Calibration of the Positron Polarimeter for the E-166 Experiment

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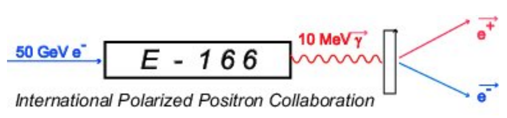
A detector for polarized positrons was built from CsI crystals, in DESY-Zeuthen, as part of the DESY-SLAC E-166 experiment. The detector was tested successfully in a TestBeam of electrons at DESY-Hamburg and was found to be fully operated with linearity response to energy and high Energy Resolution as needed for the full experiment with the positrons beam.

1 Introduction

1.1 Physic Motivation

The presence of two polarized beams in a future high-energy e^+e^- collider offers several advantages among them, an increase of the signal over background, an enhancement of effective luminosity and a higher sensitivity for the detection of a non-standard model coupling. In fact the benefits from polarized positron beam has been pointed out already in the past [1] even though it was believed to be technically hard to realize. It is generally agreed that future linear colliders (like JLC, NLC or TESLA) will required the development of polarized positron beam.

In spite of the obvious difficulty to produce polarized positron beams in linear collider, recently more attention has been given to this subject and different techniques were suggested. One of the possibility proposed is to use a Helical Undulator to produce circularly polarized photons which are then converted in a relatively thin target to generate longitudinally polarized positrons.



1.2 The E-166 Project and its Goal

The E-166 project is designed to test Undulator-based production of polarized positrons for future high energy linear collider [2]. In this experiment an electron beam of 50 GeV will pass through a 1-meter long Helical Undulator to produce a beam of circularly-polarized photons of a few MeV energy. The electron beam is then dumped so that one is left with the polarized photons. Subsequently the photons are converted to positrons (and electrons) by pair production process. The polarization of the positrons and the photons is measured in polarimeters based on Compton scattering of electrons in magnetized iron.

The E-166 layout is present in Figure 2.

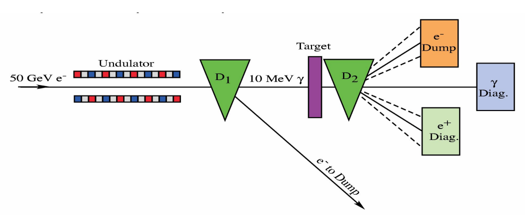


Fig. 1: *50-GeV electrons enter from the left pass through and undulator to produce a beam of circularly polarized photons of MeV energy. The electrons are deflected away from the photons by D1 magnet. The photons are converted to electrons and positrons in the thin target (D2). The polarization of the positrons, and of the photons, are measured in polarimeters based on Compton scattering of electrons in magnetized iron.*

The running of the E-166 experiment is going to take place at the Stanford Linear Accelerator (SLAC) laboratory in October 2004. The assigned DESY laboratory part in this project is the design and the construction of the the positrons' polarimeter. I personally have joined the DESY-Zeuthen group which is engaged in the positron polarimeter part of the E-166 project. To this end I went with them to the TestBeam in DESY-Hamburg where the polarimeter detector part was tested. For this reason this report will focus on the TestBeam calibration of the detector which took place in Hamburg at the end of July 2004 and on its results and their analyses, that I took part in.

2 Physics in the experiment

The aim of the experiment (the layout) is to produce Polarized Positrons via the conversion of circularly polarized photons in a thin target which should subsequently be measured.

2.1 The Helical Undulator

The process is started with a 50 GeV electron beam which passes through a 1-meter long Helical Undulator, through which a circularly polarized photons beam is created parallel to the electron beam. After passing the Undulator the electron beam is deflected away from the photons beam.

2.2 Positrons Production

Here one utilizes the fact that when a polarized photon creates an electron-positron pair in a thin target, the polarization state of the photon is transferred to the outgoing leptons according to the expression derived by Olsen and Maximon in 1959 [3]. The circularly-polarized photons going out of the Undulator hit a thin target and produce pairs of longitudinal polarized positrons as electrons. After the thin target there are photons that pass the target without interacting in addition to the positrons and electrons all of whom are polarized. Finally the electrons are dumped by a magnet filed so that one is left with photons and positrons that one wants to measure their polarization.

