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DESY and CERN Calibrations of the New Sampling Calorimeter for the Longitudinal Polarimeter at HERMES

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Abstract

The new Sampling Calorimeter for the Longitudinal Polarimeter has been calibrated up to energies of 20 GeV at the CERN H6 test beam facility. It was found to show excellent energy linearity over the entire energy range measured. In order to compare its linearity and resolution with previous test beam measurements at DESY and to define a baseline to compare with, it was also recalibrated at DESY just before bringing it to CERN. The energy linearity of the device measured in both the DESY and CERN test beams were confirmed by Monte Carlo simulations taking into account the actual test beam conditions.

Contents

1 INTRODUCTION

The Polarization 2000 Group (Pol-2000), which is the successor of the previous Polarimeter Group at HERA, is interested in reducing the statistical and systematic uncertainties of the electron beam polarization measurements to below 1%. For that reason, the TPol DAQ system was redesigned and rebuilt (to allow for single bunch polarization measurements), the LPol [1] got a new Sampling Calorimeter [2, 3] (to improve linearity and resolution), and the LPol will get a new Laser cavity system (to allow for high statistics single bunch polarization measurements with the LPol). Although the LPol group has already designed, built, tested, and used a new Sampling Calorimeter in the HERA beam, opinions were voiced that we should test its excellent energy linearity above 6 GeV, so we eventually could reduce the LPol's systematic uncertainties in the beam polarization measurements[1] to below 1%. In addition, Pol-2000 intends to use the same hardware and software, that was developed recently for the TPol, for the LPol. Therefore, we tested the performance of the Sampling Calorimeter with the new TPol hardware and software at the DESY test beam before we took it to CERN to test its energy linearity and energy response. The results and conclusions are summarized in this report.

2 SETUP

We first describe the DESY and then the CERN test beam facility setups.

2.1 DESY Test beam

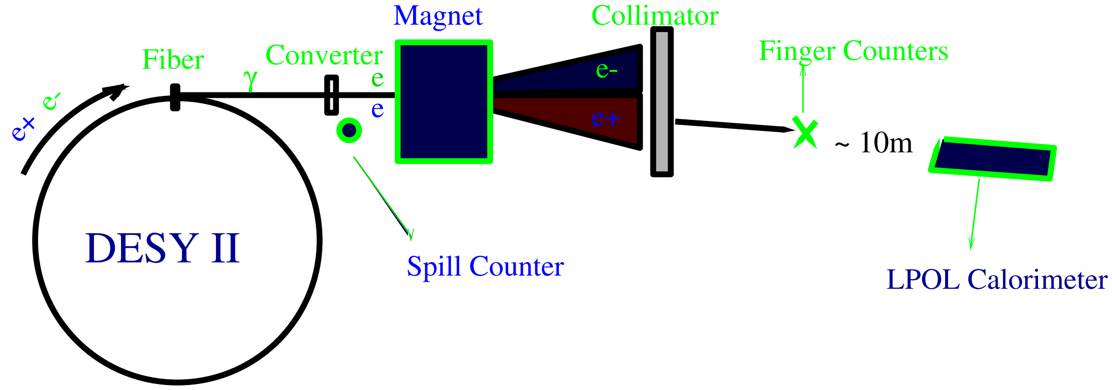

Figure 1. Schematic view of DESY setup. The finger counters were mounted 10 m before the LPol Sampling Calorimeter.

The DESY test beam is a low intensity electron beam, providing energies up to 6 GeV. The electron beam is obtained from the DESY II synchrotron ring, which stores $e^{\pm}$ and reaches a maximum energy of 7 GeV, the following way. The DESY II beam is extracted and steered to hit a 10 micron thick fiber, giving rise to Bremsstrahlung photons. These in turn are converted by a converter plate into $e^{\pm}$ pairs. A magnet separates the e^- from the e^+ and a collimator plate allows e^- to reach the test beam area T22. By changing the current in the separation magnet, it is possible to vary the test beam energy between 0.5 GeV and 6 GeV. Average rates obtained were ≈ 40Hz during calibration. Fig. 1 shows a schematic layout of the test beam facility. The test beam is equipped with a pair of finger counters which define the size of the beam ($1 \times 1\text{cm}^2$) by taking the coincidence between the two counters. During our calibrations, conditions were not optimal. The test beam area T22 has only two movable tables. The first one was occupied by the Transverse Polarimeter (TPol) silicon detector which supported the finger counters to allow accurate beam position measurements. The LPol calorimeter therefore had to be installed on the second movable table, unfortunately ≈ 10m away from the finger counters. Since the beam size was measured with the silicon detector to be 10.2mm (sigma) [4], as shown in Fig. 2, and its divergence was estimated to be 0.66mrad, the actual beam spot at the LPol calorimeter position was 12.1mm (sigma).

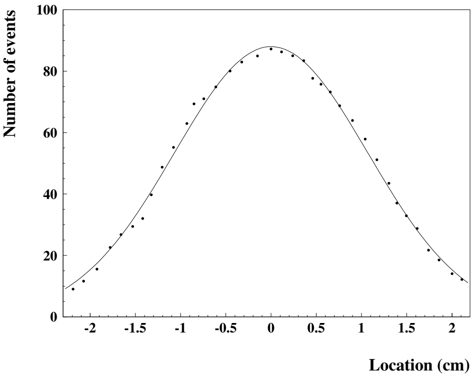

Figure 2. DESY test beam vertical (y) profile 10 m before the LPol position.

