Transverse Polarimeter Systematic Errors

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Abstract

TPOL systematic uncertainty of 2.91% is derived exploring regular measurements, scans, simulations and offline analysis. Some ways to reduce this error are outlined.

TPOL Systematics

HERA transverse polarimetry uncertainties have been estimated in [1], relying mainly on simulations and with limited operational experience. A conservative accuracy of 9.4% was claimed at that time. Following rise-time measurements allow to determine the polarisation overall systematic error from a spread of the absolute calibration constant k. The $\sigma_k \approx 3.5\%$ has been assigned as the TPOL canonical error and with small modifications it is in use up to now. Meanwhile an elimination of statistical fluctuations of the k (to retain only the systematic variations) brings the σ_k and the associated systematic error down to 1-2% [2]. However, this is possibly not the whole truth since during the rise-time calibrations special stable beam conditions have been provided otherwise the measurements are rejected from the analysis. In other words, the obtained errors relate to rise-time measurement periods only while the regular, day-to-day operational errors can be much higher. And, of coarse, story above was about the prehistoric, HERA-I era.

This study is dedicated to the current state of the error sources and magnitudes. Part of the sources are specific to the online method (Π_η) while some of them are common and originate from the TPOL setup. A breakdown of the TPOL uncertainty is presented in table 1 where δP denotes absolute errors at $P = 100\%$ polarisation i.e. stands for relative error $\Delta P/P$.

We do not display the errors which are addressed in [1] and are shown to have negligible contribution (mainly related to the laser optics and light polarisation), these are ignorable also for the polarimeter current configuration. The displayed sources are discussed below in details to find out dominant contributions and propose some methods for a better error at the end.

Source	Name	Magnitude [%]
Electronic Noise		≈ 0
Calorimeter Calibration		≈ 0
Background Subtraction		≈ 0
Light Polarisation	δP_{lin}	0.10
Focus Correction	δP_{focus}	1.04
Compton Beam Centering	δP_{table}	0.44
Interaction Region	δP_{IR}	0.33
Interaction Point	δP_{IP}	2.04
Absolute Scale	δP_{scale}	1.70

Table 1: TPOL Error Sources. Absolute errors at 100% polarisation are displayed.

1 Electronic Noise

Major manifestations of the noise, baseline and ADC pedestal variations are handled by zero-suppression and event by event pedestal subtraction. In addition per cycle averaged pedestals and timing variables are monitored online and display a reliable short and long term stability. Thus, an error associated with the electronic noise in general considered to be vanishingly small.

2 Calorimeter Calibration

After each 1 min cycle the calibration constants are derived using measured energy-spatial distributions according to an algorithm which is described elsewhere (see e.g. [1]). These constants are applied to the collected data to resample the 2-dim histograms and only then the polarisation is calculated. This procedure allows to cancel gain variations and channels mismatch and ensure energy-position calibrations reproducibility i.e. stability of the transformations $E-N$ (energy to ADC channel) and $y-\eta$ (vertical position to Up-Down energy asymmetry). The resampling itself is mathematically accurate, the only introduced error is coming from histogram's non-zero bin width which in our case is small enough, especially along the most important spatial direction.

To verify the calibration-resampling approach we change the calorimeter's Up channel HV to miss-calibrate both energy and spatial scale. Resulting changes of apparent Compton edge position and polarisation measurement are displayed on fig.1. From the presented stability fit one can deduce that despite of the calibration constants variation over a wide range the polarisation measurement is not compromised. Recalling an allowed 0.5% tiny range of the calibration constants tolerances during the regular data taking, we conclude that polarisation systematic errors due to calorimeter miss-calibration are just negligible.