2.3 Polarized Photons

Measuring polarization of photons in many cases is based on the spin dependence of Compton scattering [4, 5]. In one method one observes the scattered electrons and/or photons which emerges from a thin, magnetized iron target [6]. A second method is based on the measurement of the transmission of the un-scattered photons through a thick, magnetized iron absorber [7, 8, 9] which due to its simplicity has been chosen to be used in the E-166 experiment (and is been shown in Figure 3).

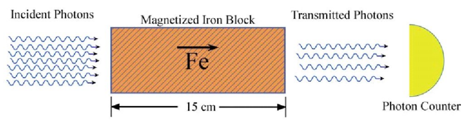


Fig. 2: *The photons polarimeter sketch.*

2.4 Polarized Positrons

The polarization measurement of the positrons is achieved by converting them back to photons and applying the photon transmission method described above. The polarization level will then be extracted out of the photon transmission asymmetry observed when the magnetic field orientation is reversed so that it is once parallel and once anti-parallel to the positron beam (for more details see section 3.3).

3 Physics in the detector

3.1 Overview

The polarimeter (polarization detector) is made out of 9 CsI crystals. Each crystal has a profile of 6 cm x 6 cm and a length of 28 cm. All 9 crystals are grouped in a way that when looking at the profile of the detector one can see an array of 3x3 (this is what the incoming beam should 'see').
The detector will be sited in a way that its long length is in parallel to the incoming beam direction.

3.2 The CsI crystals

Transmitting a high-energetic beam (for example: electron or photons) through the CsI crystals results in a scintillation. In our case high-energetic photons are passing through the

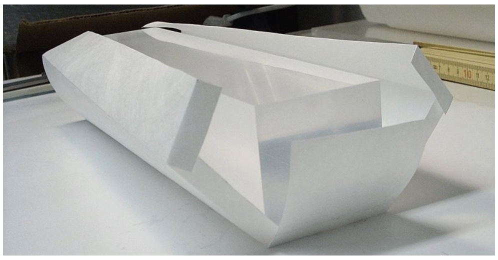


Fig. 3: *Wrapping a crystal.*

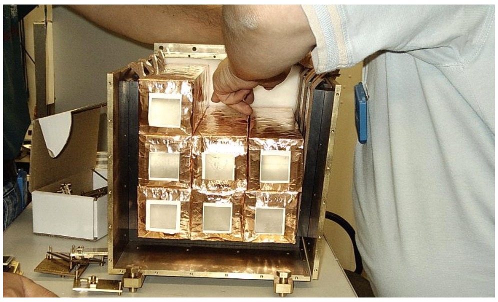


Fig. 4: *Wrapped crystals are been placed together, the place left for the Photo-Diode can be clearly identify.*

crystals and interact electromagneticly with the matter and transfer part or all of their energy to electrons or positrons (via pair production). Now these electrons and positrons interact again electromagneticly and transfer part or all their energy to photons thus creating what is known as a cascading process. At the end of this cascading process one observes visible photons that can be collected and detected. For example, if a 1-GeV photon enters a CsI crystal it will be 'broken' into a thousand of 1-MeV photons that can be detected.

3.3 Polarization detection

The transmission probability $T^{\pm}(L)$ for photons with helicity P_γ through a magnetized iron whose length is L, is given by

$$T^{\pm}(L) = e^{-nL\sigma_0} e^{\pm nLP_eP_\gamma\sigma_p} \qquad (1)$$

where n is the density of the atoms in the iron, $T^{\pm}$ applies to electron spin parallel or anti-parallel to the direction of the incident photons and (σ_p[1]) σ_0[2] is the (un)polarized cross section.

The asymmetry (δ) in transmission of photons through the iron absorber when the sign of P_e is the magnetization of the iron can be written as

$$\delta(L) = \frac{T^{+}(L) - T^{-}(L)}{T^{+}(L) + T^{-}(L)} \approx nLP_eP_\gamma\sigma_p \qquad (2)$$

By measuring the transmission asymmetry (δ) with the knowledge of the P_e of the magnetized iron, its length (L) and the polarized cross section(σ_p) the polarization of the photons can be calculated as:

$$P_\gamma = \frac{\delta}{nLP_e\sigma_p} \qquad (3)$$

Here it should be noted that all this procedure is already described in the E-166 original proposal [2].