2.2 CERN Test beam

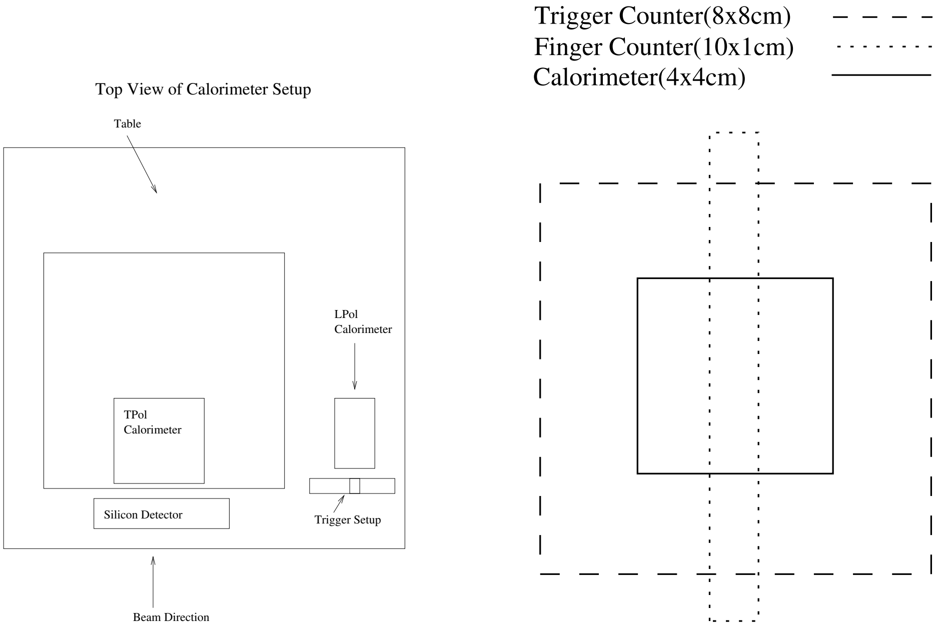

Figure 3. Top view of CERN setup (left panel), and sketch of front view of positions of trigger and finger counters relative to calorimeter (right panel).

At DESY, the maximum energy available at the test beam is 6 GeV, which is far below the energy of the backscattered Compton photons obtained from scattering the 532 nm photons of the green laser from the 27.5 GeV electrons in the HERA ring. The backscattered Compton photons reach energies up to 13.6 GeV, which defines the so-called Compton edge, while the bremsstrahlung photons reach all the way up the electron beam energy. This makes it desirable to cover an energy range up to 27.5 GeV. The calibration of the calorimeter at energies higher than 6 GeV was done at CERN using the secondary beam H6 from the SPS 450 GeV/c primary proton beam. Due to the design of the H6 beam line (see http//nicewww.cern.ch/sl/eagroup/beams.html#h6 for details) it always runs at the same polarity and at half the momentum of the H8 beam. During our beam time, we ran in the "non privileged" user mode, making it impossible to go below 10 GeV. Yet another "handicap" was that this beam time was officially allocated for the Transverse Polarimeter (TPol) position sensitive silicon detector calibration, disqualifying us from influencing the run plan and thus not allowing us to cover the full energy range. Therefore, the highest energy measured was 20 GeV, instead of the desired 30 GeV. To accept the maximum statistics available at the H6 test beam, the small trigger counter (1×1 cm^2) was replaced by a large trigger counter (8×8 cm^2) which is much larger than the size of the LPol calorimeter, creating inefficiencies in our calorimeter calibration. To reduce this effect, we installed a second counter (1×10 cm^2) just in front of the calorimeter and inserted it into the trigger logic. A schematic view of the trigger counters in front of calorimeter used at CERN is shown in Fig. 3. The calibration setup was installed in the H6B zone, 156 m away from the T4 target (see the beam line optics at http//nicewww.cern.ch/sl/eagroup/h6ht98a4bw.ps). At CERN, the beam size was measured with the silicon detector (8.4 mm sigma) at the LPol calorimeter position, and is shown in Fig. 4.

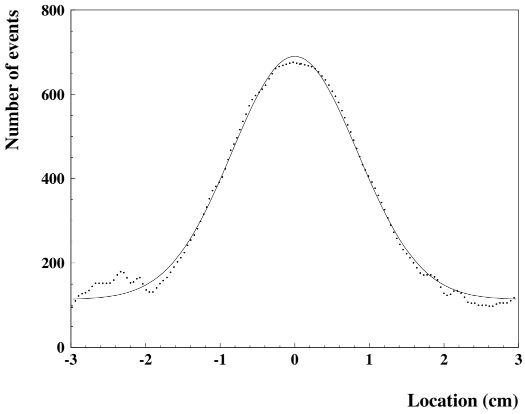

Figure 4. CERN test beam vertical (y) profile at the LPol position.

2.3 DAQ and Trigger Setup

The test beam calibration was done using the upgraded TPol DAQ system, which aims to measure the beam polarization more precisely. The advantages of this are: event-wise pedestal subtraction, faster readout, and the ability to measure the polarization in each single bunch. We incorporated the LPol calorimeter signal as a one channel readout into this scheme and used it for data taking during calibration. A schematic view of the trigger logic and the DAQ are displayed in Fig. 5. The whole scheme was still under commissioning; thus there were differences between the CERN and DESY setups. Most importantly, during DESY calibrations the VME TDC was not yet ready and we therefore used a TAC (Time to Amplitude Converter) to record the time difference between the MFCC internal trigger and the external trigger provided by the finger counters. Another difference was in the size of the finger counters, while at DESY we used the 1×1 cm^2 size, at CERN, to accept higher events rates and to not disturb the TPol Silicon detector setup, a 8×8 cm^2 size was used.

