Energy calibration of the DESY test beam in beamline 21

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Abstract

The energy calibration of the DESY test beam area 21, my project as a summer student at DESY, is presented. This was, though the measurement has been taken in collaboration with other summer students, a standalone project containing the experiment, a simulation and an analysis.
The deflection angle of the particle beam, deflected by a dipole magnet with known magnetic field, was measured using the DATURA Beam Telescope and reconstructed by the software EUTelescope. In order to get information on the particles momenta, this was compared to a simulation of the track of the particle inside the magnetic field.
The results showed a deviation from a theoretical prediction by about 17%, which lead to the discovery of a miscalibration of a power supply control and therefore wrong predictions for the beam energy. After a recalibration, the prediction and the analysis of the measurement show a good compliance.
The impact of the miscalibration on recent experiments performed in DESY test beam area 21 has to be reviewed after the summer student program.

Contents

1 Introduction

1.1 DESY test beam facility

The DESY test beam facility provides three electron/positron beams with energies from 1 to 6 GeV, used for the development and testing procedures of particle detector prototypes and readout systems.

For the generation of these beams a carbon fibre is moved into the beam of the DESY II storage ring, containing electrons or positrons at 6.3 GeV. This leads to bremsstrahlung which is converted to electron positron pairs inside a target (see Figure 1 and Appendix A.10). The electrons and positrons created are then deflected by a dipole magnet, which separates the particles due to their different momenta. The particles exiting the magnet with a certain outgoing angle are extracted into the test beam area. The current of the magnet and therefore the energy of the particles extracted to the test beam area can be set by the beamline user via a control panel on a PC.

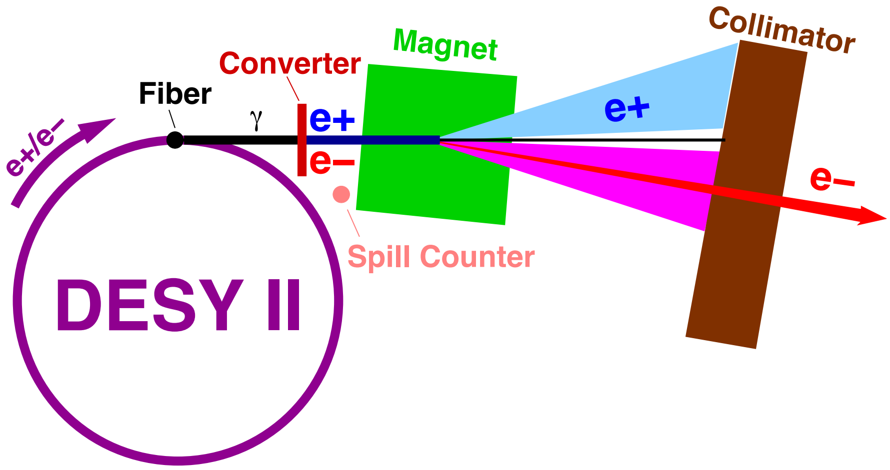


Figure 1: Creation of particle beams at the DESY test beam facility. Electrons or positrons hitting a carbon fiber generate bremsstrahlung, which is then converted to secondary electron positron pairs. These pairs are lead through a dipole magnet, which together with the collimator works as a spectrometer, picking particles of a certain momentum range depending on the operating current. [1]

1.2 Telescope

In all three test beam areas a telescope is provided, each slightly different. In test beam area 21 the DATURA test beam telescope is located, consisting of six MIMOSA26 silicon pixel sensors [2] as shown in Figure 2. The area of each sensor is 2 cm^2, containing 576×1152 pixels with a pitch of 18.4 µm. The sensors are arranged to two arms, upstream and downstream, consisting of three sensors each. Four scintillators, two located in front of the first sensor plane and two behind the last one, are used for a fourfold coincidence trigger. From the readout of the pixel sensors the particle tracks can be reconstructed with very high precision. This allows one to investigate a particle detector prototype, called DUT (Device Under Test), which can be placed between the two arms of the telescope.

For this project the telescope planes have been arranged with a plane distance of about 19 mm. This was necessary in order to get tracks with hits in every plane even for deflected beams. The experimental setup can be seen in Figure 5.