3.4 Interim summary

We have polarized photons that inherited their polarization from the positrons (that hit the reconversion target). Therefore, we can know the positrons' polarization by collecting and detecting the photons polarization.

4 DESY-Hamburg TestBeam

4.1 Detector layout

Each of the 9 crystals used is wrapped to enhance the effectiveness of the scintillated photons collection. At the rear side of each of the wrapped crystals, a Photo-Diode was placed to collect the cascaded and 'bounced back' photons (see Figures 3,4).

To enable one to read the signal coming out from the detector, there is the need to transfer the signal from the detector to the counting house. This is achieved by using a transmitting amplifier (Figs. 5 and 6) that sends the signals to far distances and a receiving amplifier that decodes the signals and feed them to the collecting devices (ADC's) situated in the counting house. Both of these were designed and built in DESY-Zeuthen. The preliminary test of these devices working together was carried out in DESY-Zeuthen. However a full scale

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[1] $\sigma_p = \frac{2\pi r^2{}_0}{k_0}[\frac{1+4k_0+5k_0^2}{(1+2k_0)^2} - \frac{1+k_0}{2k_0} ln(1+2k_0)];$
$r_0 = e^2/mc^2; k_0 = E_\gamma/mc^2$

[2] $\sigma_0 = \frac{2\pi r_0^2}{k_0}[(1 - \frac{2}{k_0} - \frac{2}{k_0^2}) ln(1+2k_0) + \frac{1}{2} + \frac{4}{k}{}_0 - \frac{1}{2(1+2k_0)^2}]$

test of the whole combined systems working together was still required.

4.2 TestBeam Goals

The DESY-Hamburg TestBeam facility offers a 1 to 6 GeV electron beam with an additional background disturbance that is an unavoidable part of any running accelerator environment.

The use of this TestBeam in Hamburg for our experiment allows to carry out a full scale testing of all the devices working together in an environment as close as possible to the one where the detector, as part of the E-166 experiment, will be operated in SLAC. In particular the goals of this TestBeam running in our case was to find out how does the detector works when all its components are fully connected (that means 72 transmitting cables for example shown in Figs. 18, 19 and 20). Other goals of the TestBeam run was to uncover problems and give the opportunity to study and learn e.g. much more on the detectors behavior in high energies, to find its weak spots and other properties. In addition, another important aspect of the TestBeam was to understand how one should calibrate the full detector for the positron beam run.

4.3 List of actions

The TestBeam run in Hamburg lasted for two weeks and included:

- Shooting the beam into each crystal to see its response (if at all).
- Horizontal, Vertical and Diagonal scan of the detector focusing especially on the response when shooting occurred between two crystals.
- Another important test was the Energy scan, to this end we shot the middle crystal with electron beams of 1,2,3,4,5 and 6 GeV energies. From this scan we derived later the Energy resolution of our detector which is one of the most important parameters.
- In addition to a beam source we radiated the detector to a ^{60}Co radioactive source and collected its spectrum lines for future analyses. These data play a crucial role in the final calibration.

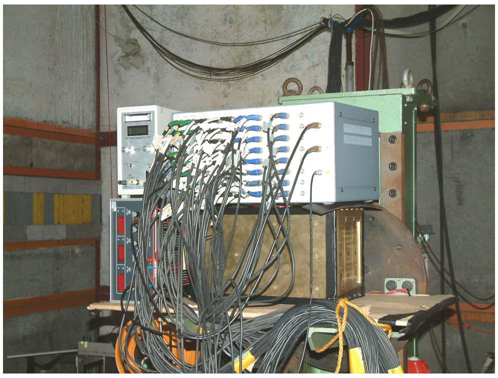

Fig. 5: *The transmitting amplifier upon the positron detector (the beam is coming from the right).*

Fig. 6: *The cables connecting between the detector and the transmitting amplifier.*

4.4 Lost and Found

The TestBeam yielded a lot of findings. Here I will list only the important ones:

- Detector:
  1. One of the crystal had a swapped output cable.
  2. Two Photo-Diodes were found not to be attached to their crystals !!
- Transmitting Amplifier:
  1. One of it's inner boards was not working properly.
  2. Grounding of the outgoing cables was found to be wrongly placed since there was a cross talking between different cables and other parts of the amplifier).
- Receiving Amplifier:
  1. Two burned chips were found.

