DRAFT - DRAFT - DRAFT

Accuracy of the electron beam polarization measurement in the first half of 1999.

A. Borissov
University of Michigan

The data of the longituginal (LPOL) and transverse (TPOL) polarimeters from the first half of 1999 were analysed based on data from online programs. Corrections were made to the LPOL data due to a dependence of the measured polarization on the left-right asymmetry of the calorimeter signals. Statistical errors for the LPOL and TPOL are presented versus beam polarization. Also shown is the statistical accuracy of LPOL versus calorimeter signal. The LPOL/TPOL ratio was studied as a function of time over which data were averaged. The smoothing of the polarization values was done using spline interpolation. The same procedure was performed to the LPOL and TPOL data. The total error of the polarization measurement was calculated on a fill by fill basis, and a new method of extracting systematic errors was applied. The extracted systematic errors and their dependence on the beam polarization performance are being discussed.

Contents

I. INTRODUCTION

The stable operation of the longitudinal (LPOL) and transverse (TPOL) polarimeters during the first half of 1999 with quite large polarization of high intensity electron beam allows us to perform offline analysis of the accuracy of HERA electron beam polarization measurement on a high statistics data sample.

After a cut on beam polarization ($P_b > 40\%$) which is used for the HERMES physics analysis and a cut on the period of stable operation (from the middle of February up to the middle of April 1999) the polarization of electron beam over all measured points and the LPOL over TPOL ratio of averaged over five minute intervals are presented in Fig. 1.

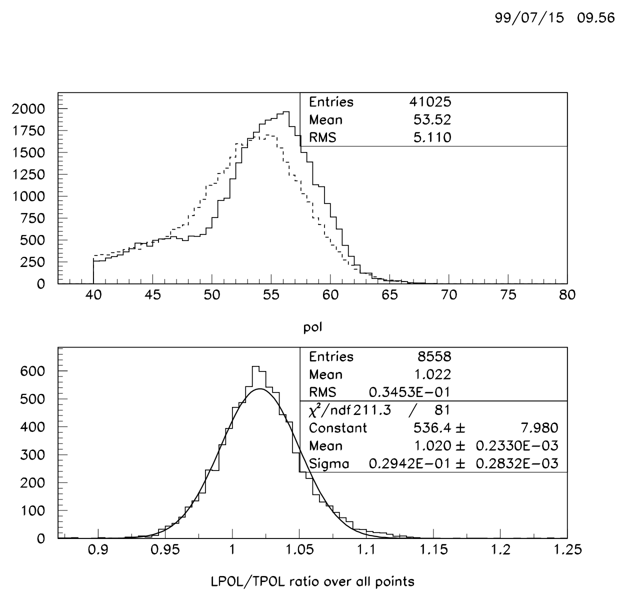

FIG. 1. Uncorrected polarization values of the electron beam in the first half of 1999 as measured by LPOL (solid line) and TPOL (dashed) are shown in top (a) panel. The bottom (b) panel displays the LPOL over TPOL ratio averaged over five minute time intervals.

The observed systematic shift of the polarization profiles indicates that a correction have to be applied. This is discussed in the next section. Note that the width of the LPOL over TPOL ratio is consistent with the result obtained ealier by A. Most's analysis for 1997 data.

The ratio of corrected LPOL over TPOL has been used for systematic studies of the stability of the polarization measurement, and allows one to estimate the squared sum of systematical errors of both polarimeters. From the smoothing procedure on a fill by fill basis, the average total error of the polarization measurement was obtained for LPOL and TPOL data. Taking into account the average statistical accuracy of the polarization points, the contribution of the LPOL and TPOL systematic errors and the error of the smoothing procedure have been extracted separately.

II. η_X, η_Y DISTRIBUTIONS AND CORRECTIONS

An essential feature of the polarimeter response is its symmetric uniformity relative to the centre of polarimeter. The setup of the longitudinal polarimeter combining four crystals allows us to measure the left-right $\eta_x = (E_{left} - E_{right})/(E_{left} + E_{right})$ and up-down $\eta_y = (E_{top} - E_{bottom})/(E_{top} - E_{bottom})$ asymmetry of the energy deposited in the crystals.

The distribution of η_x and η_y accumulated over the entire data taking period is presented in Fig. 2a,b for $P_b > 40\%$. It shows that the data are concentrated in the region $-0.1 < \eta_x < 0.4$ and $-0.05 < \eta_y < 0.1$. So those cuts were applied to the data. The very narrow η_y range corresponds to the stable, auto-corrected y position of the calorimeter table. Wider fluctuations of the beam in the horizontal plane and limited movement of the table position in one x direction are the reasons for the asymmetric picture in x direction, and thus the necessity of corrections.