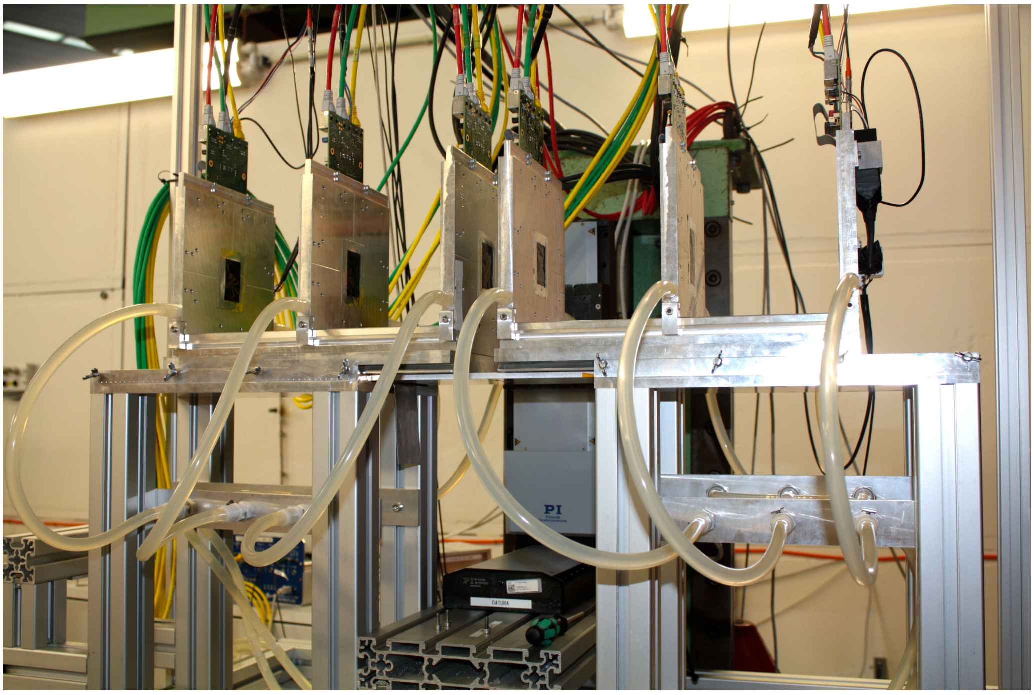


Figure 2: The DATURA beam telescope. The MIMOSA26 pixel sensors and their readout systems are mounted on aluminum planes. The arms of the telescope can be moved apart in order to place a DUT (Device Under Test), such as a pixel detector prototype, in the middle of the telescope. In front of the first plane (right) and behind the last plane (hidden in this perspective) two crossed scintillators each are located, which are used for a fourfold coincidence trigger. Beam incident from the right. The assembly had to be changed for the experiment in this project in order to get tracks with hits in every sensor plane. Figure 5 shows the acutal experimental setup. [3]

1.3 Data acquisition

In order to control and read out the telescopes a data acquisition (DAQ) system and software has been developed for the high precision telescope EUDET and can be used for other types of telescopes [4]. The equivalent DAQ system for test beam area 21 can be seen in Figure 3 and is shortly described in the following.
Before the telescope can take data, the readout chip registers have to be programmed. This can be done by using a JTAG software and it is distributed to the single chips by the **JTAG Board**. The electrical power for the chips is provided by a **power supply**. The **Trigger Logic Unit** provides power to the photomultipliers, processes their signals and gives the trigger signal in order to start a readout of the telescope. The event is read out by the **National Instruments PC** (NI PC) and stored to a **RAID-Array**. The software controlling all these components can either run on the NI PC itself or on a seperate **RunControl PC** in order to reduce the workload of the NI PC. A **LAN Router** connects the two DAQ PCs to the control room, so

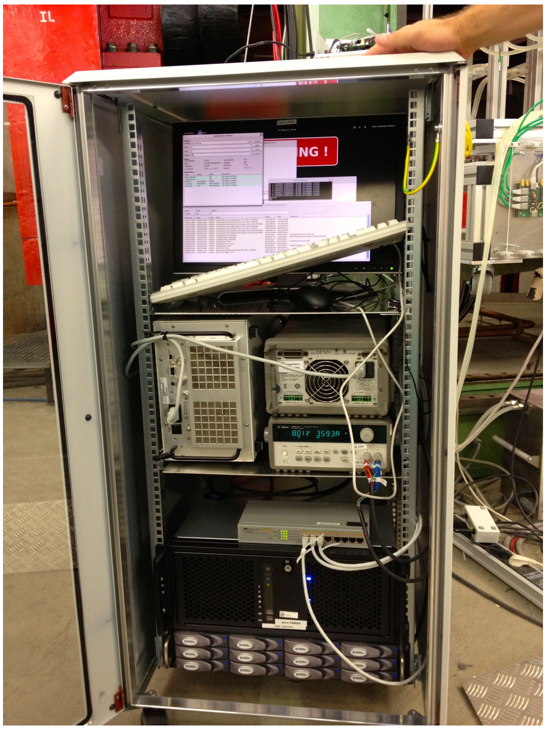


Figure 3: Data acquisition system for the DATURA beam telescope, consisting of (from the bottom) a RAID storage, the RunControl PC, a LAN router, two power supplies and a National Instruments PC, mounted into a 19" rack. The Trigger Logic Unit and the JTAG and Clock distribution boards are hidden on this image.

the whole measurement can be controlled from outside the test beam area.

The software used for data acquisition is EUDAQ [5], which is developed and maintained at DESY. EUDAQ consists of independent modules, each controlling a dedicated hardware part or task. EUDAQ e. g. configures the TLU and the data collector module, stores the data and allows to monitor the data while measuring.