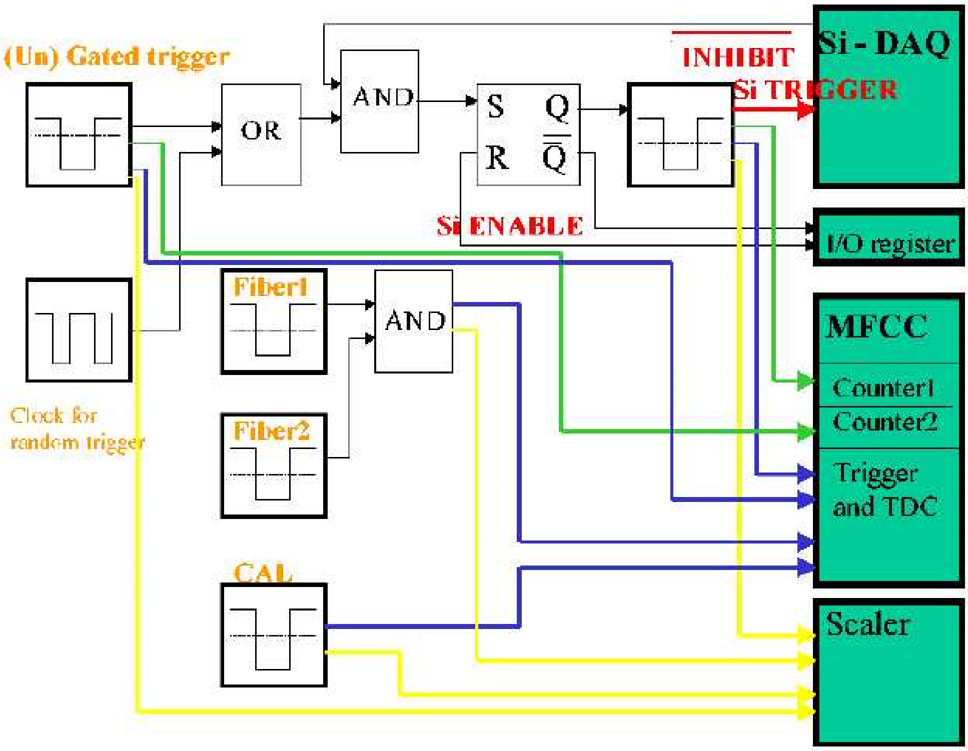

Figure 5. New DAQ system of TPol used for LPol test beam measurements.

2.3.1 Single Event Pulses

The new DAQ scheme for the TPol is tuned to the HERA pulse repetition rate of 10.4 MHz, which defines the time difference of consecutive electron bunches (96 nsec apart). It continuously digitizes the signal from the calorimeter PMT every 25 nsec and writes it into a pipeline (MFCC). The signal can be synchronized with specific electron bunch numbers, using the TDC signals. This allows us to define the time interval of integrating the signal, and to assign the calorimeter signals to individual bunch crossings. In turn, this enables us to accept high rates and makes bunch polarization measurements feasible in short time periods. The characteristics for this scheme of digitizing pulses for energies of 10, 15, and 20 GeV are shown in Fig. 6. Note, that the entire signal can be distributed over four digitization bins, since the signal width is about 70 ns.

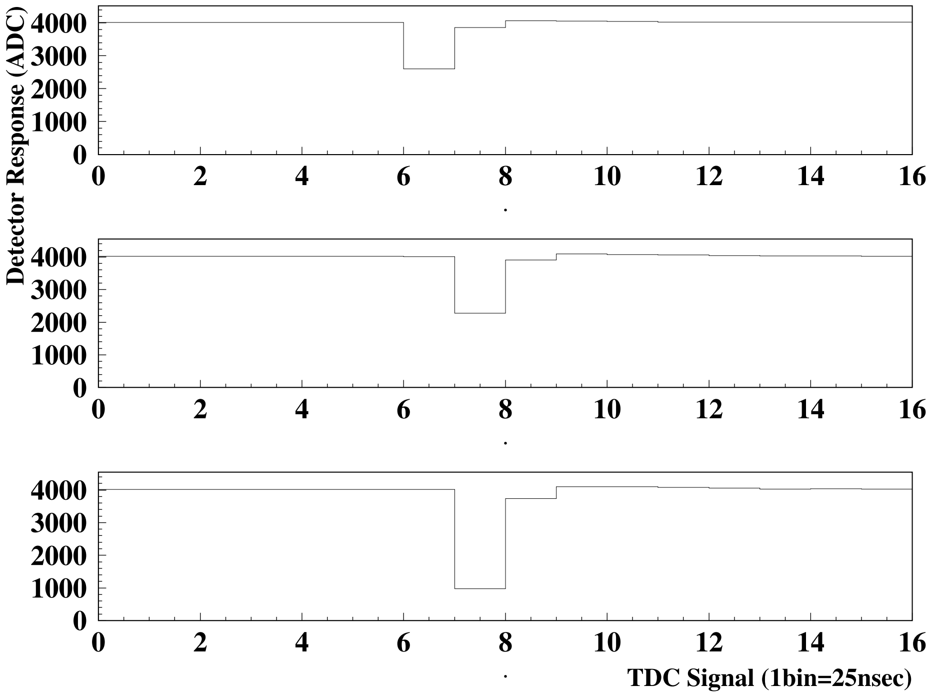

Figure 6. Single event pulse shapes using new TPol DAQ for 10 GeV (top panel), 15 GeV (middle panel), and 20 GeV electrons (bottom panel).

2.3.2 Average Pulse Shapes

The average pulse shapes of the calorimeter can then be reconstructed by using many events and by performing pulse shape integration (even) offline. This is demonstrated in Fig. 7, where the two-dimensional summary plot of pulse shapes over thousands of events is shown in the left panel. It is constructed by using only the maximum bin in a single event and by plotting it versus the TDC signal. The average pulse shape, as shown in the right panel, is then extracted from this plot as the energy response of the calorimeter for the three test beam energies used at CERN, where the average trigger rate was $\approx$ 100 Hz.

Unfortunately, there is a fundamental difference in operating the DAQ in the HERA tunnel and in the test beam facilities. The problem is that in the test beam facilities at DESY and CERN the event rate interval is not fixed to 96 ns as in the HERA tunnel, rendering synchronization of the flash ADC internal clock and the external trigger (provided by the trigger counters) impossible. The random nature of the external trigger creates a time jitter with respect to the flash ADC internal clock, which yields a broadening of the calorimeter response signal and thus a variation in the extracted amplitude with frequency of ADC internal trigger (25 ns). This is demonstrated in Fig. 8 (upper panel). The amplitude was calculated using all 4 bins which contain the signal (maximum amplitude plus neighboring bins: -1 & +2 bins from maximum). One can clearly see the effect of the time jitter between the flash ADC internal trigger and the external trigger.