2. One shortcut cable was found.
3. One of the on-boad circuits was found to be not operating.

4.5 Interim summery

A lot was learned about the detector in the Hamburg TestBeam, problems were discovered and fixed and the behavior of the detector was understood better, including how to calibrate it for the future positron beam run in SLAC.

5 Analyses

5.1 Method of the analyzes

5.1.1 General overview

To start with it is important to mention that output signals from every Photo-Diode comes in two kinds of scales - 'High gain' and 'Low gain'. The difference between these scales is the intensity of the out going signal.
This has been designed in order to have a wide spectrum. For example, when using a ^{60}Co source the output signals are weak and therefore it would be better to use the more enhanced output signal (the 'High gain') to try and interpret the signal. However, when a 2 or 3 GeV beam is applied, the enhanced signal channel (the 'High gain') will saturate, in this case the 'Low gain' channel is a better choice to try and interpreted the beam output.

5.1.2 Definitions

Run - is a recorded data collection (data was saved to disc).
ADC - Analog to Digital Channel is the device that interpret the incoming signal into an integer number (=ADC scale).
Pedestal run - collecting data from the detector when no source is applied. These runs will serve us as baselines (these data will be subtracted out of any run leaving out the true signal).
Each crystal will have two ADC channels (for 'High' and 'Low' gain).

5.1.3 The Method

At start the pedestal values are collected, after that the 'High gain' ADC scale is converted to Energy scale from the fact that the Energy spectrum lines of the ^{60}Co source are known.
Next will be to export this Energy scale from the 'High gain' scale to the 'Low gain' scale, taking into consider several factors like trigger delay and different dumping.

5.2 Step by step

First Step
Find our Pedestal values for each channel in any Pedestal run that was collected.
This should be done by fitting each channel histogram with a Gaussian, assuming that a Pedestal run is a collection of noise that should have normal distribution. The mean value of this fit is the desirable pedestal value.

Second Step
Convert the High gain ADC scale to an Energy scale. This can be done from the fact that ^{60}Co has two spectrum line, one at 1.17 Mev and the other at 1.3 MeV.
For each crystal we have a run that shows the ^{60}Co lines. This run shows for each channel a sum of three things: system noise and both Gaussian peaks. Fitting these data should take into consider all three components. Our fit gives us a mean value that correlates with the 1.17 MeV peak, as can be seen in Figures 7 and 8.

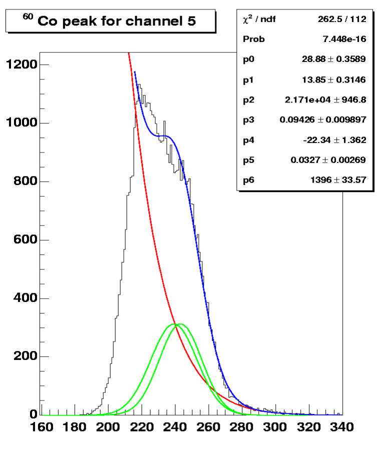

Fig. 7: *Cobalt lines fit - Some time it is hard to separate the signal from the noise, as can be seen here. The four lines are presenting the two Gaussian peaks (in green), the noise (in red) and the sum of all (in blue).*

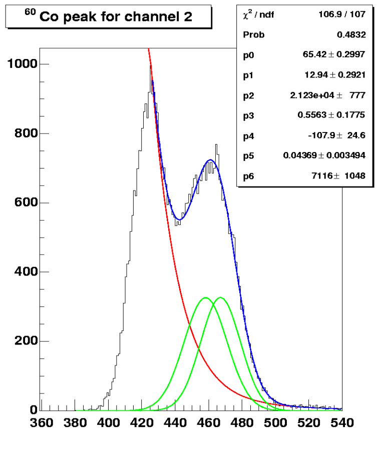

Fig. 8: *Cobalt lines fit - Here the Cobalt lines peak can be seen clearly from the data.*

With this value one can find for each channel a fixing factor that will allow him to read 'High gain' histograms in Energy scale instead of ADC scale.

Third Step
After having an Energy scale, for the 'High gain' channels, we can try and look at beam runs in Energy scale but before doing so we should export the energy scale from the 'High gain' scale to the 'Low gain' scale. Exporting 'High' to 'Low' gain can be done by looking at 'High gain' vs. 'Low gain' data and finding a linear region. Then applying a linear fit to this region (a snapshot of this search in provided in Figure 9).