1.4 EUTelescope

The data collected by EUDAQ contains the binary signals of responding pixels for every event. This data has to be processed to reconstruct the actual particle tracks through the telescope. This can be done by the software EUTelescope [6], which is maintained at DESY. Due to the diversity of applications of measurements using pixel beam telescopes, the software was built in a modular design. This means that every single analysis step is executed by a specific processor as indicated in Figure 4 and enables the opportunity to adapt the single processors to the individual requirements of users. For the analysis of this experiment the fitter processor had to be slightly changed in order to get the angles of the particle tracks.

In the following the processors of an analysis are briefly summarized:

- **Converter**: In this first step the raw data written by the DAQ software is converted to the LCIO [7] format, a framework developed for the purposes of linear collider studies. Additionally hot pixels, meaning defective pixels firing too often, are indicated in this step and excluded in the following ones.

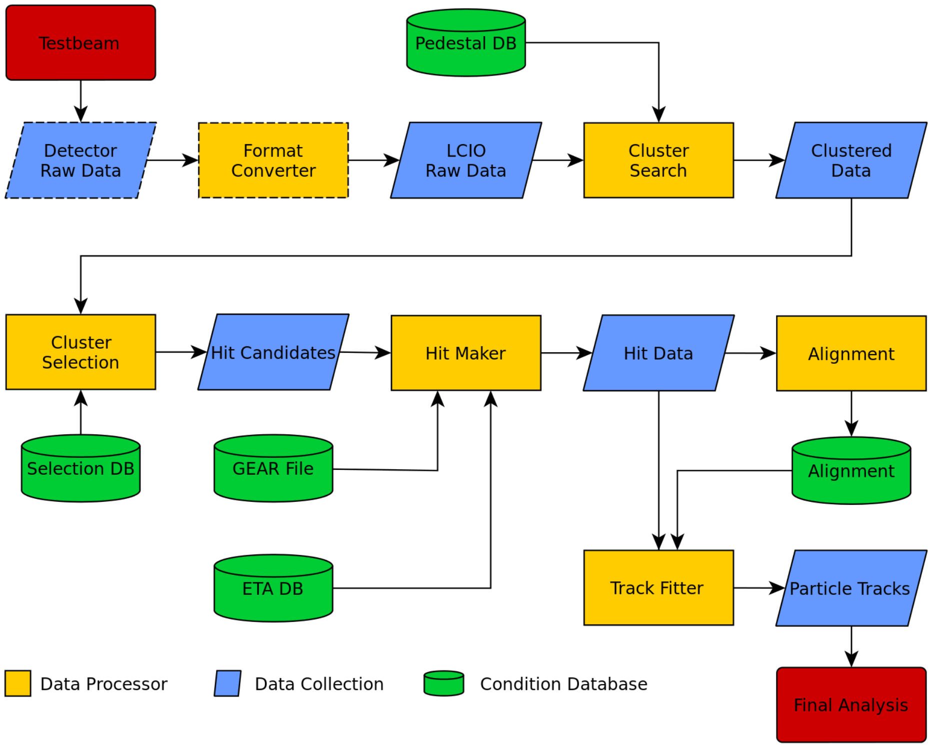


Figure 4: Scheme of the analysis chain executed by EUTelescope. Every single processor can be changed individually in order to adapt the analysis to individual requirements. [6]

- **Cluster Search**: Particles hitting a sensor plane are very unlikely to produce a signal in just one pixel of a plane. This module looks for adjacent pixels responding in the same event, which form so called clusters and belong to one hit.

- **Cluster Selection**: Depending on the individual analysis one can reject or accept clusters due to properties like signal, noise or signal to noise ratio. This step has not been used in this analysis.

- **Hitmaker**: The Hitmaker processor calculates the center of gravity for each cluster to yield the best estimate of the position at which the particle passed through the sensor. Furthermore the hit position on the sensor is translated into a coordinate in the global telescope frame of reference. Therefore an input file has to be written and included, containing information on the telescopes geometry. Input parameters are e. g. the positions and tilt angles of the sensor planes, as well as their size, thickness and radiation length.

- **Alignment**: When handling pixels in the order of several microns it is impossible to align the telescope perfectly mechanically. The alignment processor uses track fitting algorithms in order to slightly correct the positions of the telescope planes in a way that the fitted tracks yield the best compliance with the actual hits. The alignment constants can be applied to the data by the following steps in order to correct the coordinates of the hits produced by the Hitmaker.

- **Track Fitter**: The track fitter combines the hits found in one event to fitted tracks through the telescope. For the analysis performed in this experiment an implementation of the DAF (Deterministic Annealing Filter) Fitter has been used. The DAF Fitter includes a Kalman Filter [8, p. 53], an algorithm commonly used for tracking. This algorithm starts with a hit in the first plane and a first estimation of a track, which sets an area on the second plane, in which another hit of this track is expected. Finding a hit in this area, the previous estimation of a track is corrected and again propagated to the next plane. If no hit is found, the track is either rejected or propagated to the next plane, depending on the settings of the user. This is processed up to the last plane of the telescope, giving the best estimation of a track as a result.