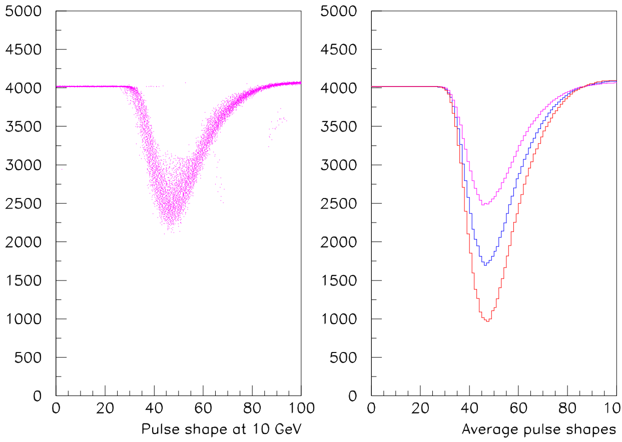

Figure 7. Pulse shapes formed by using several thousand single pulses. In the left panel all events collected at 10 GeV are displayed. In the right panel the average pulse shapes are shown (from top to bottom) for 10 GeV (magenta), 15 GeV (blue), and 20 GeV(red).

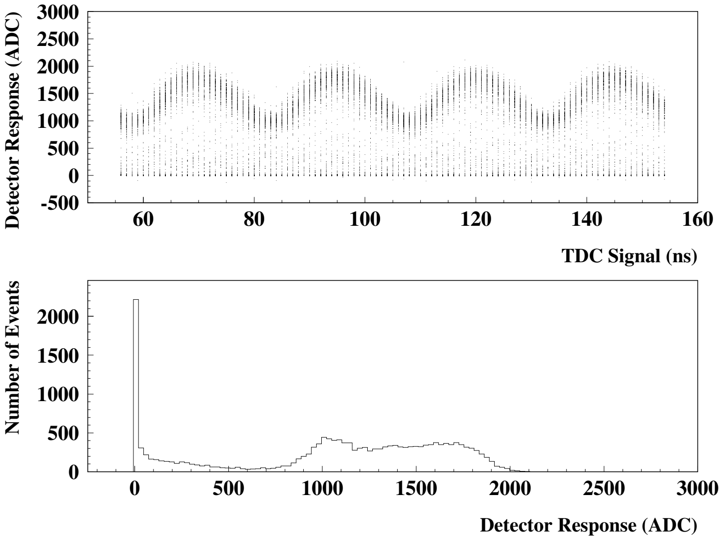

Figure 8. Upper panel shows uncorrected two-dimensional spectrum of ADC vs TDC for 10 GeV beam at CERN. Lower panel shows signal broadening of the one-dimensional ADC spectrum due to the time jitter.

Also notice the region below the signal region (channels $0 - 1000$ in lower panel of Fig. 8) originating from inefficiencies in the trigger counter which is much larger than the size of the calorimeter, and from the $\approx 7\%$ pion contamination in H6 CERN test beam. This created an additional difficulty in the analysis, for we had to correct the data for these effects before we could start studying the linearity and resolution of the calorimeter.

3 Analysis

3.1 Correcting Data

As can be noticed, the time jitter between the flash ADC trigger and the external trigger creates an artificial "sine" modulation of the data which has to be corrected. This correction was made iteratively for both the DESY and the CERN data sets. For the CERN data, the ADC spectrum is first plotted against the TDC spectrum, then a correction function for the ADC amplitude was found empirically (see Fig. 9) that allowed to "smooth out" the data. For the DESY data in contrast, no properly functioning TDC was available yet. Thus instead of a TDC, an additional ADC channel was used to record the timing signal that was converted in a TAC (Time to Analog Converter).

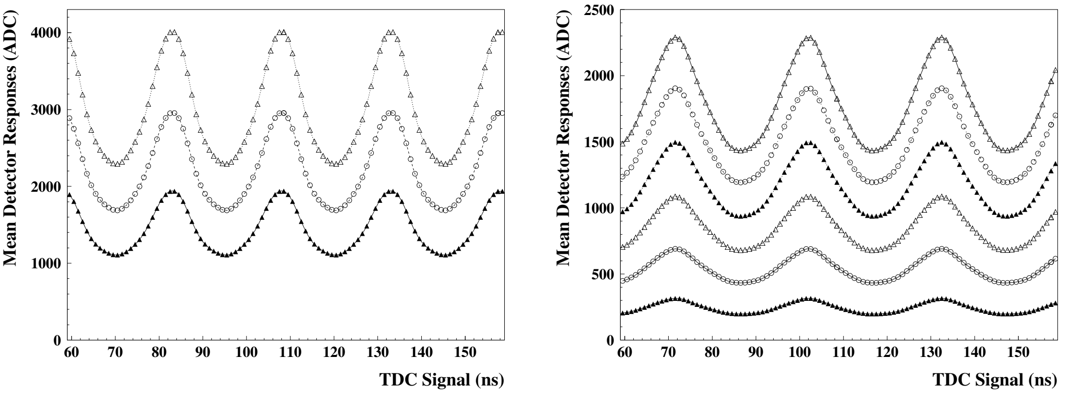

Figure 9. Left Panel: Correction functions for 10, 15, and 20 GeV (from bottom to top) as used for the CERN data. Right Panel: Correction functions for 1 – 6 GeV (from bottom to top) as used for the DESY data.