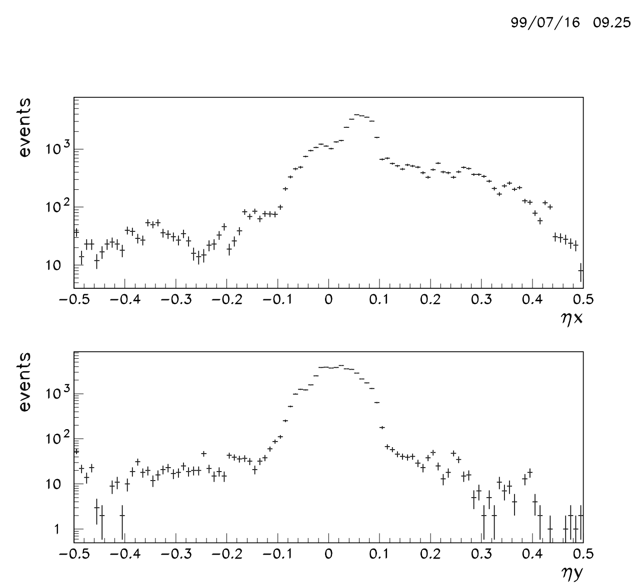

FIG. 2. Distributions of η_x (a) and η_y (b) variables.

The LPOL/TPOL ratio was studied with respect to a dependence on the η_x and η_y values. Some inclination of mean value of LPOL/TPOL ratio with η_x is observed in Fig. 3.

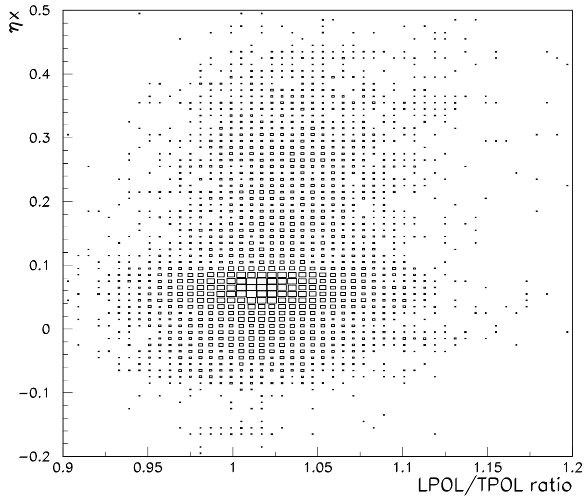

FIG. 3. Uncorrected LPOL/TPOL ratio versus η_x.

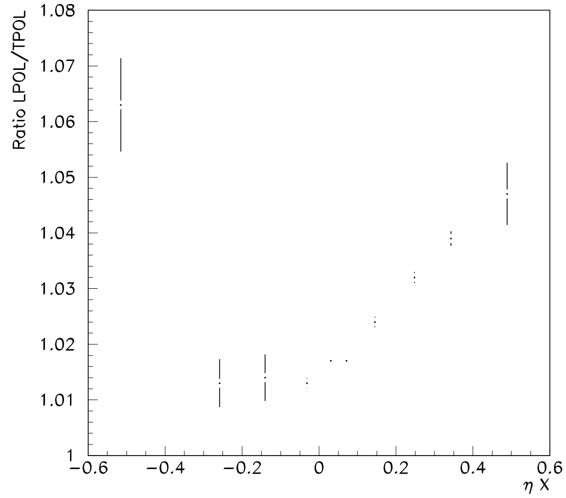

FIG. 4. Mean value of uncorrected LPOL/TPOL ratio in η_x bins.

The plotted ratios represent an average over each bin in η_x in Fig. 4 and η_y in Fig. 5. Significant decrease of statistics outside of the discussed regions allows the data to be present only in much wider bins. The observed dependence of the mean ratios on η_x was fitted in linear form, see Fig. 6. According to the fit the following correction was applied to the LPOL data:

$$P_{b(LPOLcorr)} = P_{b(LPOLraw)}/(1.013 + \eta_x * 0.0698)$$

Note that the analysis presented here is based on normalization to TPOL data, and the offset is included due to that. The reason of such systematic shift of LPOL/TPOL ratio is till unknown and requires special studies for both polarimeters. For example, more detailed calibration information is needed to correct properly for the horizontal fluctuations of the electron beam at HERA.

One cross check was done for the stability of TPOL data itself versus inclination of the TPOL table position. It was ensured by putting a cut of $\pm 50 \mu$m on the inclination during the time intervals used for the determination of LPOL/TPOL ratio.