- **Analysis**: The fitted tracks can be used for the final analysis, for example the examination of a prototype particle detector. In this case, the analysis was done by the track fitter itself, which stored the angle of every track into a ROOT [9] histogram.

2 Energy Calibration of test beam area 21

For certain experiments executed in the DESY test beam areas it is essential to have information on the incoming particles energy. As mentioned in Section 1.1 the beam energy can be set by the beamline user through adjusting the current of the magnet positioned before the concerned test beam area. From theoretical considerations using the magnetic field of the dipole, years ago a table was created predicting the mean particles energy from the current set to the magnet. In collaboration with other summer students working on test beam related projects an experiment was planned and executed in order to measure the dependency of the particles mean energy on the magnet current.

2.1 Principle

For the measurement of the particles momentum in test beam area 21 a dipole magnet, shown in Figure 5, was used to bend the particle tracks. The outcoming tracks were measured by the DATURA Beam Telescope and reconstructed using EUTelescope. This yielded the deflection angle and was then compared to a simulation of the deflection of particles inside the magnetic field.

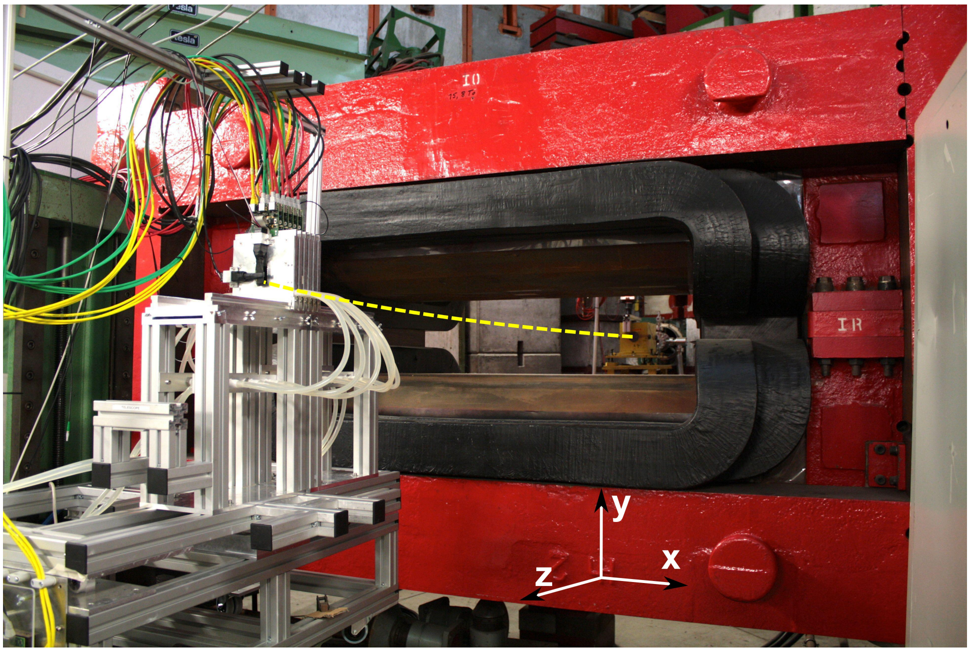


Figure 5: In order to measure the particles energy the dipole dipole magnet was used to bend the particle tracks. The deflection angle of the outgoing tracks was then used to reconstruct the particles' momentum. [3]

2.2 Simulation

For the simulation of the particles motion in the magnetic field the CYLRAD algorithm [10] was used. In contrast to other numerical methods this algorithm assures the conservation of speed in a purely magnetic field. In absence of an electric field the algorithm is shortly described by the equation

$$\vec{v}^{n+1} = \vec{v}^{n} + \left(\vec{v}^{n} + \vec{v}^{n} \times \vec{t}\right) \times \vec{s} \tag{1}$$

using

$$\vec{t} = \frac{q\Delta t}{2\gamma m}\vec{B}(\vec{x}) \qquad \text{and} \qquad \vec{s} = \frac{2\vec{t}}{1+|\vec{t}|^2}, \tag{2}$$

where n is the current timestep, q is the particle charge, m the particle mass, Δt the timestep size of the simulation and γ as the relativistic Lorentz factor. $\vec{B}(\vec{x})$ is a space dependent magnetic field. After the calculation of the particle speed the space coordinate has to be updated from timestep n to step $n+1$:

$$\vec{x}^{n+1} = \vec{x}^{n} + \vec{v}^{n+1}\Delta t \tag{3}$$

This method was tested using a constant magnetic field $\vec{B}(\vec{x}) = B\hat{e}_y$ and fitting a circular function to the trajectory. Since the radius R of the trajectory matched the prediction from $R = p/(eB)$, derived from the equality of centripetal force and Lorentz force, the code was expanded to a simulation of a particles motion in an arbitrary magnetic field. For the final analysis a timestep of $\Delta t = 0.01$ mm$/c$ was used. Going to smaller stepsizes yielded higher computation time but no significant increase in accuracy.