Since the signal modulation is not precisely a sinusoidal function, it was necessary to do the corrections in two steps. In the first step, a nine parameter fit of the following form was performed (which was slightly different for CERN and DESY)

$$\begin{aligned} t &= \frac{2\pi(x-0.5-p_1)}{25}\ \text{(CERN)}; \qquad \frac{2\pi(x-p_1)}{30.4}\ \text{(DESY)}, \\ ADC &= p_2\,[1+p_3\ \sin(t)+p_4\ \sin(2t+p_5) \\ &\quad +p_6\ \sin(3t+p_7)+p_8\ \sin(4t+p_9)], \end{aligned} \tag{1}$$

where p_1 determined the time offset, p_2 the overall scale, and $p_3 - p_9$ the weights and phases of the sin functions. In the second step, the following eight parameter fit was used

$$\begin{aligned} u &= \frac{2\pi(x-0.5-p_1)}{25}\ \text{(CERN)}; \qquad \frac{2\pi(x-p_1)}{30.4}\ \text{(DESY)}, \\ ADC &= ADC\,[1-p_2\ \sin(u)-p_3\ \sin(2u+p_4) \\ &\quad -p_5\ \sin(3u+p_6)+p_7\ \sin(4u+p_8)], \end{aligned} \tag{2}$$

to allow for a different time offset. The criterium of this procedure was to get the profile of the ADC to the TDC spectrum to be flat, such that there was no time dependence in the calorimeter response, as demonstrated in Fig. 10. Note that Fig. 10 displays the same data as shown in Fig. 8, except that now the corrections for the first (upper panel) and the second (lower panel) iterations have been applied.

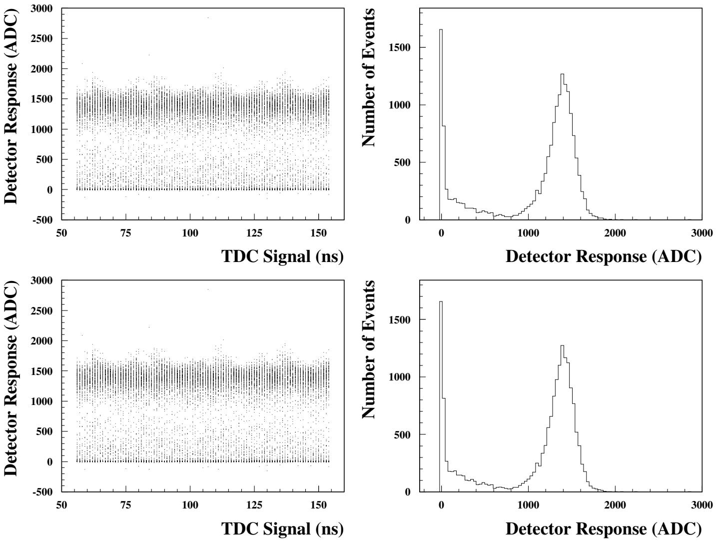

Figure 10. CERN 10 GeV data are shown after corrections of first iteration (upper panel) and second iteration (lower panel) have been applied.

3.2 Fitting Data to Gaussian

In a next step, the corrected data was plotted in a one-dimensional histogram then fit to a Gaussian curve, as shown in Fig. 11.

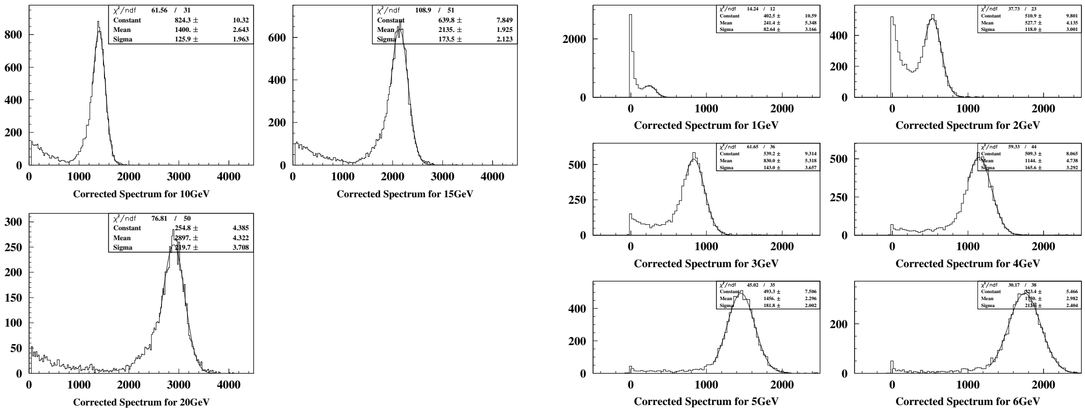

Figure 11. Corrected energy spectra for CERN (left panel) and DESY (right panel) data with gaussian fit results overlaid.

Even after these corrections, the fit ranges of the energy spectra had to be restricted to avoid contributions from hits located far away from the center of the calorimeter. A GEANT MC simulation of the actual beam particle composition at CERN revealed that the π^- background is limited to energies far below the electron peak position, as shown in Fig. 12. The one-dimensional spectra, now in a nearly Gaussian shape, were fitted to a Gaussian curve. Choosing the range proved to be not entirely trivial. If the lower bound was too low, the background would begin to affect the results, forcing the centroid to the left. If the lower bound was too high, the results would not cover enough of the peak region to be accurate. After finding the proper fit range, the detector linearity and resolution could be extracted.

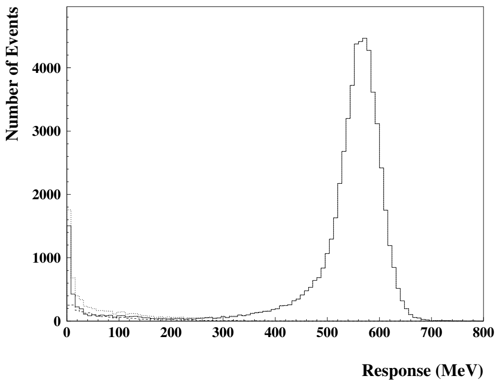

Figure 12. MC simulation of detector response of CERN test beam is shown, including a 7% pion contamination (dashed line). The response to electrons (solid line) and the combined response (dotted line) is also shown.