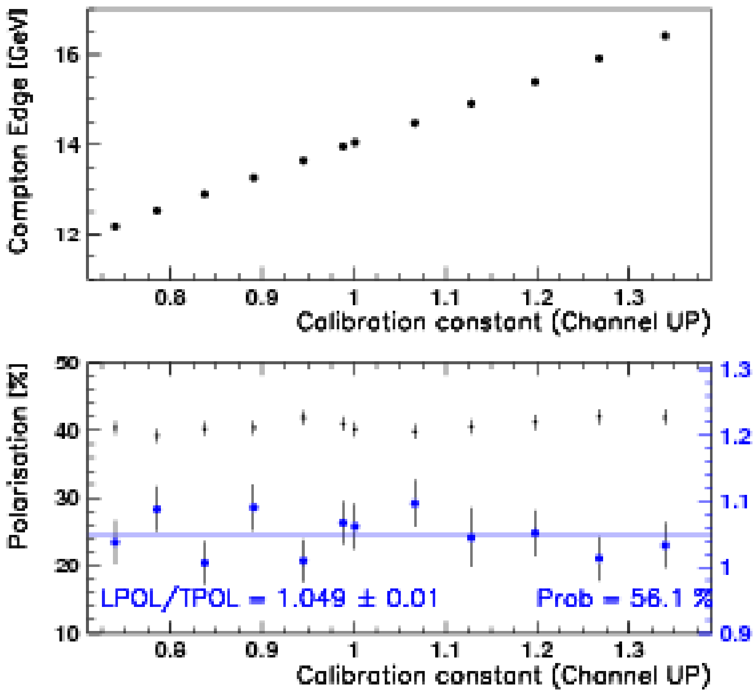

Figure 1: Calorimeter miss-calibration influence on the polarisation measurement. Upper plot: apparent Compton edge. Lower plot: TPOL polarisation and LPOL/TPOL ratio (right scale) with stability fit results.

3 Background Subtraction

Part of each cycle is dedicated to background measurement by blocking the laser light. This dark (or 'laser off') histogram is then subtracted from the 'laser on' measurement after properly weighting it with on/off times to obtain pure Compton spectra. Such procedure is safe enough if the measurement cycle is much shorter comparing to background changes. or, in other words, if the background does not considerably change within the cycle. This condition may not always hold given the HERA lepton beam intensity decay, especially at low lifetimes. Therefor, we have to estimate the beam finite lifetime influence on accuracy of the TPOL.

Assuming laser on/off measurement times T/T_B and a lepton lifetime τ, for Compton and background Bremsstrahlung rates R_C, R_B we start from exponential decay formulas

$$R_C(t) = R_C e^{-t/\tau} \qquad\qquad R_B(t) = R_B e^{-t/\tau}$$

Number of corresponding events collected during the on/off times will be for the Compton

$$N_C = \int_0^T R_C e^{-t/\tau}\ dt$$

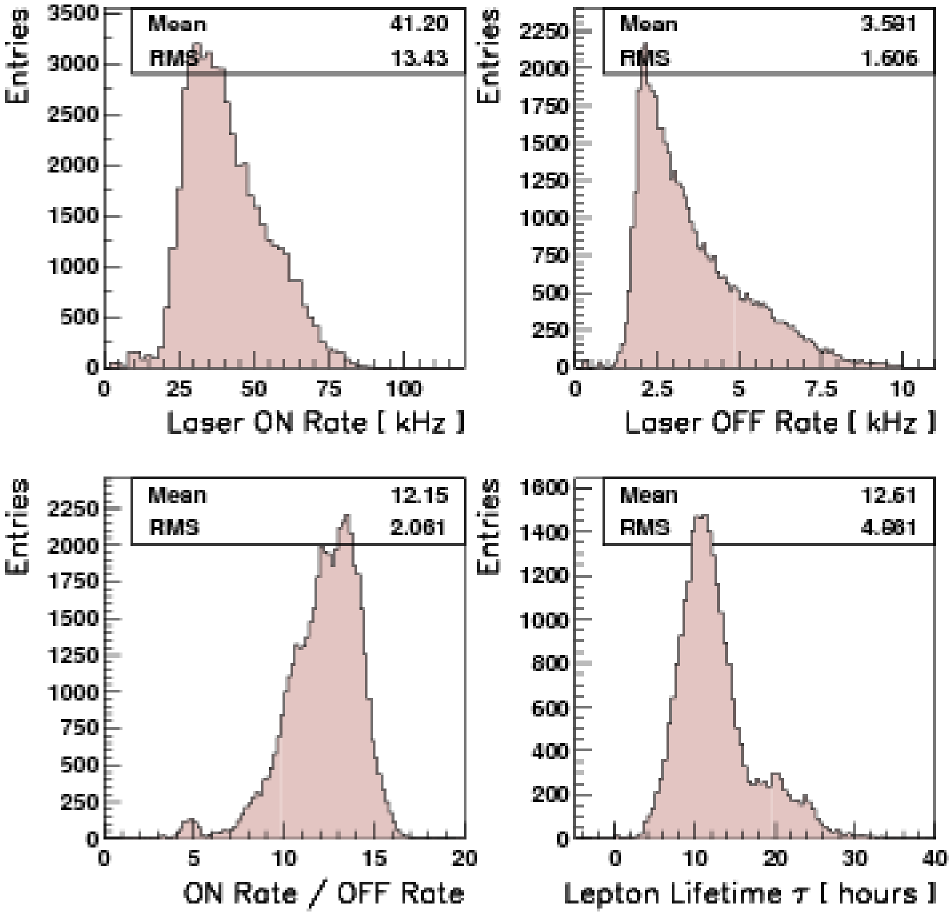

Figure 2: Beam lifetime and TPOL rates for a period Feb-May in 2006.

for the Bremsstrahlung

$$N_B = \int_0^{T_B} R_B e^{-T/\tau} e^{-t/\tau}\ dt$$

since the background is measured at the end of cycle, and for the combined signal and background

$$N_{C+B} = \int_0^{T} (R_C + R_B) e^{-t/\tau}\ dt$$

.