After application of the η_x correction the LPOL/TPOL ratio is found to be quite flat as a function of η_y as shown in Fig. 7. After correction the observed inclinations are much less then 1%, and are neglected (Fig. 6, 7). No further corrections are applied to the LPOL data.

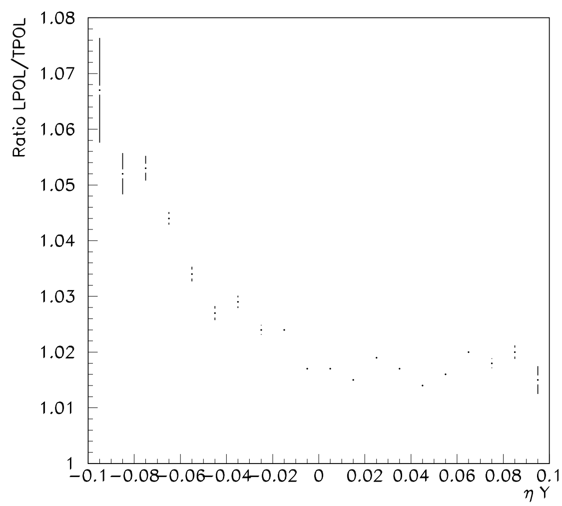

FIG. 5. Mean value of uncorrected LPOL/TPOL ratio in η_y bins.

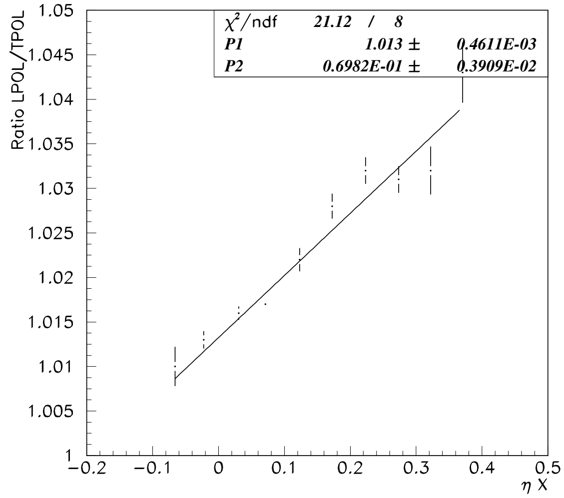

FIG. 6. Fit of mean value of uncorrected LPOL/TPOL ratio as function of η_x.

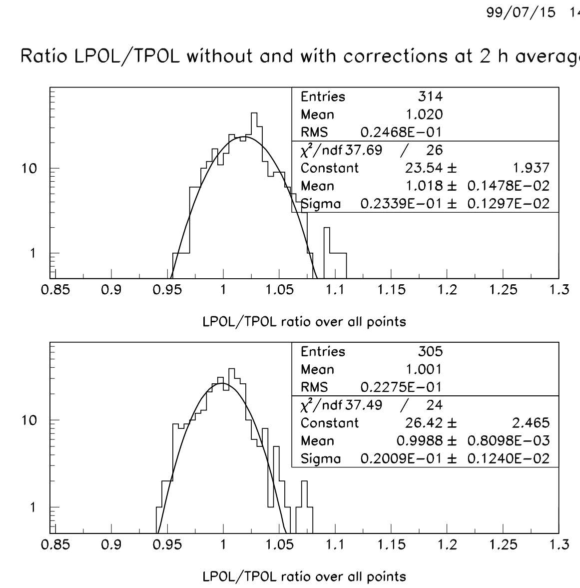

FIG. 8. Ratio of polarizations of LPOL over TPOL averaged in two hour bins (a) without corrections and (b) after η_x corrections and cuts on η_x and η_y regions.

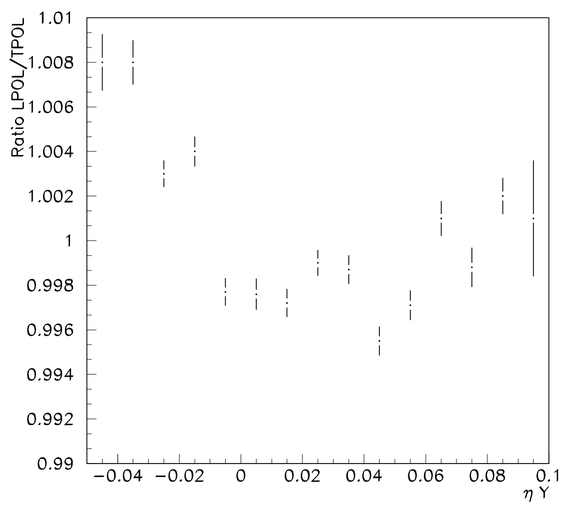

FIG. 7. Mean value of the LPOL/TPOL ratio as function of η_y after application of η_x corrections.

