratio of 1.018 with an error of the mean $\sigma/\sqrt{N}$ of less than 0.001.

Since the statistical fluctuations are vanishing with higher averaging periods, one can estimate the systematic error of the TPOL measurement $(\Delta P/P)_{TPOL}$ from the observed rms $\sigma = 0.025$ of the 25 min distribution and the quoted LPOL systematic error $(\Delta P/P)_{LPOL} = 1.6\%$ [7]. Assuming uncorrelated errors for the two polarimeters, we obtain $(\Delta P/P)_{TPOL} = [\sigma^2 - (\Delta P/P)^2_{LPOL}]^{1/2} = 1.9\%$.

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