In the experiment we measure N_{C+B}, N_B and apply background subtraction to get Compton events

$$N_C^M = N_{C+B} - N_B \frac{T}{T_B}$$

A difference between the real and measured Compton numbers then reads

$$\Delta N = N_C - N_C^M$$

and using the previous relations we find

$$\Delta N = \tau R_B \Big[e^{-T/\tau} - 1 + \frac{T}{T_B} \Big(e^{-T/\tau} - e^{-(T+T_B)/\tau} \Big) \Big]$$

The last expression is greatly simplified for an approximation $T, T_B \ll \tau$ (i.e. cycle period is much shorter than the lifetime)

$$\Delta N = \frac{T^2 R_B}{2\tau}$$

Relative contribution of these asymmetry diluting events

$$\frac{\Delta N}{N_C} = \frac{T}{2\tau}\frac{R_B}{R_C}$$

could be estimated by substituting average numbers $R_B/R_C = 0.082$ and $\tau = 12.6$ hours from fig.2 and laser ON cycle T=45 sec. The result $< \Delta N/N_C >= 4.1 \cdot 10^{-5}$ is very small and even at lowest operational lifetimes of $\tau \approx 2$ hours and the rates $R_C/R_B \approx 5$ a contamination $\Delta N/N_C = 6.3 \cdot 10^{-4}$ could be neglected.

4 Light Polarisation

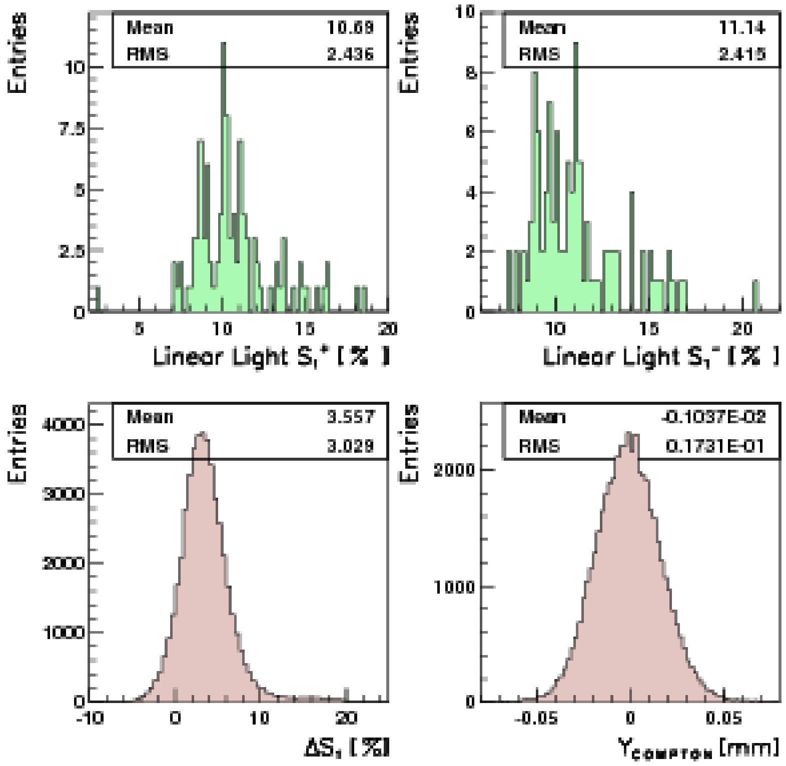

Figure 3: Upper row: Optical measurements of linear light components at laser beam dump (once per fill). Lower left: Difference of the linear components derived from Compton scattering asymmetry (measured once per 1 min cycle). Lower Right: Compton cone vertical centering relative to the calorimeter mid plane. Measurements cover the same period as in fig. 2