In order to simulate the particles motion in an arbitrary magnetic field, the field had to be evaluated at every space coordinate $\vec{x}^n$. A set of measurements [11], taken in 1985 (see Figure A.11), contains the vertical component of the magnetic field of the MD dipole magnet along the beam axis with a relative precision of 10^{-4} for various currents set to the magnet. Since the spatial resolution of the measurement is rather high ($\Delta z = 2$ cm) and the dependency of the magnetic field on the current is in good approximation linear, both the spatial and the interpolation between the currents have been implemented as a linear interpolation.

A quick review of the magnetic field of the dipole magnet using a Hall probe was made in order to examine, which deviation of the field strength arises from the displacement of the axis along which the measurement was taken and the actual beam axis. This review verified the measurement from 1985 and showed a deviation of about 0.5% in the magnetic field strength for the vertical ablation of the beam and measurement axes by about 7 cm.

2.3 Analysis

The data taken by the telescope was evaluated using the software EUTelescope as described in Section 1.4 in order to yield the particles momentum. For the reconstrution of the deflection angle, an output histogram was added to the Fitter processor, showing the distribution of the angles in the xz plane (see the coordinate system in Figure 5) of every fitted track inside the telescope during a run. For this purpose the x-coordinate of the hit of the fitted track in the first (x_0) and the last sensor plane (x_5) as well as their z-positions (z_0 and z_5) have been used to calculate the deflection angle

$$\theta = \arctan(\frac{x_5 - x_0}{z_5 - z_0}). \tag{4}$$

Figure 6 shows the histograms for a current of $I_E = 149.6$ A set to the energy magnet in front of the beamline. Equivalent data was taken for ten specific currents I_E.

For the purpose of yielding the actual mean momentum of the positron beam for a certain run, the input momentum of the simulation was adapted in such a way, that the simulated deflection angle equals the mean value of the measured angular distribution. Figure 7 shows the momentum plotted against the energy current I_E combining the results for every run taken at a specific current. The parameters of the linear fit

$$p = a \cdot I + b \tag{5}$$

to the measured curve are $a = 0.0323$ GeV A^{-1} and $b = 0.0458$ GeV. The prediction gives a slope of $a' = 0.0267$ GeV A^{-1}, which deviates from the measurement by about 17%.

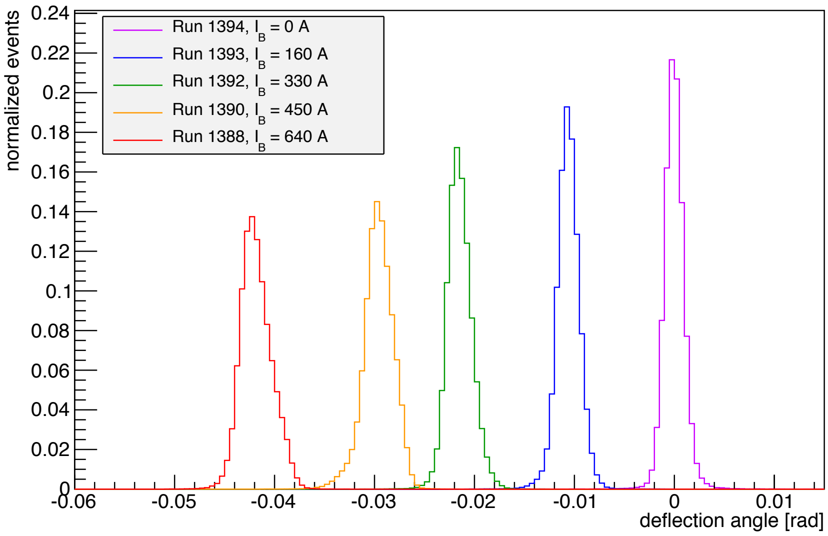
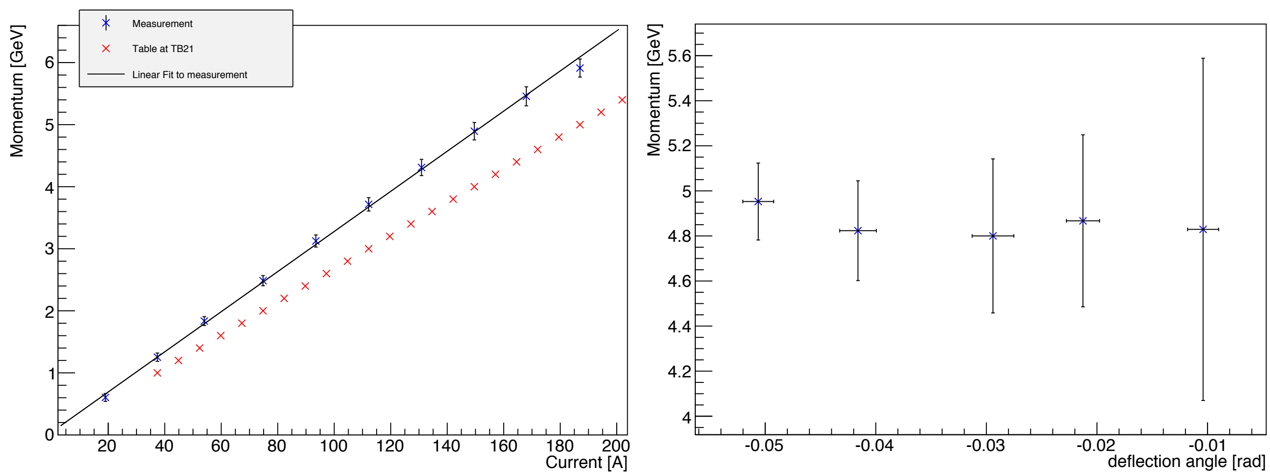