The extracted linear multiplying factor is the correction factor between 'High' and 'Low' gain.

Fourth Step:
The linear correction is not the only factor, there are two more factor that needs to take into consider:

1. Different trigger delay -
   On one hand the ^{60}Co data is being collected after self triggering, on the other hand the Beam data is collected after an external triggering system. These two methods give different current collection for the same signal (exampled in Figure 10), therefore this should be corrected.

2. Different dumping factors -
   'High' and 'Low' gain are different in there electric circuit setup, this fact should be

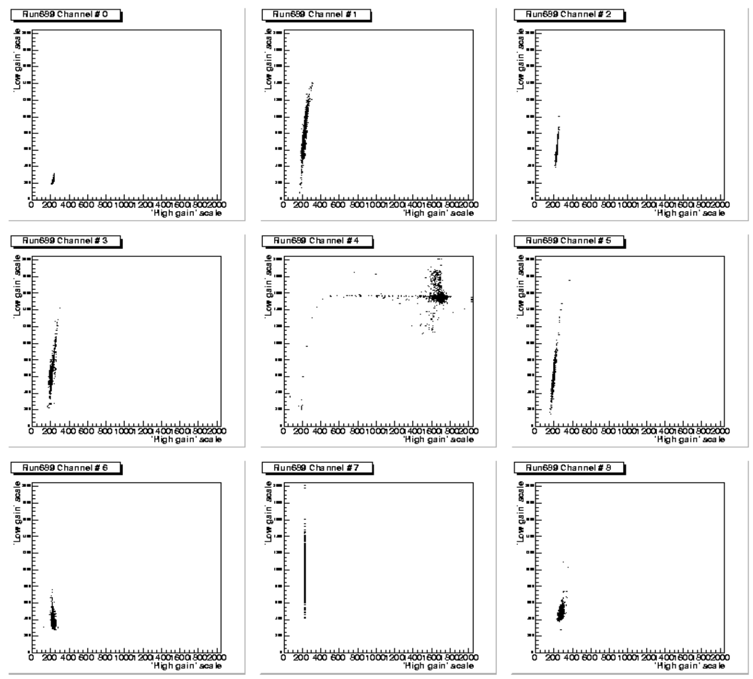

Fig. 9: *Looking for linearity between 'High gain' and 'Low gain'. channels 1,2,3 and 5 have a linear region when channel 4 is seen saturated.*

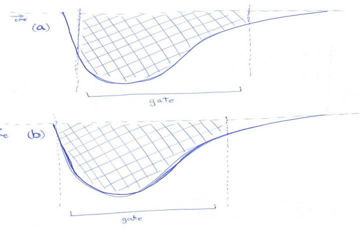

Fig. 10: *a - Self triggering. b - External triggering. The current collection for the same gate time but different trigger delay, is present by the marked areas.*

taken into consider too, in the final correction factor.

After applying all these factors we get the right correction factor between 'High' and 'Low' gain.
Now both ADC scales ('High' as 'Low') can be read as Energy scales (for example see Figure 11).

Last Step:
Gathering all information from individual crystals to a full detector picture.
Looking into the data one can see that the fitting function should be a combination of a rising exponent and a Gaussian (an Expo-Gaussian

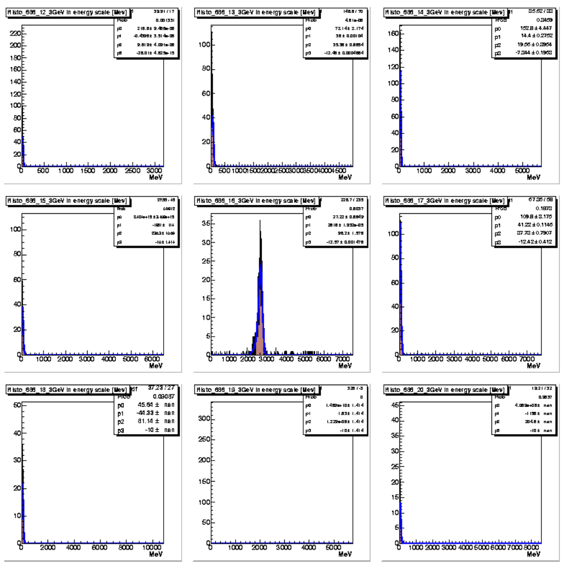

Fig. 11: *Looking at a 3 GeV bean hitting the middle crystal (all crystals read out is present in Energy scale).*

shape) as can be seen the Figure 12.