After the η_x correction the mean value of the LPOL/TPOL in Fig. 8 is stable and equal to one and the sigma of the fit becomes smaller.

III. STATISTICAL ERRORS FROM ONLINE PROGRAMS

To study the combined contribution of statistical and systematic errors to the mean dispersion of polarization measurements, the average values of statistical errors versus polarization are plotted in Fig. 9 for each polarimeter separately. Statistical errors were taken from online programs and cross checked for LPOL [1].

In spite of sligtly different time of accumulation of the statictics ($\sim$ 62 s for LPOL versus $\sim$ 66 s for TPOL) for one data point of polarization the average values are comparable. The single photon mode of data taking of TPOL can be a reason for its larger statistical error.

[1]More precise expression can be used in LPOL program for error determination. Instead of factor $4(S_L^2 \delta S_R^2 + S_R^2 \delta S_L^2)$ better to use $(\delta S_L^2 + \delta S_R^2)(2S_L^2 + 2S_R^2)$ where $S_{L(R)}(\delta S_L)$ sum (error) of energy deposition in calorimeter at left (right) laser polarization. But the error from the direct approach varies only by $\sim 0.02\%$.

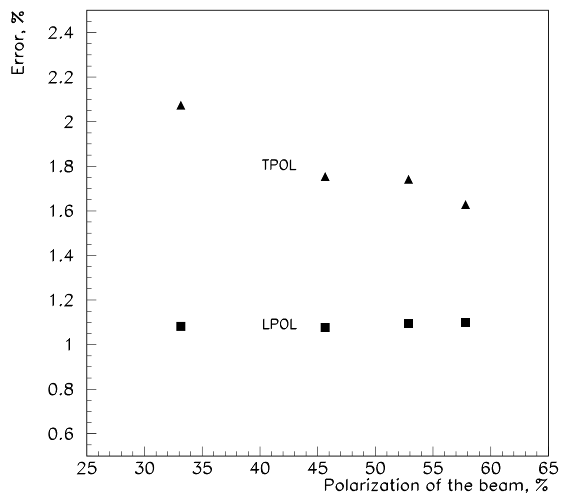

FIG. 9. Average statistical error of measured polarization from online TPOL and LPOL programs. Each measurement represents about one minute of data taking.

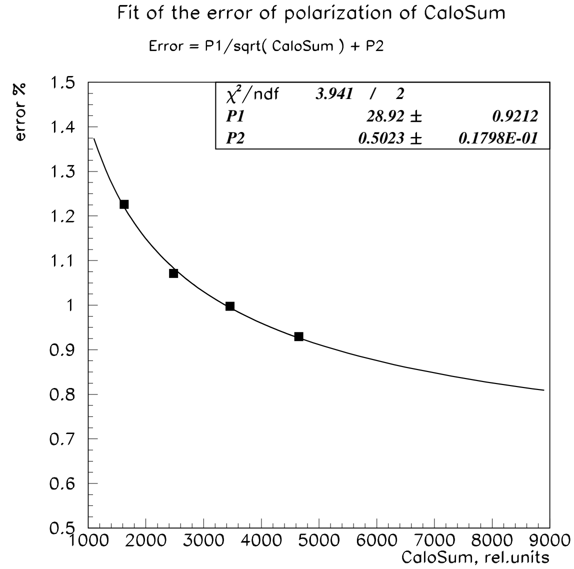

FIG. 10. Average statistical error of measured by LPOL polarization in the dependence of calorimeter signal.

The average statistical error of the LPOL measurement is plotted versus energy deposition in the calorimeter and fitted to the shape of standard calorimeter resolution (Fig. 10)

$$\delta P_b = 28.92/\sqrt{(}E) + 0.5\%$$

The working regime of 1999 ($E \approx 2500$) is far below the maximum value of $E \approx 8000$. This allows one to increase the statistical accuracy of the polarization measurement by a factor of ~ 1.4 by going to $E \sim 7000$.

Note that LPOL online program separately determines the polarisation of pilot (noncolliding) and colliding bunches. While the pilot bunches have larger polarization, their relative contribution to the total polarization is so small that the total polarization is determined mainly by the colliding bunches.