Laser light linear polarisation is analyzed downstream of IP and the measured components S_1^+, S_1^- (fig.3) are utilized to calculate a difference of the circular light components ΔS_3 which is essential for the electron beam polarisation (P) measurement. According to eq.(38) in [1] the Compton beam helicity dependent vertical displacement is proportional to ΔS_3 (and P of coarse). A term with ΔS_1 is omitted from the eq.(38) for $\Delta S_1 \ll \Delta S_3$ but also since the term contains an even ($\cos 2\phi$) component which brings a contribution to the average position to zero. However, if Compton beam is not centered on the calorimeter, this term will have a finite magnitude introducing some systematics. In the language of mathematics the $\cos(2\phi) \propto (1 - 2y^2)$ since $\sin(\phi) \propto y$ (eq.(38) in [1]) and the contribution to average vertical position

$$< y >= \int_{-\infty}^{+\infty} (1 - 2y^2) y dy = 0$$

while with a Compton beam offset y_0 there appears an even term under the integral and the term with

$$< y >= \int_{-\infty}^{+\infty} (1 - 2(y - y_0)^2) y dy \neq 0$$

becomes finite.

Since the ΔS_1 and Compton beam offset are measured (fig.3), we can estimate the systematic error associated with the linear light, simulating a linear polarisation scan in the following way. First note that an average of the optical measurement is 11% while an average of ΔS_1 is only 3.6%. This tells us that the phase difference between the +/- linear components is 0.29π. With this fixed phase difference and Compton beam offset equal to 1 σ of the $Y_{COMPTON}$ distribution from the fig.3, we start to variate the linear light amplitudes to obtain apparent polarisation changes ΔP initiated by non-zero contribution of the ΔS_1 term (see fig.4). Parameterizing

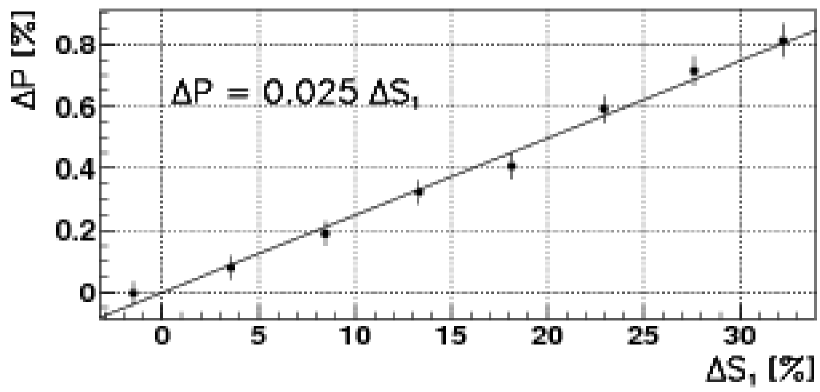

Figure 4: Dependence of the analyzing power on linear light components (ΔS_1). Vertical errors originate from limited MC statistics.

the dependence by $\Delta P = 0.025 \Delta S_1$ we find a change corresponding to the average measured $\Delta S_1 \approx 4\%$ which answers to our initial question on the systematic error magnitude: $\delta P_{lin} = 0.1\%$.

Alternatively one could utilize this parameterization to apply a linear correction proportional to ΔS_1 though that would became significant only at large magnitudes and variations of the linear light.

5 Focus Correction

Situation is somewhat different for a TPOL variable focus linked with the electron beam divergence. To compensate relatively large variations of the HERA II vertical emittance at TPOL IP we apply a focus dependent correction to analyzing power (the procedure is described in [3]).

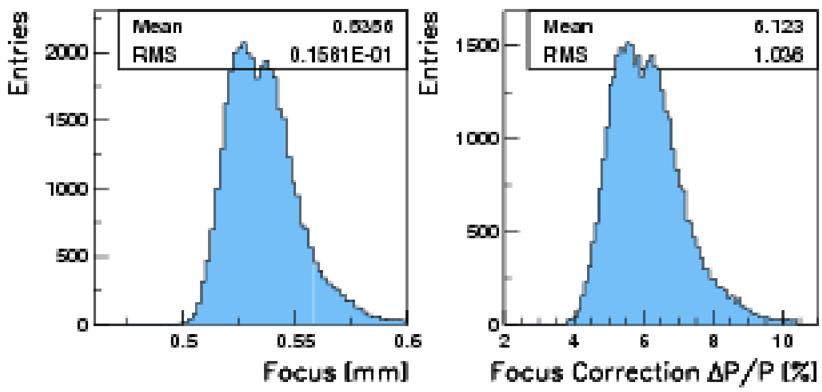

Figure 5: Focus and associated correction for data collected during the same period as in fig. 2

To find out how much systematic error is introduced by the focus correction we analyze the focus and corresponding correction distributions shown on fig. 5. According to usual probabilistic interpretation all the focus corrected polarisation values became uncertain in proportion to the ΔP (the correction magnitude) distribution width. In other words after the focus correction we should assign an additional relative uncertainty to the polarisation equal to 1σ/RMS of the $\Delta P/P$ distribution which is $\delta P_{focus} = 1.04\%$.