Remember that for the DESY test beam facility the set point for the energy selection magnet current does not define the actual energy of the beam (at least not better than to 1%). Therefore, the readout current had to be recorded for each energy setting, which allowed to determine the actual energy by a fraction of 1% [E(GeV) $=$ I(A)$\times$ 37.4 or B(Gauss)=I(A)$\times$ 40.099]. In addition, at currents above 200 A, the energy selection magnet would start to get into saturation, which is displayed in Fig. 13. A correction for this saturation effect had to be applied only for the 6 GeV data point. Table 1 shows the difference between the estimated and actual incident energies at DESY.

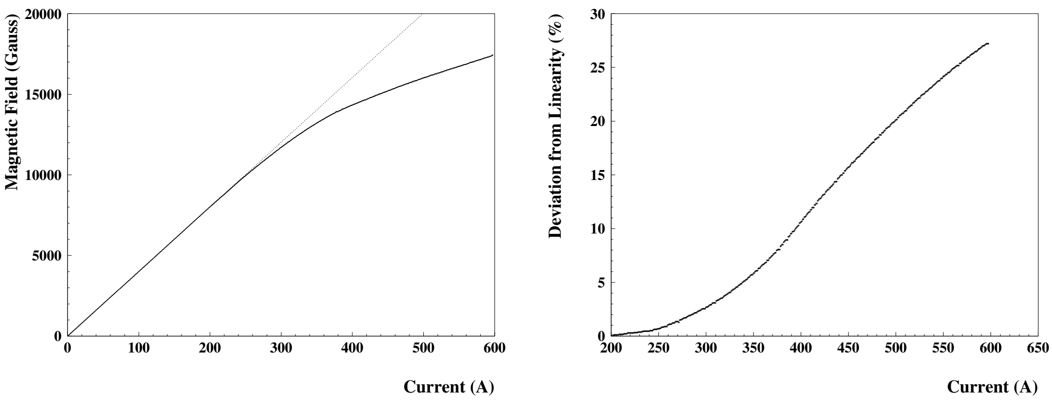

Figure 13. Left panel: Magnetic field versus current in separating magnet at DESY test beam. Right panel: Deviation of magnet field from linearity above 200 A.

Table 1. Comparison of Estimated and Actual energies at DESY.

Energy setting (GeV)	Current Reading (A)	Energy Reading (GeV)	Actual Energy (GeV)
1.0	37.0010	0.989332	0.989332
2.0	75.0910	2.00778	2.00778
3.0	112.551	3.00939	3.00939
4.0	149.001	3.98398	3.98398
5.0	188.549	5.04142	5.04142
6.0	222.567	5.95099	5.93909

3.3 Combining DESY and CERN Results

To explore the entire ADC range of 4096 channels, the PMT voltage at DESY was set at 1450 V, while at CERN it was set to 1250 V, because we planned to include beam energies up to 30 GeV. These PMT voltages were chosen from a HV scan that was performed using the 3 GeV beam at DESY. The results of the HV scan are summarized in Fig. 14. The different HV settings at DESY and CERN explain the offset in the linearity curves plotted in Fig. 15 (left panel).

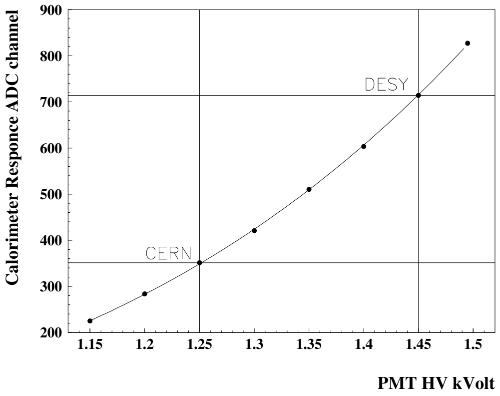

Figure 14. HV scan to determine the ratio of signal responses at DESY and CERN.

In order to extract the overall energy linearity of the calorimeter, the two data sets had to be combined into a single set. The signal strength of the DESY data set was however not multiplied by the ratio of the signals at 1250 V (349.1) and 1450 V (745.9), which resulted into a factor 0.468. Instead, it was multiplied by the ratio of the slopes (148.2/309.8=0.478) shown in Fig. 15 (left panel) which was slightly larger and automatically cancels any small HV offsets in different HV supplies. The effect of this correction is shown in Fig. 15 (right panel). As can be observed in Fig. 15 (right panel), there was still a small offset between the two data sets. This offset is most likely because the beam could not be centered exactly on the calorimeter at CERN.

Since the detector response depends on the location of beam incidence with respect to the center location (uniformity is not exactly constant), this little offset was observed.

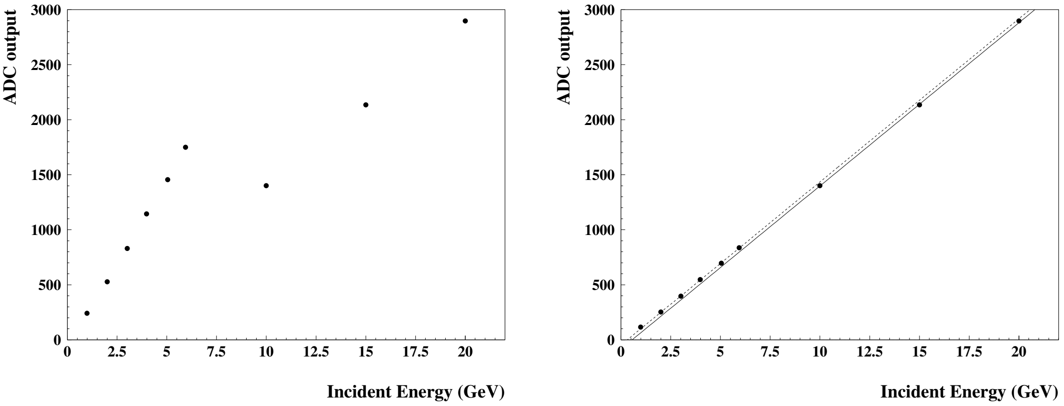

Figure 15. Linearity of DESY and CERN data sets. Left panel shows the data sets without rescaling, while the right panel includes the rescaling factor due to the different HV settings at DESY and CERN.