IV. LPOL/TPOL RATIO FOR STUDY OF SYSTEMATIC ERRORS

The stability of LPOL and TPOL operation was studied via the ratio of the average polarization measured of LPOL and TPOL on the same time period. The given accuracy of the recorded UNIX times (1 s) is sufficient to fix the start time for both polarimeters and the average measured polarizations for the next, for example, five minutes later. Since both online programs deliver polarization values roughly each minute, the time of averaging can be varied between a few minutes and several hours, limited only by the duration of the electron fill. The cut ($P_b > 40\%$) effectively removes the beginning period of the fill when the synchronization accuracy is more important and the polarization is not very stable. Note that stable operation of both polarimeters was checked by comparing the mean values for several non-overlapping data taking periods of half month duration.

The accuracy of the beam polarization measurement can be estimated from the dispersion of LPOL/TPOL ratio. At small time intervals the dispersion is determined by statistical and systematic errors, whereas at large time intervals the dispersion is determined mainly by the systematic errors and approaches an asymptotic limit. The dispersion of LPOL/TPOL ratio is presented in Fig. 11 as a function of the averaging time, which was varied between 180 s and 12000 s. It can be clearly seen that the error of the ratio becomes constant ($\sim 2.2\%$) at averaging times of more than one hour.

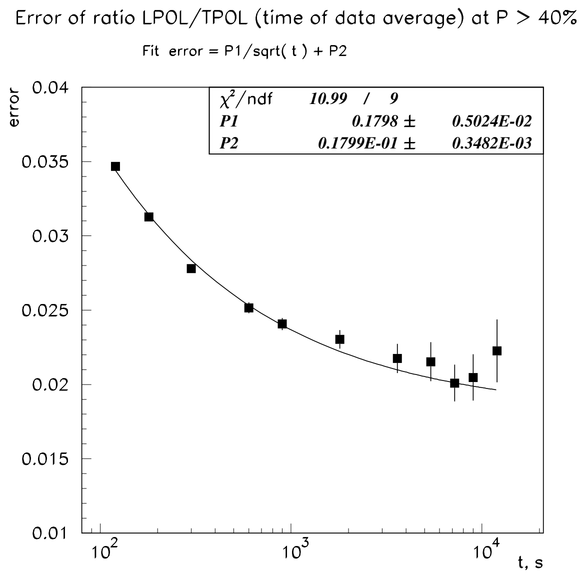

FIG. 11. Dispersion of LPOL/TPOL ratio as function of the time over which data were averaged.

The same dispersion is presented in Fig. 12 for different polarization bins. Due to the limited duration of fills at average polarization less then 50% the available statistics at large times is much smaller and the dispersion of the Gaussian fit is larger. But inspite of these larger errors, it is demonstrated that the asymptotic value of the dispersion does depend on the beam polarization.

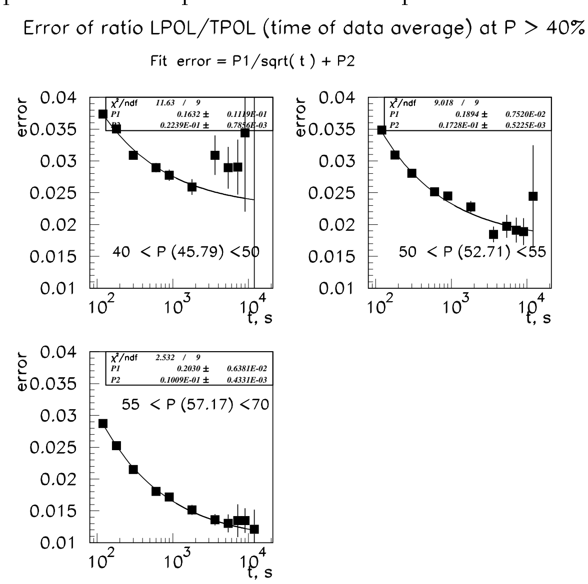

FIG. 12. PRELIMINARY. Dispersion of LPOL/TPOL ratio as function of time during which data were averaged in different bins of the beam polarization.

V. FILL SMOOTHING FOR TOTAL ERROR

For the physics analysis polarization values are needed in short time intervals ($\sim 10s$). Therefore the polarization measurements are smoothed by splines to reproduce the polarization profile of the beam. Even for good 1999 data the profiles did not always correspond to the theoretical rise-time curve,

$$P_b(t) = P_{max}(1 - e^{-t/\tau}),$$

due to either tuning of polarization during a fill, inclinations of the orbit of the beam, or different operations with magnets of HERA experiments. That explains the use of splines as a universal but conservative procedure, instead of exponential fit.