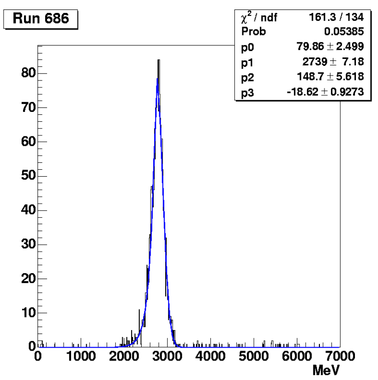

Fig. 12: *The Expo-Gaussian shape of data and its fitting.*

The energy deposit of the detector, by this analyzes, is the mean value of the fit.

5.3 Final results

Two interesting plots can be drawn from this analyzes.
First is the Energy Deposit of the full detector plots with respect to the beam energy that was applied to the detector. This plot will tell us what is the efficiency of our detector.

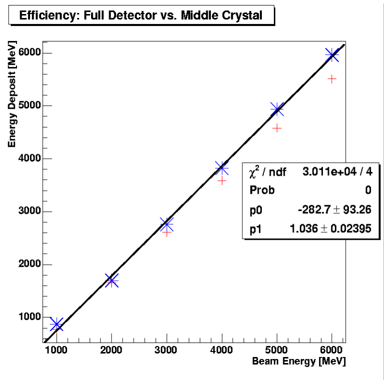

Fig. 13: *Pluses present the middle crystal data. Starts presents the full detector. The fit is applied for the full detector.*

fitting the full detector data show a very good linearly, as can be seen in Figure 13. These results show that our detector has a strong linearity dependence in energy.
Second interesting plot will be the sigma over mean value of the Energy Deposit with respect to the beam energy. This is the Energy resolution of our detector (Figure 14).

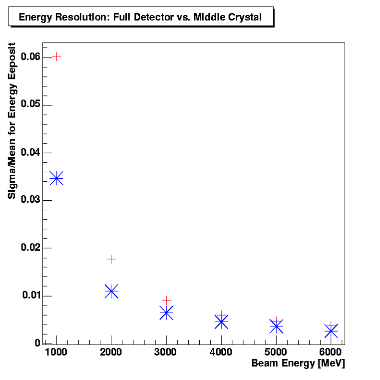

Fig. 14: *Pluses present the middle crystal data. Starts presents the full detector.*

This last data can be fitted by the following function:

$$\sqrt{((\frac{a}{\sqrt{(E)}})^2 + (\frac{b}{E})^2 + c^2)} \tag{4}$$

This function correlation is known - first term corresponds to the statistic of our data, the second term corresponds to the noise in our data and the third corresponds to the baseline value. Applying this fit to our data is seen in Figure 15.

As can be seen from the fit our detector had

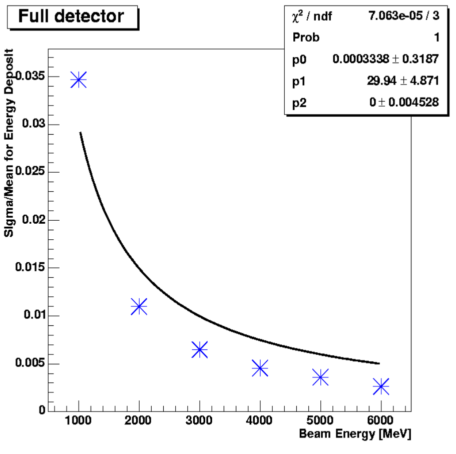

Fig. 15: *Energy resolution of full detector - preliminary results.*

a very good energy resolution at the TestBeam in Hamburg. Moreover, this fit tells us that the most disturbing component at the TestBeam was noise.

5.4 Simulation Vs. TestBeam Results

All this can be compared with a simulation that was made by Karim Laihem in GEANT 4. Both Energy deposit and Energy resolution for the full detector are show here in Figures 16 and 17, comparing the TestBeam results with the GEANT 4 results.