6 Compton Beam Centering

When the scattered photon beam hits the calorimeter off-center the analyzing power degrades following the position resolution. However, the off-center focus measurement is also affected and the applied focus correction is also changes. As a result the measured polarisation growths as was observed during a calorimeter table vertical scan displayed on fig. 6. The upper left plot shows a good correspondence between the table position and the measured Compton beam centering ($Y_{COMPTON}$). The measured polarisation and focus are then plotted versus the $Y_{COMPTON}$ since during the normal operation it is the only measure of the table/beam centering. A MC simulation has been performed for positive beam positions only to gain more statistics since the distributions are more or less symmetric around the zero. The MC fits satisfactory reproduce the data and that increases our confidence on the measured dependences. To estimate the Compton beam off-centering systematic contribution into the polarisation measurement we again turn to the $Y_{COMPTON}$ distribution measured during the regular operation.

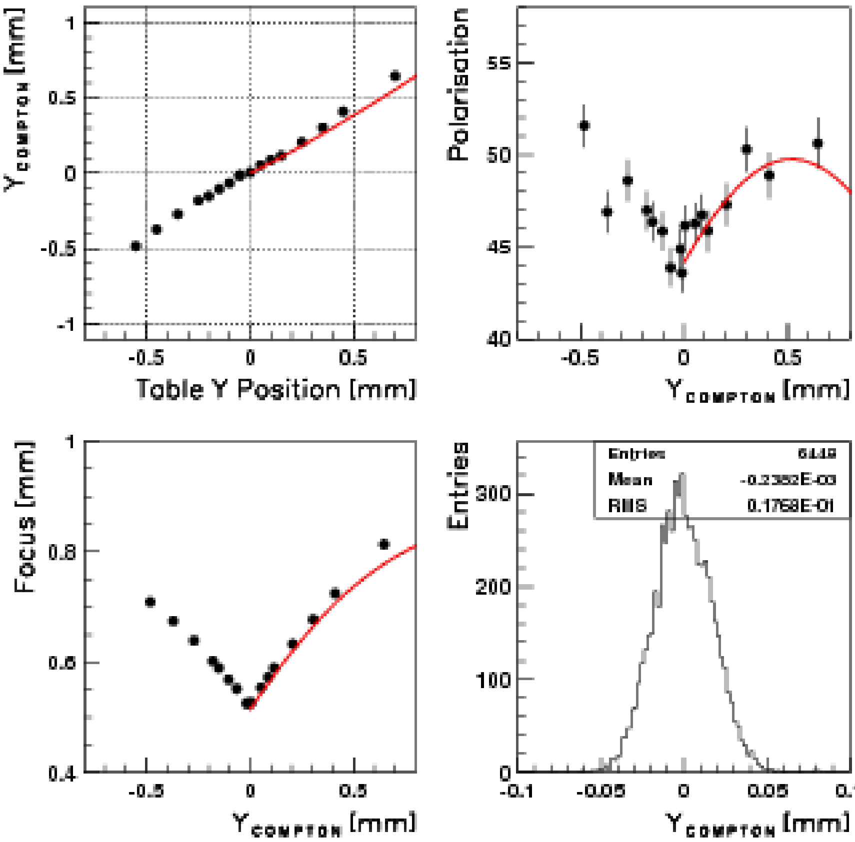

Figure 6: Calorimeter table vertical scan results. The red line is MC simulation.

Lower right plot of the fig. 6 displays $Y_{COMPTON}$ measurements during the first week of Sep 2006. The distribution's mean and RMS are pretty much similar to the few months' average values from the fig. 3 and we can use either of them to evaluate the polarisation uncertainty δP_{table} due to the table off-centering. For a 1σ(RMS) of $18\mu m$ a polarisation change on the upper right dependence of the fig. 6 is at most $\Delta P_{table} = 0.2\%$ which at the corresponding polarisation of 45% contributes as a $\delta P_{table} = 0.44\%$ relative error.