For systematic studies, fills with good operation of LPOL and TPOL were choosen, with cuts and corrections applied only to LPOL data. Just raw TPOL data have been used so far. The smoothing procedure was applied to both in the same way, see as example the same fill from LPOL data in Fig. 13a and TPOL in Fig. 14a. The difference between spline values and measured points was plotted and the dispersion of that difference presented for the same fill in Fig. 13b for LPOL, Fig. 14b for TPOL. This difference was treated as the total error of the polarization measurement for that fill. The relative total error discussed below is the ratio of that error to the average polarization of the fill. This error is determined for each fill separately and is fill dependent. This total error incorporates the following three uncertainties: statistical, systematic and the error of smoothing procedure. As we have no consistent time shape of polarization, and the beam current is different from one fill to another, the statictical errors are essential to the smoothing. The smoothing was performed from one point of measured polarization to another as the time between those points is almost constant. Also note that the 10% smaller number of polarization points at TPOL in the same time is not influencing the extracted value of the dispersion. The systematic errors described in previous section also influence the smoothed results due to the standard duration of the fills of eight or ten hours in data taking period. The error of smoothing procedure by interpolation with splines is the third type of error which takes into account some rough changes of the polarization value in time as well as application of splines itself.

Note that the total error of the beam polarization measurement is done in a conservative way in the sense that it is not very procedure dependent. The number of knots in splines as input parameter for the interpolation was limited to 25 due to the smooth variations of the polarization during fills. Within this limit it was varied with the goal to obtain the minimum value of total error of the fill. The dependence of the resulting smoothing error on beam performance and polarization is discussed below.

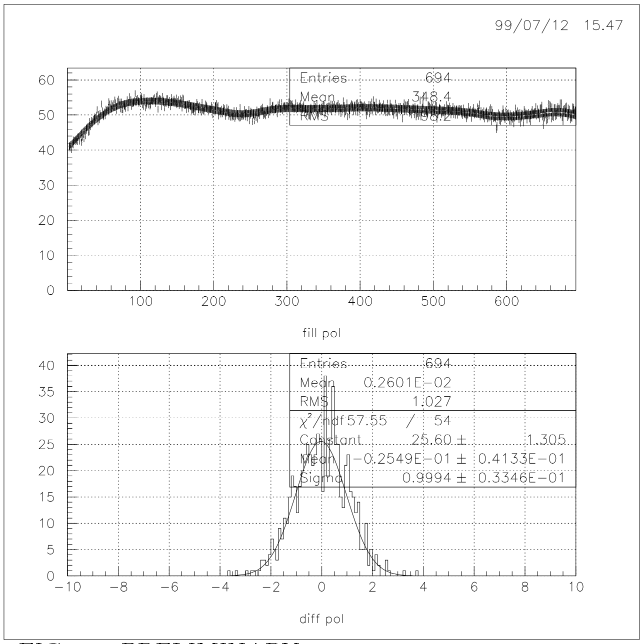

FIG. 13. PRELIMINARY.
Smoothed LPOL data of one fill (a). Difference between smoothed and data points (b), dispersion of gauss fit is presented as total error of polarization measurement of that fill. Total relative error is the ratio of the dispersion over the average polarization of that fill.

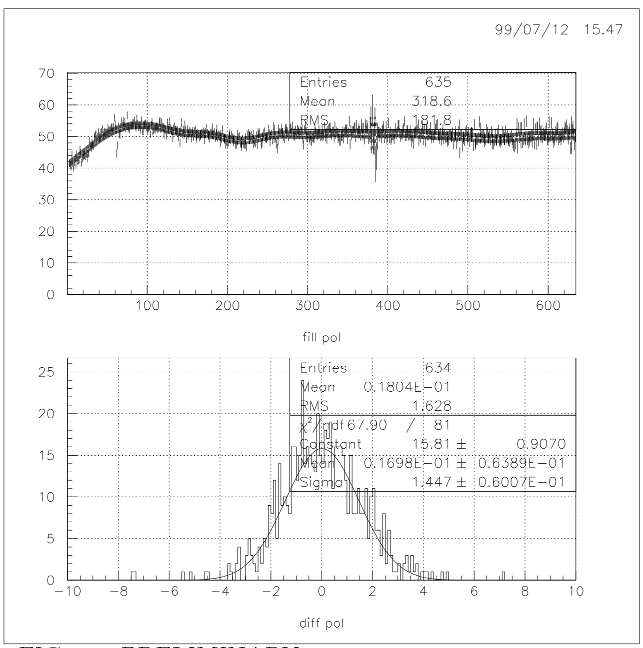

FIG. 14. PRELIMINARY.
Smoothed TPOL data of the same fill (a). Difference between smoothed and data points (b), dispersion (sigma) of gauss fit is presented as total error of polarization measurement of that fill. Total relative error is the ratio of the dispersion over the average polarization of that fill.