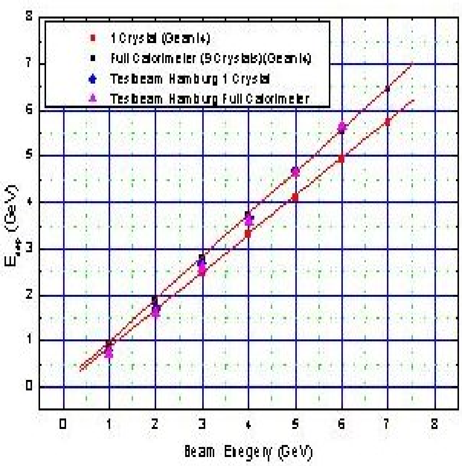

Fig. 16: *Energy deposit of the TestBeam in Hamburg compare with the GEANT 4 simulation results.*

The comparison of the TestBeam result be-

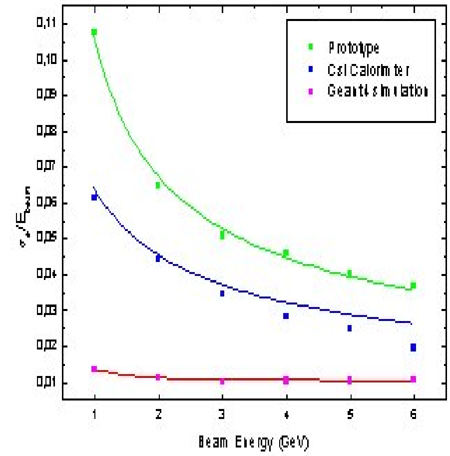

Fig. 17: *Energy resolution of the detector compared between the CsI prototype (in green), Hamburg Test-Beam at July 2004 (in blue) and GEANT 4 simulation (in purple).*

havior with the simulation behavior shows a good agreement between the two.

6 Conclusion

DESY part in the E-166 experiment, the positrons' polarimeter, is ready and have been tested to show very good results.
The TestBeam in Hamburg was proven to be very important. The detector behavior was studied and better understood (as preparation for the full experiment).
Another important thing that the TestBeam yielded is the analyzes method to calibrate the full detector, this method will help in the full experiment with the positron beam.
The analyzes results showed that we have a fully working Polarimeter (from the Photo-Diode to the Receiving Amplifier) with a very good energy resolution and strong linearity dependence. This last point influence directly our sensitivity to the different polarization states. This difference will give us the ability to calculate the beam polarization that is the main goal of the E-166 experiment.

Acknowledgments

I want to start and thanking Achim Stahl for letting me be part of a great working team, for answering every little question and sharing with

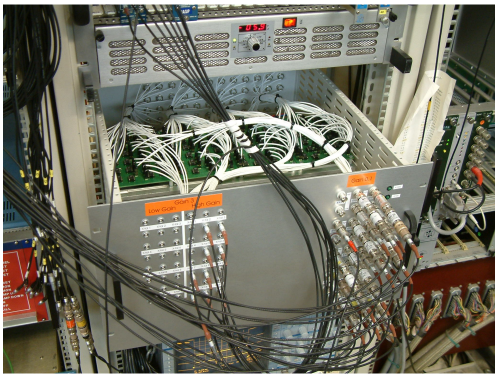

Fig. 18: *Receiving Amplifier in the counting house.*

Fig. 19: *Receiving Amplifier - Rearview.*

me his experience. also I want thank Karim Laihem and Roman Poeschl for the long days as night that we spend together including the cigarette breaks discussions.
More then that, I would like to thank Gideon Alexsander for encouraging me to participate in the Summer-Student Program and for all the suggestions, comments and talks we had together, they are always a learning experience.
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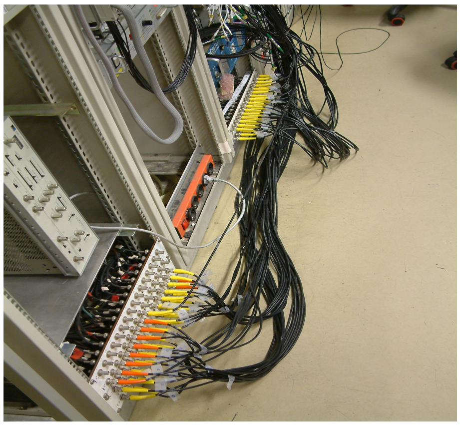

Fig. 20: *Cables in the counting house.*

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