Digital Calorimetry Using Pixel Sensors
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Digital Calorimetry Using Pixel Sensors

Digitale Calorimetrie door middel van Pixel Sensors

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

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Abstract

The subject of this thesis is a new type of electromagnetic calorimeter, which is not based on proportionality of deposited energy, but instead on counting the number of showering particles. This calorimeter is a proof of principle for a proposed upgrade of the ALICE experiment at the Large Hadron Collider.

This thesis starts with giving the reader an understanding of the fundamental processes governing the development of electromagnetic showers, in order to correctly comprehend the effects underlying the performance of the calorimeter. It also aims to explain how the different choices in detector construction in combination with these processes affect the measurements of particles.

Next, the choice of detector components is explained as well as the working of these components. This is followed by the explanation of the software used and the different steps in both data processing and analysis are examined piece by piece and should give a prospective user of this software an understanding of the underlying principles.

This is followed by a discussion the simulation software used and the additions made to this software to fully model the behaviour of the sensors used in the prototype. The results of several analyses done on the data obtained from beamtests at both DESY and CERN, as well as compare these results with simulations done are discussed. This will test both the validity of the simulations as the quality of the beamtest results.

The conclusions drawn from the analyses will be used to give a final impression based on all results. A number of suggestions for future improvements to the prototype and detectors derived from the prototype will also be given.
## Contents

1 Introduction ............................................. 7
   1.1 Quarks and Gluons .................................. 7
   1.2 ALICE .................................................. 9
   1.3 Summary of Chapters ................................. 13

2 Principles of Calorimetry ............................... 15
   2.1 Electromagnetic Showers ............................ 15
      2.1.1 Electromagnetic Shower Fundamental Interaction Processes ............................... 16
      2.1.2 Critical Energy .................................. 23
      2.1.3 Shower Anatomy .................................. 24
      2.1.4 Material Effects on Shower Development ........................................ 26
      2.1.5 Longitudinal Shower Profiles ...................... 27
      2.1.6 Transverse Shower Profiles ....................... 28
      2.1.7 Fluctuations in Shower Development ............... 28
   2.2 Principles behind Calorimeter Functionality ........ 29
      2.2.1 Differences between Signals of Homogeneous vs. Sampling Calorimeters ............ 30
      2.2.2 Calorimeter Response ............................. 31
      2.2.3 Fluctuations of Signals in Sampling Calorimetry .................................. 33
      2.2.4 Calorimeter Calibration ............................ 35
   2.3 Current EM Calorimeter Designs ...................... 35
      2.3.1 FCal at ATLAS .................................... 35
      2.3.2 Electromagnetic Calorimeters at CMS .......................... 36
      2.3.3 ALICE’s EMCal .................................... 38
      2.3.4 ECAL at LHCb ..................................... 38
      2.3.5 PAMELA ............................................ 39
      2.3.6 Comparison of Calorimeter Performance ........ 40
   2.4 The FoCal detector in ALICE .......................... 41

3 Detector Prototype ...................................... 45
   3.1 General Construction ................................ 45
   3.2 Prototype Construction ............................... 48
   3.3 The MIMOSA sensor ................................... 50
   3.4 FoCal Coordinate System ............................. 54
   3.5 Data Acquisition System ............................. 54
      3.5.1 Trigger system .................................... 55
Chapter 1

Introduction

1.1 Quarks and Gluons

All atoms that make up the universe consist of electrons and atomic nuclei, which themselves are combinations of protons and optionally neutrons. While the electrons have not yielded information about any internal structure at the time of writing this thesis, hadrons such as protons and neutrons contain a number of sub-particles called quarks. According to Quantum Chromo Dynamics (QCD) quarks need to possess a property called colour charge, of which there are three different types, in addition to spin and electric charge to account for the observed properties of hadrons. The system of interactions between quarks possessing different combinations of colour charge is called the strong interaction, which is mediated by particles called gluons.

From the equations describing the strong interaction follow two important predictions about the behaviour of quarks and gluons, namely confinement and asymptotic freedom. Confinement means that quarks are never observed as independent particles in nature, they are always confined inside hadrons. Asymptotic freedom means that the interaction that keeps quarks together becomes weaker as the energy increases and the distance decreases.

In high-energy nuclear collisions the system will reach high energy density, which for a thermal system corresponds to high temperature. At sufficiently high temperature the coupling of QCD decreases and the long-range confining potential disappears. The quarks and gluons of nuclei then transform into a new state of matter called the Quark Gluon Plasma (QGP). The ALICE experiment is mainly designed to study the QGP, but these studies are not the focus of this thesis and will not be discussed further.

The relative contributions of the quarks and gluons to the total momentum of a hadron are described by the Parton Distribution Function (PDF). This distribution is not only a function of the momentum fraction of a parton in the hadron, but of the momentum transfer $Q^2$ involved in the interaction with the hadron as well.