For all 1999 fills treated such way, the total relative error versus average polarization of the fill is presented on Fig. 15 (a) for LPOL and (b) for TPOL. Note that at larger polarization values the error is varying less and the total error is smaller in Fig. 15. The projected beam polarization profile is exactly the same for both polarimeters after the described corrections to LPOL data.

The total errors of the LPOL and TPOL measurements are different and presented in Fig. 16. The average value of the total erros from Fig. 16 can be taken as a total error of the polarization measurement for the first half of 1999 data taking for each polarimeter.

Note that the total error of the combined measurements the mean LPOL(2.35%) and TPOL(3.4 %) errors results in a total accuracy of $\sim 1.93\%$ of the beam polarization measurement in the first half of 1999 [1].

Another estimation of accuracy of the polarization measurements can be done for the best fills taking the peak values of total relative errors from Fig. 16 instead of the mean one. In this case LPOL provides $\sim 2\%$, TPOL $\sim 2.5\%$ and the combined accuracy of the electron beam polarization measurement in the first half of 1999 is $\sim 1.6\%$.

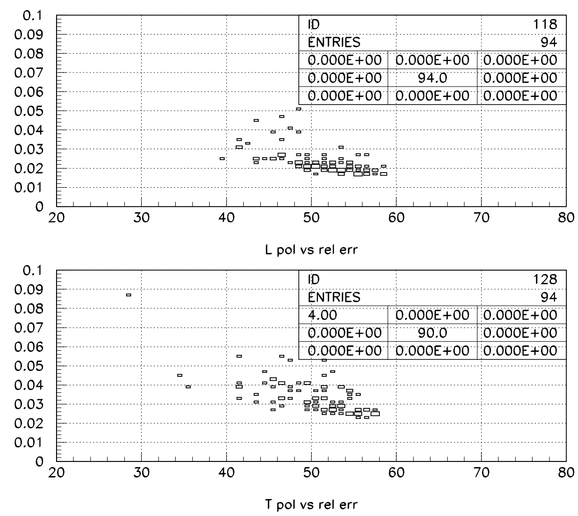

FIG. 15. PRELIMINARY.
Total relative errors of polarization measurement calculated on fill by fill basis for LPOL (a) and TPOL (b) versus the average polarization of those fills.

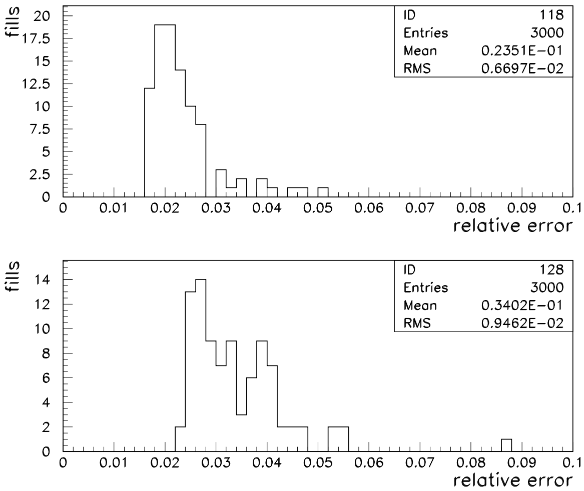

FIG. 16. PRELIMINARY.
Distribution of total relative errors of polarization measurement calculated on fill by fill basis for LPOL (a) and TPOL (b).

VI. ANALYTIC INTERPRETATION AND SOLUTIONS

Above, several independent results of measurements have been presented. Analytical presentation and combination of them allows to work out and evaluate different components of the errors. That results in better understanding of all components of the accuracy of polarization measurement. Always relative errors measured in % are presented and discussed.

From the LPOL/TPOL ratio averaged over large enough time intervals ($1 \div 3$ hours) (Fig. 11, 12) it is possible to present time fluctuating systematic errors of LPOL (L_{syst}) and TPOL (T_{syst}) as

$$L_{syst}^2 + T_{syst}^2 = a^2 \tag{1}$$

where a is the value of LPOL/TPOL ratio at large time intervals. In the present analysis the LPOL data are normalized to TPOL so a possible scale error determined by rise time curves is not included here.

The total error of polarization measurement can be subdivided into statistical only $L(T)_{stat}$, systematic $L(T)_{syst}$, and smoothing error Spl introduced by the splines procedure and polarization performance of the fill. As all of them are independent it is possible to present:

$$L_{stat}^2 + L_{syst}^2 + Spl^2 = b^2, \tag{2}$$

and

$$T_{stat}^2 + T_{syst}^2 + Spl^2 = c^2, \tag{3}$$

where b and c are the mean total errors of LPOL and TPOL measurements extracted from Fig. 16. The average statistical errors from the LPOL online program ($L_{stat} = 1.07\%$) and TPOL program ($T_{stat} = 1.7\%$) were incorparated into the equations above to solve them.