7 IP Position

Nominal interaction point of the laser and electrons is defined by the setup geometry and may change depending on relative orientation/position of the interacting beams. Since the TPOL effect is based on the spatial measurements the position of the IP directly couples to the analyzing power. According to MC simulations a ΔZ shift of the IP will bring a measured polarisation change

$$\delta P[\%] = 1.0183 \Delta Z[m]$$

. The IP change could be forced by

- finite size of the interacting beams which extends the interaction point into an interaction region (IR)
- electron beam position and slope variations
- laser beam movements

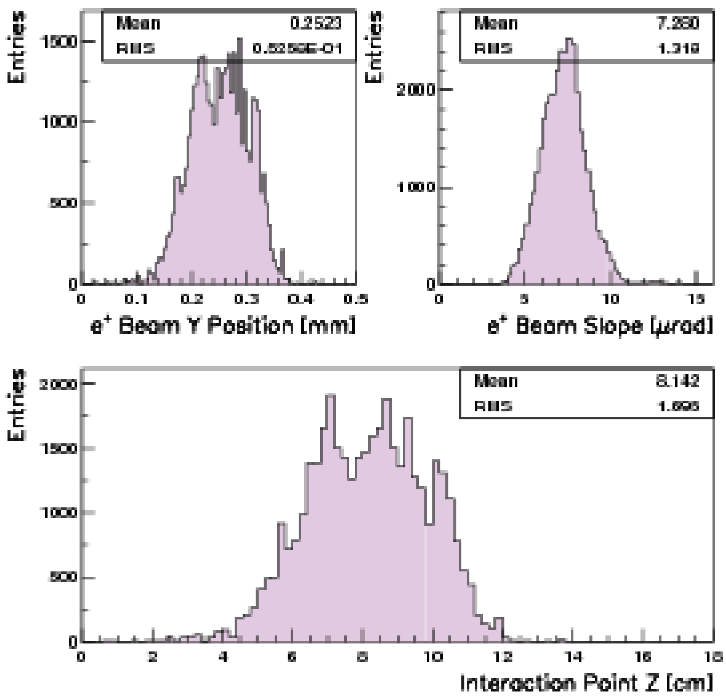

Figure 7: Electron beam vertical position and vertical angle measured at TPOL IP for the same data set as in fig. 2. Evaluated IP shifts are shown on the lower plot.

7.1 Interaction Region

Recalling that the laser hits electrons head-on under a vertical angle $\alpha = 3.1\ mrad$, from simple geometrical considerations we can express the IR as

$$\Delta Z = \frac{\sigma_L}{tg(\alpha)}$$

where $\sigma_L = 1\ mm$ is the laser beam size while the electron beam vertical size (tens of μm-s) is ignored. This limits the IR contribution to the polarisation systematic error to

$$\delta P_{IR} = 1.0183 \frac{\sigma_L}{\alpha} = 0.328\%$$

7.2 Electron Beam

IP dependence on the electron beam vertical position Y and angle θ could be written as

$$Z = \frac{Y}{tg(\theta) + tg(\alpha)}$$

The Y is monitored by a HERA BPM at the TPOL IP and the slope θ is derived using calorimeter table position and the Compton beam offset $Y_{COMPTON}$. Fig. 7 displays Y, θ as well the corresponding Z measurements during the 2006 February-May data taking period. Obtained $< Z >= 8.1\ cm$ and $RMS_Z = 1.7\ cm$ values bring sub-per-mille polarisation changes hence, the electron beam drift contribution to the systematics is ignorable.

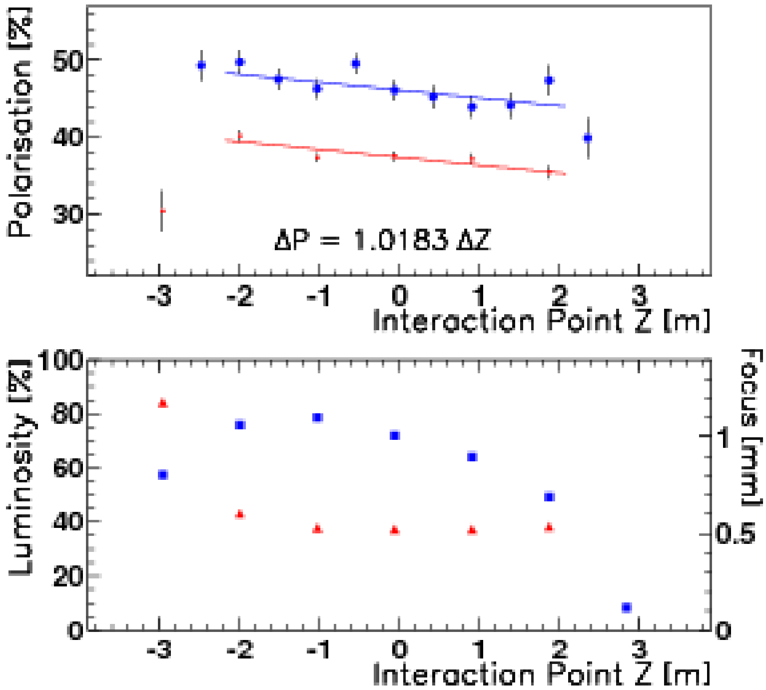

Figure 8: IP distance effects on polarisation measurement. Upper plot: the blue points are per minute adjacent polarisation measurements and the red points are results of another, more precise measurement. The straight lines are MC fits. Lower plot: the blue squares represent luminosity (left scale) and the red triangles show Compton beam size (right scale) on the calorimeter face.