4 Results - Compared with GEANT MC

4.1 Linearity

After all corrections and rescaling factors had been applied, the calorimeter linearity was extracted. In Fig. 16 (left panel) the deviation from linearity is shown to be within 1%. It is compared to a Geant Monte Carlo simulation (Fig. 16 right panel) which took the actual beam profiles (see Figs. 2 and 4), and in the case for CERN also the pion contamination, into account. This confirmed that the calorimeter response behaved linearly over the entire measured energy range.

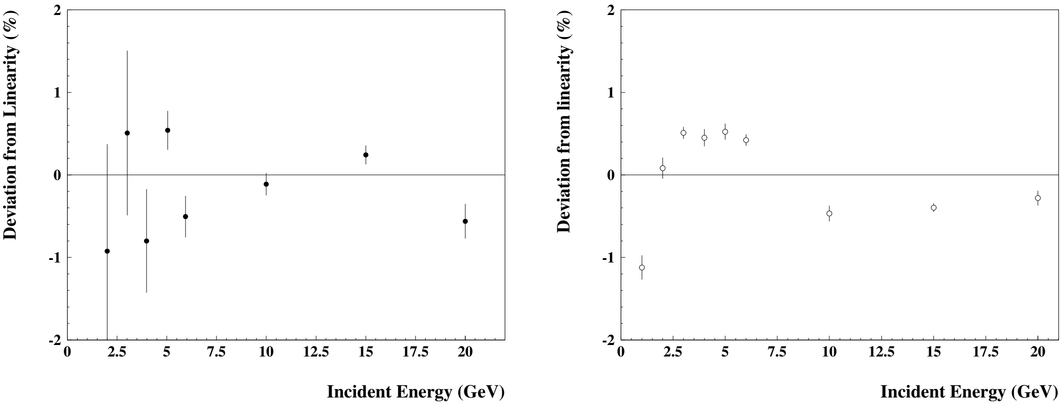

Figure 16. Deviation from linearity using data from both DESY and CERN (left panel) and Geant MC simulation of detector and test beam conditions (right panel). The filled symbols represent the data, while the open symbols represent the simulations.

Note that there is a systematic difference for the DESY and CERN Monte Carlo simulations. This is due to the different test beam profiles that have been used in the simulations. This difference is not present if a single beam profile is employed over the entire energy range. In addition, the largest deviation from linearity occurs at low energies (1 GeV), caused by the absorption of part of the signal in the first tungsten layer of the detector, which protects the detector against synchrotron radiation in the HERA tunnel. The statistics of the DESY test beam data is not high enough to make both effects discussed above visible in the data.

4.2 Resolution

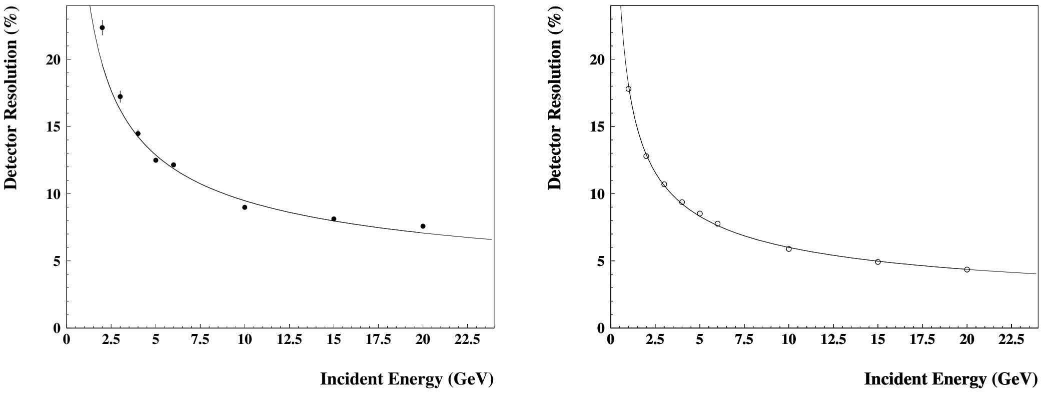

Figure 17. Detector energy resolution for DESY and CERN data (left panel), compared to Geant MC simulations (right panel).

The energy resolution for sampling calorimeters is directly proportional to the inverse of the square root of the energy [3], and is given by

$$\frac{\sigma}{E} = \frac{\alpha}{\sqrt{E}(\mathrm{GeV})} + \beta. \tag{3}$$

The results, which are shown in Fig. 17, are also listed in Table 2, where they are compared to a Monte Carlo simulation of the Sampling Calorimeter taking into account the actual beam parameters at the DESY and CERN test beam facilities for this set of measurements, and a previous Monte Carlo simulations [2] which simulated the beam as a point beam.

Table 2. Comparison of test beam and Monte Carlo resolutions. The parameters α and β are defined in Eq. 3.

	Measured	This Simulation	Previous Simulation
α	$25.9\% \pm 0.54\%$	$17.7\% \pm 0.097\%$	$15.6\% \pm 0.14\%$
β	$1.28\% \pm 0.18\%$	$0.42\% \pm 0.042\%$	$0.14\% \pm 0.07\%$

The resolution was much poorer than we expected, and seems to be due to several sources: the time jitter between the triggers, as discussed above, and the corrections applied which could be diluted by background events and are therefore not be the most suitable corrections. Also, during calibration of the calorimeter, it was not possible to fix the beam position on the front face of the calorimeter. Because the response of the calorimeter is not entirely uniform over the detector face, the recorded signal is expected to be broader compared to the situation, where the beam hits the detector center only.