The stability of solutions was checked by varying the beam polarization regions as well as taking the mean and the most probable (peak) value of errors presented in Fig. 16 for the full region of polarization from 40 up to 70 %. The resulting from the equations 1, 2, 3 systematic and smoothing errors are summarised in Table I. An uncertainty of about $\pm 0.1\%$ was obtained for end error by varying the input parameters a, b, c in equations above according to the statistical accuracy of determination of those parameters.

TABLE I. The evaluated systematic errors from spline procedure (Spl), LPOL and TPOL for the first half of 1999 data taking. All quantities are given in %.

P_{beam}	$< P_{beam} >$	type	Spl	L_{syst}	T_{syst}
40 - 70	53.62	mean	2.07±0.1	1.3±0.1	2.03±0.1
		peak	1.06±0.1	1.3±0.1	1.66±0.1
50 - 70	55.68	mean	1.55±0.1	0.83±0.1	1.71±0.1
		peak	0.98±0.1	0.98±0.1	1.63±0.1
56 - 70	58.45	mean	0.71±0.1	0.97±0.1	0.94±0.1
		peak	0.52±0.1	0.99±0.1	0.91±0.1

A decrease of the spline errors is observed as the beam polarization increases. It reflects an improvement in the beam polarization performance. The minimun obtained value of smoothing error ($Spl \sim 0.5\%$) after the optimization of input parameters of splines can be treated at present as the error corresponding to the soothing procedure itself.

A rather weak dependence of the systematic errors on the beam polarization is observed for both polarimeters. It is also supported by very small variations of those errors determined from the mean and peak values of total errors. At the well performed high polarized fills longituginal polarimeter systematic error is $L_{sys} = 1 \div 1.3\%$ and transverse polarimeter systematic error is $T_{sys} = 1 \div 1.7\%$. Both systematic errors estimated here are in very good agreement with design parameters [2,3].

Note that simplest cross check of systematic errors can be done via LPOL/TPOL ratio and equation 1 at assumption of the same value of systematical uncertainty for both polarimeters gives $L_{syst} = T_{syst} \approx 1.2\%$.

Remarks for evaluated errors

- All estimated errors are PRELIMINARY at present and still under development.
- Note that $a(P_b)$ in equation 1 is the parameter which mainly determines the dependence of systematic errors of the beam polarization.
- Systematic errors discussed above are relevant to the fluctuations of both polarimeters in time intervals of about one hour. They should be taken into account to the fill total error due to the standard duration of fills of about ten hours. More detailed reseach of the dependence of systematical errors of time intervals is foreseen.
- Due to the normalization on TPOL data at present no time-independent systematical deviations have been considered for LPOL.

VII. SUMMARY

- Accuracy of the electron beam polarization measurement in the first half of 1999 is $\delta P_b/P_b \sim 2\%$ for all fills with polarization more then 40 % and $\sim 1.6\%$ for the fills with best performace of polarization more then 55%.
- All components of errors for LPOL and TPOL are compatible:

  $L_{stat} \sim 1.1\%$, $L_{syst} \sim 1 \div 1.3\%$, $Spl \sim 1 \div 2\%$

  $T_{stat} \sim 1.7\%$, $T_{syst} \sim 1 \div 1.6\%$

  and corresponding to the design parameters [2,3].
- Some possibilities are still existing to improve and/or understand better the errors of LPOL.
  - Statistical errors can be improved in principle with increasing luminosity.
  - Systematic errors were obtained from the comparison and normalization on TPOL data. A TPOL independent and detailed calibration procedure is foreseen for direct determination of systematic uncertanties.
  - Spline error estimated from above descibed simple and conservative approach is not large. However, tuning of smoothing procedure is desirable as for the component having the maximum error for all fills with polarization more than 40 % .
- Better statistical accuracy of LPOL data is due to the multiphoton mode of operation [2].

Acknowledgements

I would like to thank W. Lorenzon for very useful comments, suggestions and discussions. Also I thank A.Simon, F. Menden and N. Makins for their interesting questions and comments.

---

[1] The European Physical Journal C. Review of Particle Physics, v 3, (1998) 1.

[2] Proposal to DESY for a Longitudinal Electron Polarimeter at HERA-East Section by the HERMES collaboration. HERMES internal note 95-023. May 1995, 19 p.

[3] D.P. Barber et al. NIM A338, 166-184, (1994), D.P. Barber NIM A329, 79-111 (1993).