Figure 6: The histogram shows the distribution of the deflection angle of the particles for different currents I_B of the bending magnet inside of the beamline. For all these runs the current of the energy magnet was set to $I_E = 149.6$ A and only the two trigger scintillators in front of the telescope had been used.



(a) (b)

Figure 7: Figure (a) shows the measured momentum plotted versus the energy magnet current I_E. Errors on the magnetic field strength, the alignment of the telescope and the angular distribution have been taken into account. For every current, several runs have been taken with different deflection angles, as already seen in Figure 6. The measurements for specific currents are combined. The red points show the prediction from the table in test beam area 21, which deviates from the measurement by about 17%. Using the example of the measurements taken at $I_E = 149.6$ A, (b) shows that the reconstructed momentum is independent on the measured deflection angle.

3 Further investigations

The causes of this enormous mismatch had to be investigated in order to ensure the right energy information for further experiments at the DESY test beam area 21. In order to exclude, that the error was due to the simulation of the particles track or a systematical error during the measurement, the energy separation itself was examined.

During a shutdown of DESY II the magnetic field of the green magnet (see Figure A.10) of beamline 21 was measured using a Hall Probe, placed as near to the geometrical center of the magnet as possible, for several currents set to the magnet by the control panel. The measured magnetic field was compared to the data sheet, of which an extraction can be seen in Figure A.12. The results are shown in Figure 8 (a). These show a discrepancy between the measured and the expected magnetic field of about 25%.

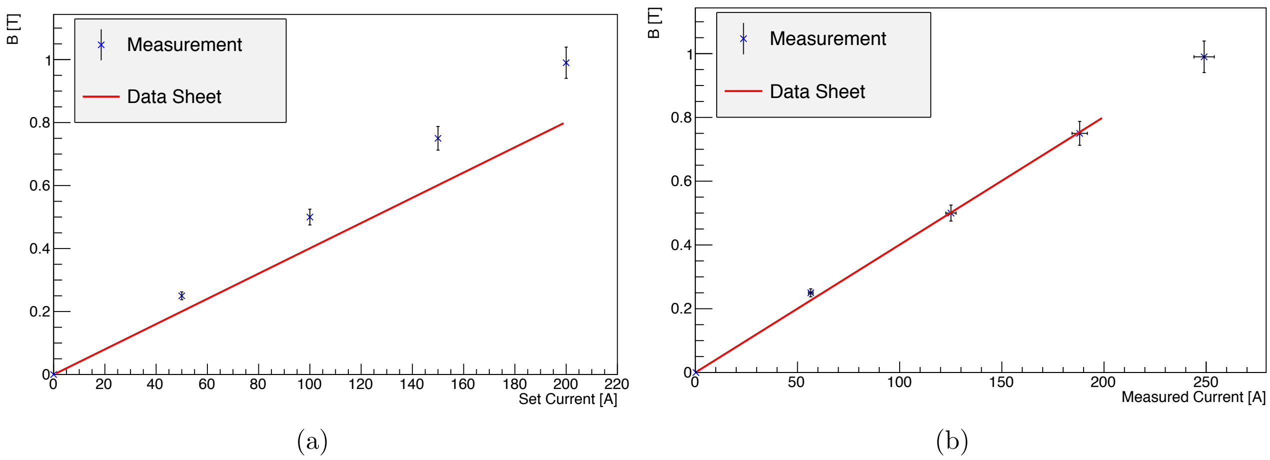


Figure 8: The measured magnetic field of the green magnet inside the beamline for test beam area 21 is plotted against the current set to the magnet by the control panel (a). Figure (b) shows the same measurement using the currents acually measured at the magnet.

In the next step, the actual current in the magnet was measured using a current clamp. This measurement showed the same discrepancy between the measured and the expected value, i. e. the value set in the control panel. Hence the plot shown in Figure 8 (a) could be corrected, changing the set current to the measured current, yielding Figure 8 (b), which shows that the magnet is working properly, but the error is due to a discrepancy between the set and the actual current of the deflection magnet.

This error was then found the be caused by a miscalibration of the control panel of the power supply by a factor of 1.25. After a recalibration was executed, the current inside the magnet was measured again, yielding values consistent with the ones set to the control panel.