7.3 Laser Beam

The laser beam transport system consists of lenses and mirrors part of which needs manual adjustment and some of them are remotely controllable. Contrary to the motor driven calorimeter table and collimators none of the mirrors has reference switch so, the laser beam steering is based on reference spots on/behind the mirrors and also on light intensity measured at beam dump by a powermeter. Manual steering is done once per few weeks while an automatic optimization is performed in between of the electron fills to maximize amount of light in the powermeter. These two operations could in principle change the laser vertical alignment and shift IP while during the fills light beam is only steered horizontally to optimize the Compton rate leaving the IP untouched. Hence, any beam-time IP change, induced by the laser beam could be related to vertical drift only which, in general, is compatible to the electron beam drift and contributes negligibly to point-to-point systematic error. The fill-to-fill and longer term contributions could be estimated by scanning the laser light along the electron beam to measure the full IP range. Results of such experiment are shown on fig. 8 and exhibit a good agreement with the simulations as well as an IP range of 4 m. On the positive side (toward the calorimeter) the range is limited by laser beam pipe aperture (sharp drop of luminosity at $Z = 2.8$ m) while upstream of the electrons before the aperture limitations the IP runs into a beam-line quadrupole QL56W (WR132) which spoils the focus dramatically. Thus, in principle, the IP could travel in between of these two easily distinguishable points within ± 2 m and we should conservatively assign an error

$$\delta P_{IP} = 2.04\%$$

to the polarisation measurement.

8 Polarisation Absolute Scale

Here we address question how well is defined the TPOL analyzing power (AP) since its uncertainty enters directly to the systematics as an overall scale error. The best measurement of the AP so far, with an accuracy of half a percent, has been done using polarisation rise-time measurements which are summarized in [2]. Since then the calorimeter setup and electronics has been modified and a bunch of test-beam and in-situ data has been utilized together with offline analysis [4] and simulations to upgrade the AP. It is worth to mention that this modified AP is connected to the rise-time calibrations via the focus correction (for details see [3]). Also, a recent advanced offline analysis [5], based on 2D energy-position multi-parameter fit, conforms the online AP within better than 1%. Anyhow, the best verification of the AP is an alternative measurement that we perform using a stand-alone Silicon detector which directly measures positions of the Compton photons and is free from the TPOL detector systematics. Results of polarisation measurements and comparison to the TPOL values are presented in fig.9. Despite of the observed large variations of statistical and systematic origin we can use the mean value of $SiPOL/TPOL = 1.013 \pm 0.017$ to calibrate the TPOL polarisation scale. Thus, after scaling the TPOL measurements by the factor of 1.013 we assign an overall scale error

$$\delta P_{scale} = 1.7\%$$

to the polarisation.

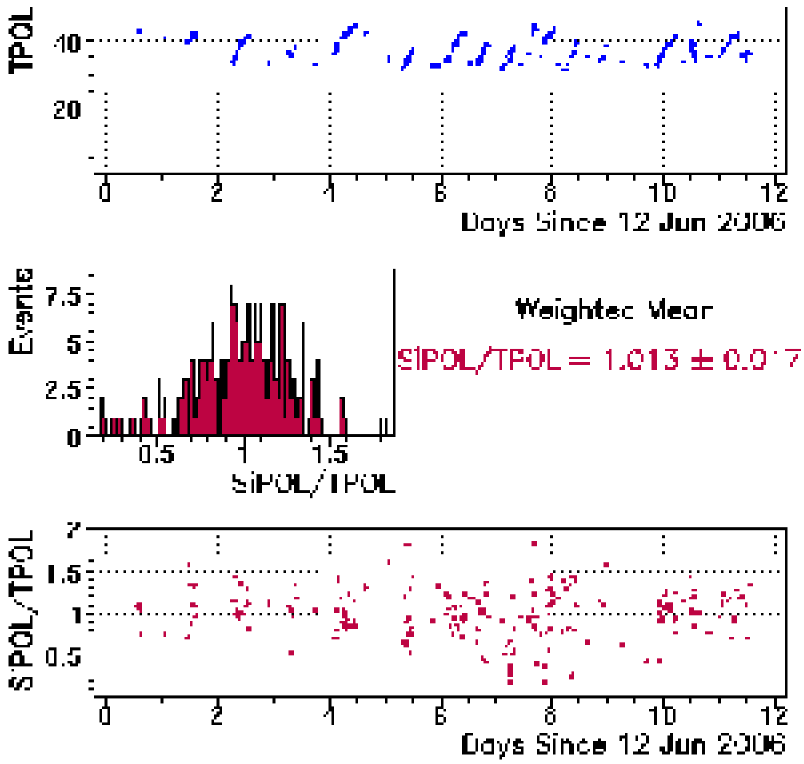

Figure 9: TPOL measurements (upper plot) and comparison with the polarisation measured by the silicon strip detector.