The evolution of PDFs is governed by the DGLAP equations. These equations predict an ever growing number of gluons at low $x$ with increasing $Q^2$, which obviously cannot continue forever. When the gluon density reaches a certain level, it will become more likely for the gluons to merge, thereby stabilizing the number of gluons and leading to gluon saturation.

A model to describe the saturated gluon state is the Colour-Glass Condensate ([1, 2, 3]) or CGC. Since the CGC provides a description of the initial state conditions of heavy-ion
collisions, combined with the fundamental physics of the CGC, make it a topic of interest. While the CGC evolves into the QGP, the uncertainties on the initial conditions have been large in measurements so far.

The state of the low-x gluons can be described as a classical colour field generated by the fast partons, which appear frozen due to time dilation. This slow variation, together with high gluon density, has given rise to the name Colour Glass Condensate.

Gluon saturation and the CGC are expected to become influential for partons with small momentum fraction $x$. The effect of gluon saturation occurs on processes below a specific momentum called the saturation scale ($Q_s$), which depends on $x$ and the nuclear mass $A$ as:

$$Q_s^2 \propto x^{-\lambda} \cdot A^{1/3},$$  \hspace{1cm} (1.1)

so the saturation scale increases (saturation effects are stronger) for small $x$ and large nuclei.

In the saturation regions the gluon density is expected to be smaller than predicted by linear QCD evolution (the DGLAP, DokshitzerGribovLipatovAltarelliParisi, equations), possibly leading to a relatively reduced number of produced particles in a collision. Because saturation becomes more influential for nuclei, one can study these effects in particular by comparing particle yields in proton-nucleus and proton-proton collisions.

Furthermore, the largest sensitivity is for small $x$. The values of $x$ of the initial state parton can be derived from final state kinematics according to:

$$x \approx \frac{2p_T}{\sqrt{s}} e^{-y},$$  \hspace{1cm} (1.2)

with $p_T$ being the transverse momentum and $y$ the rapidity of the produced particle, and $\sqrt{s}$ the Centre of Mass energy of the collision. In order to accurately examine the properties at small $x$, measurements will have to be done at high beam energy. Furthermore, due to the exponential dependence on the rapidity, sensitivity to smaller $x$-values is gained by measuring at high rapidities. Rapidity is determined from the longitudinal momentum component of a particle, and for the purposes of heavy ion physics can be approximated reasonably well by the pseudorapidity $\eta$:

$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right),$$  \hspace{1cm} (1.3)

meaning that large rapidities imply small angles $\theta$ relative to the beam direction. Measurements at these angles are usually referred to as being forward measurements.

Current measurements have not been able to give conclusive results yet. For some types of hadrons, such as the $\phi$ or the $J/\psi$ mesons, measurements indicate a suppression in proton-nucleus collisions at forward rapidities [4, 5, 6]. However, it is still unclear to which degree these results can prove the existence of the CGC. In particular, there are many intermediate steps between the production of hadrons in the partonic collision and the observation of their products, e.g. fragmentation and scattering, so their relation to the initial $x$ is less direct.

Photons would give much more direct access to the parton kinematics, because photons can be directly produced in a partonic scattering, photons will give direct access to the parton kinematics and photons do not suffer from final state interaction. However, at this moment, measurements of direct photons in the adequate kinematic range is not possible at any experiment. This has lead to the proposal of a new detector to be implemented in the ALICE experiment: a Forward Calorimeter (FoCal) to measure photons in the forward region.
In any interaction of hadrons at high energy a large number of extraneous particles are produced. The neutral pions, while being some the most abundant particles, decay almost instantaneously into two photons. It is these decay photons that are much more abundant than the direct photons and form an important background which obscures the measurement of the signal of interest. It is therefore of great importance to discriminate between this background and the signal.

At forward rapidities all particles have much higher momenta on average. For neutral pions this leads to very small opening angle of the decay products in the detector frame of reference, resulting in two photons located very close to each other in the detector. This gives the risk that signals of the two photons overlap and cannot be distinguished from a single photon.

The main challenge of the new detector will thus be gaining the ability to separate the signals of two photons with very small spatial separation, which requires a small transverse spread of the signals induced and a high granularity. The research on such a high granularity detector is the main topic of this thesis.

1.2 ALICE

ALICE (A Large Ion Collider Experiment) is one of seven detector experiments at the Large Hadron Collider (LHC) at CERN [7]. It is optimized to study the QGP which is produced when two lead nuclei are collided by the LHC. The way this state of extremely high energy density behaves as it evolves will shed light on the properties of the strong interaction.