The calibration factor was also applied to the values for the currents in the analysis in Section 2.3, yielding the results shown in Figure 9. The plot shows a good consistency of the predicted and the measured values of the beam energy.

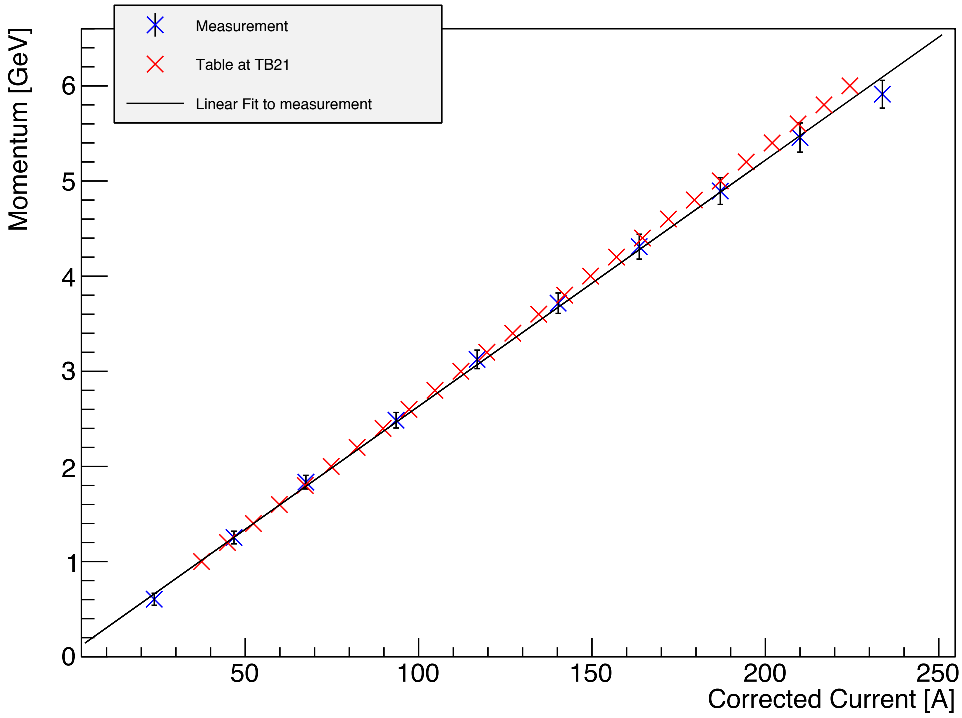


Figure 9: Analysis of the measurement similar to Section 2.3 with recalibrated current axis. The values from the table are consinstent with the ones reconstructed from the measurement.

4 Conclusion

During my time as a summer student at DESY, a small but standalone project consisting of measurement, simulation and analysis could be realised. This increased my knowledge on data acquisition, programming and the planning, execution and analysis of experiments.

The results presented and the changes made are essential for the further operation of the DESY test beam area 21. The wrong calibration of the control panel of the power supply for the energy magnet can be dated back to a timeframe from summer 2012 to winter 2013, which means, that the data taken since then has to be reviewed if dependent on the beam energy. For future experiments and their analysis the beam energy from the table can be used.

For further projects the data taken and the simulation written for this project can be used and developed in order to get information on the energy distribution of the particle beam.

Appendix

A. Figures

(a) Extraction beamlines (2006)

(b) Conversion targets and dipole magnet (2013)

Figure 10: Figure (a) shows a view into the DESY II tunnel [1]. The extraction beamlines for the three test beam areas can be seen, as well as the green magnets used in order to set the beam energy. The conversion targets are placed directly in front of the magnets, which is showed in Figure (b). Behind the magnets the shutters and collimators are located. The photon beamlines from DESY II to the magnets have been removed meanwhile.