4.3 Uniformity

A number of uniformity scans were performed at the CERN test beam facility, however only a small fraction was taken under conditions that seemed good enough to extract a meaningful result. Unfortunately, there was no position sensitive detector available for the LPol and the trigger setup was far from optimal as discussed above. This did not allow to control the beam spot on the detector surface. The one scan that was chosen to be analyzed was taken at 15 GeV in the vertical (y) direction from -10 to $+10$ mm. The detector response appeared unchanged for a range of ±5 mm, if the large trigger was employed, as shown in the left panel of Fig. 18 (filled circles). If, however, the finger counter was included in the trigger setup (filled triangles), the response would drop to 95% from the value in the center position over the same range. This variation in detector response, termed uniformity, is not supported by the MC simulation as shown is Fig. 18 (right panel), and we could only speculate why there is this discrepancy. The most obvious guess would be that the experimental conditions were not sufficiently controlled to allow a precise comparison to a MC simulation.

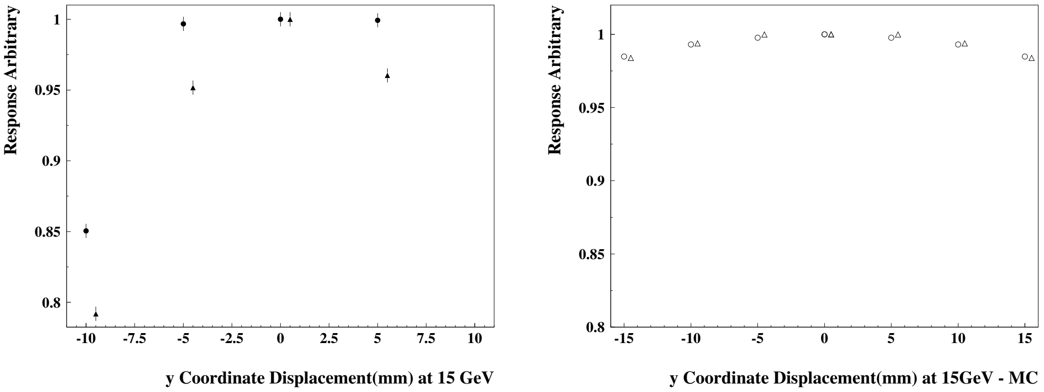

Figure 18. Detector uniformity versus detector offset for CERN data (left panel), compared to GEANT MC simulations (right panel). The circles (triangles) represent the setup with the large trigger (finger counter, shifted by 1mm for better viewing).

Fig. 18 shows the resolution of the Sampling Calorimeter as a function of the beam offset from the center of the detector. The left panel displays the data, for both trigger options, and the right panel displays the MC simulations. One can see a similar trend in the data and the simulations for the two trigger options, but again, the magnitudes are quite different. At ±5 mm, the data show a three times worse resolution then the simulations. Again, we do not know the exact reasons for this discrepancy, but we are not too concerned about it, since we believe the experimental conditions were not sufficiently controlled.

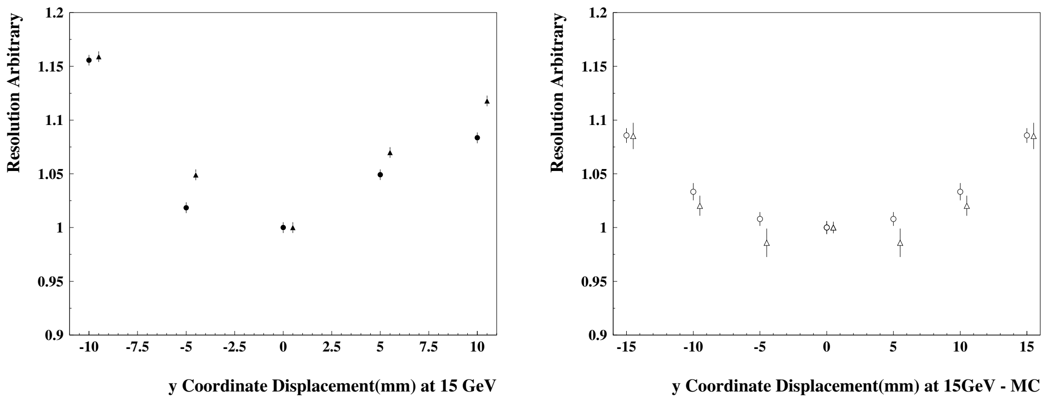

Figure 19. Detector resolution versus detector offset for CERN data (left panel), compared to GEANT MC simulations (right panel). The circles (triangles) represent the setup with the large trigger (finger counter, shifted by 1mm for better viewing).

5 Conclusions

It has been shown, that the Sampling Calorimeter, previously only studied in the DESY test beam, displays an energy linearity which is better than a fraction of a percent over an energy range of 1 to 20 GeV. The new Flash ADC system, designed for the specific properties of the HERA electron machine, is not adequate to use in test beam facilities, if one attempts to measure energy resolution in addition to energy linearity. Monte Carlo simulations, which take into account the specific beam parameters in the DESY and CERN test beam facilities, agree very well with the energy linearity, but cannot be used to study the energy resolutions, unless (this is speculation) one attempts to simultaneously also simulate the Flash ADC characteristics.

6 Acknowledgment

We thank S. Schmitt for helping to make this calibration possible in hardware and in software areas and for many fruitful discussions.

References

[1] M. Beckmann et al., Nucl. Instr. Methods A479 (2002) 334-348. "The Longitudinal Polarimeter at HERA"

[2] A. Raj and W. Lorenzon, Internal Polarimeter Report IPR-00-01. "GEANT Monte Carlo Simulations for a Sampling Calorimeter"

[3] C. Scarlett and W. Lorenzon, Internal Polarimeter Report IPR-00-02. "A New Sampling Calorimeter for the Longitudinal Polarimeter at HERMES"

[4] Collins-Tooth et al., ZEUS 01-019 C. "The Transverse Polarimeter (TPOL) Test Beam at DESY in January-February 2001".