Summary and Outlook

Collecting all the partial errors from the above factors (table 1) and summing up quadratically, for the TPOL systematic error we get

$$\delta P = 2.91\ \%$$

For some analysis it may turn useful to separate point-to-point (δP_{pp}), fill-to-fill (δP_{ff}) and the overall scale errors

$$\delta P = \delta P_{pp} \pm \delta P_{ff} \pm \delta P_{scale}$$

with $\delta P_{pp} = 0.53\%$ and $\delta P_{ff} \equiv \delta P_{IP}$, i.e.

$$\delta P = 1.19\ \% \pm 2.04\ \% \pm 1.7\ \%$$

.

The dominant source of the error is the IP uncertainty due to the laser beam movements. This source could be suppressed gradually (down to be compatible with the δP_{IP}) by one of following means:

- upgrade laser beam transport system to measure the beam vertical position at the WR133.5 (nominal IP)

- during each fill perform an automatic laser beam vertical scan
- use lower energy Compton spatial distributions to fetch offline the absolute IP position.

Most attractive among this possibilities is the last one since the other two are hardware resource and/or beam time consuming. In addition the offline method will allow to post-apply it and re-process all the last years data. The bottleneck for this method is that in the η distributions the IP effect is convoluted with the Compton beam size effect. However, using a proper deconvolution (e.g. a δ-function method applied in [6]) it should be possible to separate and measure the IP.

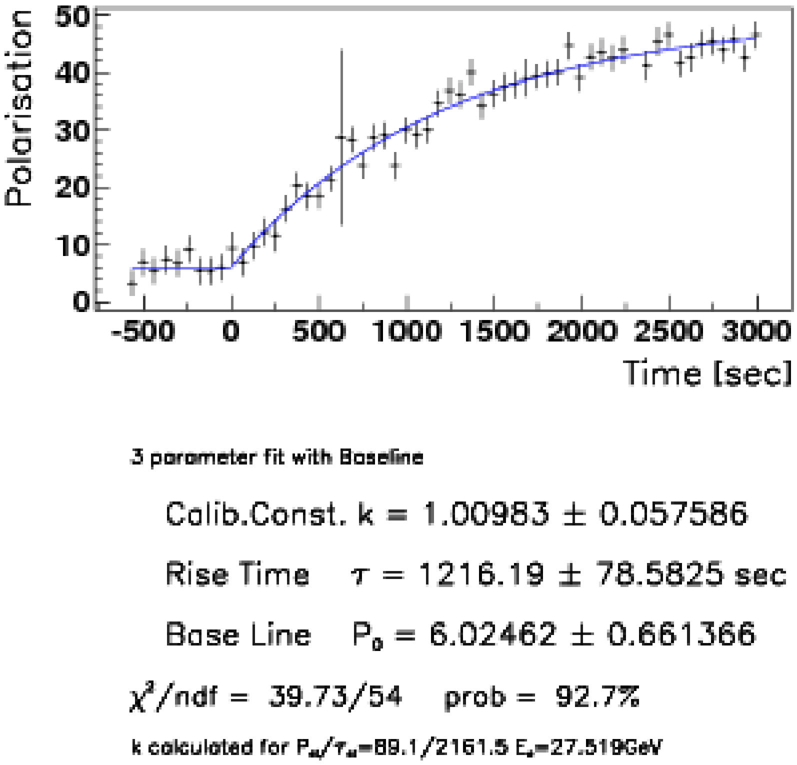

Figure 10: Rise-time calibration. Time=0 corresponds to 21.06.2006 14:29:10.

Next significant uncertainty is the polarisation scale calibration error. To improve the δP_{scale} one simply would need more statistics i.e. more silicon runs. To reach an accuracy of 0.5% (compatible with the δP_{pp}) about 5 month silicon running is necessary. A faster alternative would be rise-time calibration (a recent measurement is shown on fig. 10). The same accuracy 0.5% could be achieved with about 20x2 hours measurements i.e. in two week period if we take one measurement per fill. However, here we encounter large theoretical uncertainties and an interference with other experiments.

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