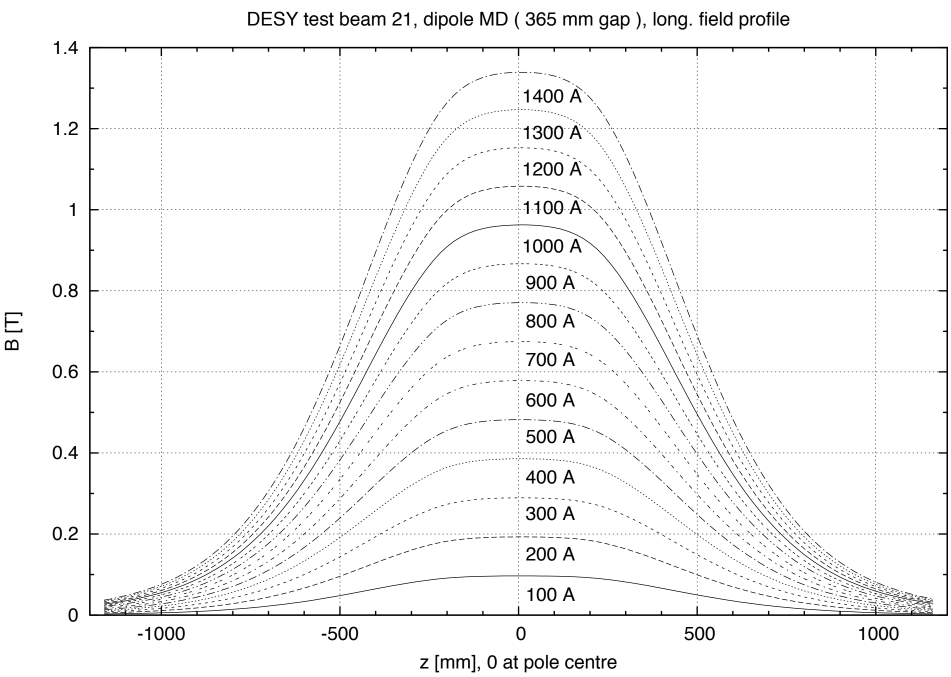


Figure 11: Measurement of the vertical component of the magnetic field inside the MD dipole magnet in test beam area 21. [11]

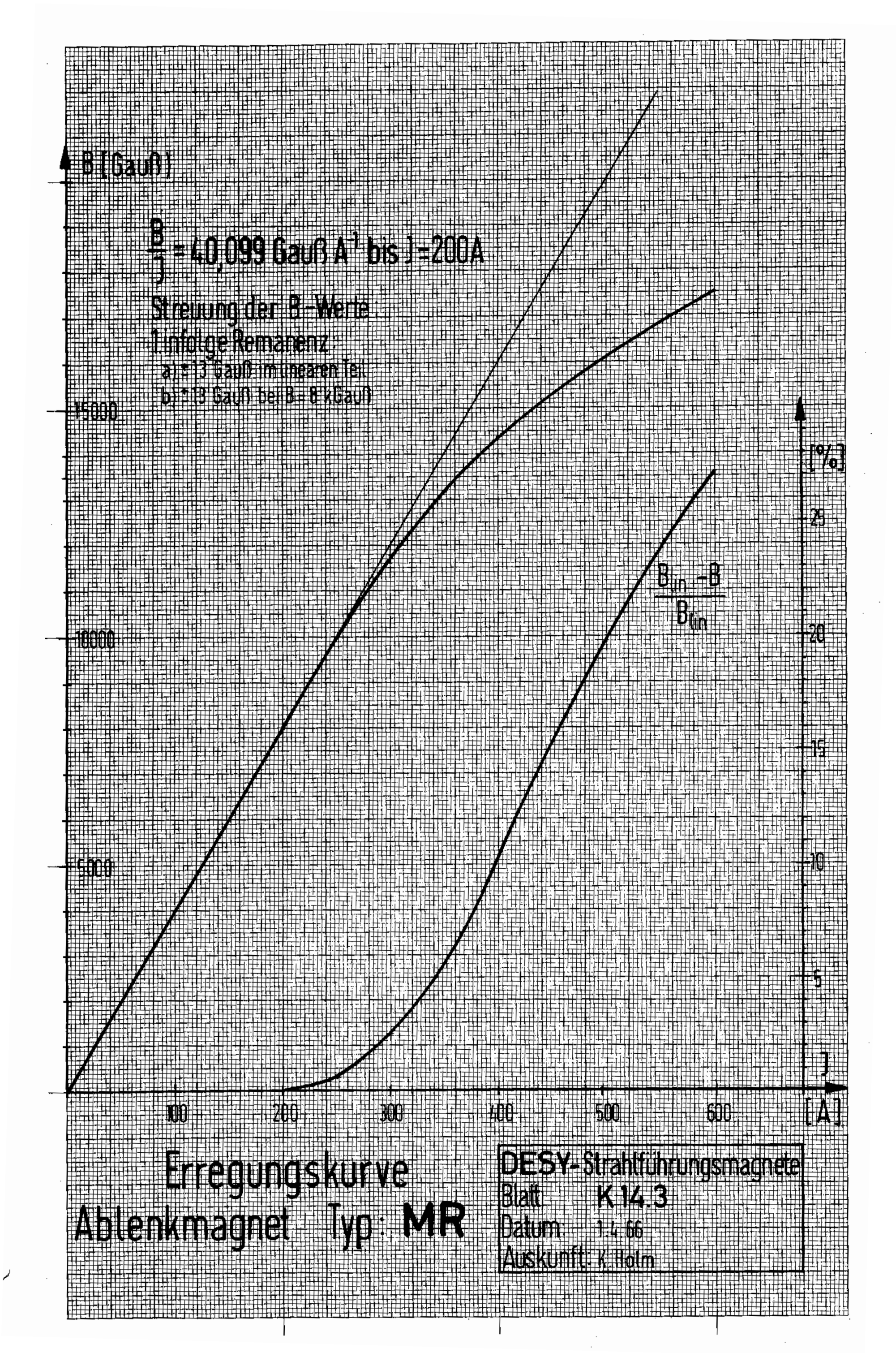


Figure 12: Extraction of the data sheet for the green bending magnet, which causes the separation of the particle beam by the particles momentum. [1]

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