The setup of the ALICE experiment is shown in figure 1.1. Working from the interaction point outwards, particles produced in the interactions in the ALICE experiment can be expected to pass through a certain sequence of detectors which will be examined in more detail below.
For particles with low pseudorapidity, and therefore large angles relative to the beam axis, the first detector they pass is the Inner Tracking System (ITS), consisting of the silicon pixel-, drift-, and strip-detectors. This tracking system is mounted on an extremely low-density carbon-fibre structure, to provide as little impediment to the particles passing through it as possible. The ITS covers the rapidity range of $|\eta| < 0.9$ for all vertices located within the length of the interaction diamond ($\pm 5.3$ cm along the beam direction). The extremely high granularity (over 9.8 MPixels in $0.21 \text{ m}^2$ of detector surface for the innermost (pixel) layers), allows for a spatial resolution down to 12 $\mu\text{m}$ in the $\phi$ direction and 100 $\mu\text{m}$ in $z$.

For low pseudorapidity particles the next detector passed is the Time Projection Chamber (TPC). This detector is a cylindrical gas-filled vessel with a length of 500 cm and an inner radius of 85 cm and outer radius of 250 cm. An electrical field is present between a central membrane and sensors on both faces of the cylinder. The electrons generated by particles passing through the medium inside the vessel are attracted to the endcaps of the cylinder where they are multiplied in multiwire proportional chambers with pad readout. By measuring the amount of charge and drift time, the tracks of charged particles can be reconstructed and their specific energy loss can be measured. When combined with the magnetic field inside ALICE, the momenta of the particles can be measured as well. The TPC has coverage for $|\eta| < 1.5$ for tracks with reduced momentum resolution, but coverage for $|\eta| < 0.9$ for tracks with full radial track length. The measurement part of the detector is a large cylindrical field cage with a volume of 9 m$^3$ filled with a Ne-CO$_2$-N$_2$ mixture.

Next is the Transition Radiation Detector (TRD), which was designed to trigger on high-momentum particles and to identify particles with high velocity, i.e. mainly positrons and electrons. The TRD consists of a radiator section and a drift chamber. The radiator section of the TRD faces the inside of the detector and in it high-velocity charged particles generate X-ray photons as so-called transition radiation. The drift chamber is then used to measure the energy deposited by the particles themselves through ionization and the X-ray photons produced in the radiator section. The drift chamber is filled with a Xe-CO$_2$ mixture, and the charges generated are collected through a system of electrodes.

Lastly, located outside the TRD, and aimed at measuring central-rapidity particles,There are the Time-Of-Flight detector (TOF), the High-Momentum Particle Identification Detector (HMPID), the ElectroMagnetic Calorimeter (EMCal) detectors and the PHOton Spectrometer (PHOS).

TOF is a barrel of Multigap Resistive Plate Chambers (MRPC) designed to measure the arrival time of charged particles with a resolution of better than 100 ps which is then used to determine the time of flight.

HMPID is designed for inclusive measurements of identified hadrons at $p_t > 1 \text{ GeV}/c$. To this end, incoming charged particles pass through a C$_6$F$_{14}$ radiator. The Cherenkov radiation is measured by this detector and by analysis of the radius of the Cherenkov ring, the velocity of the particles can be inferred. HMPID has coverage for $|\eta| < 0.6$ and $1.2^\circ < \phi < 58.8^\circ$.

EMCal is a lead-scintillator sampling calorimeter located at a distance of approximately 4.5 m from the interaction point. It has coverage for $|\eta| \leq 0.7$ and $\Delta \phi = 107^\circ$. It is designed to aid in the measurement of jet physics at ALICE.

PHOS is designed as a high resolution, high granularity electromagnetic spectrometer. Its most basic element is a $22 \times 22 \times 180 \text{ mm}^3$ lead-tungstate crystal coupled to a $5 \times 5 \text{ mm}^2$ avalanche photo-diode. These elements are mounted together to give a total coverage of $|\eta| \leq 0.12$ and $220^\circ < \phi < 320^\circ$. The main objective of PHOS is to measure low-$p_t$ direct photons to allow insight into the thermal and dynamic properties of the initial phase of the
Measurements at high pseudorapidity are done at ALICE by the muon spectrometer, which has coverage in the region of \(-4.0 < \eta < -2.5\). This detector allows the measurement of the complete spectrum of heavy-quark vector-meson resonances (i.e. \(J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon''\)), in addition to the \(\phi\)-meson through the \(\mu^+\mu^-\) decay channel. This information will be used in combination with that gathered from the central barrel of ALICE, ATLAS and CMS at mid-rapidity.

The muon spectrometer has three main components, namely the absorbers, the tracking system and the trigger system. The front absorber has a length of 4.13 m (\(\approx 10\lambda_{\text{int}}\) or \(\approx 60X_0\)) and is made primarily of carbon and concrete to reduce energy loss and scattering by traversing muons. The front absorber has a conical geometry to reduce background particle interaction for the length of the detector. Additionally there is a 1.2 m thick iron wall placed after the last tracking chamber, for protection of the trigger chambers.

The tracking chambers are designed for a spatial resolution of 100 \(\mu\)m, which is necessary to achieve an invariant-mass resolution of 100 MeV/c\(^2\) at the \(\Upsilon\) mass. They are also designed to be able to discriminate between the few hundred particles that are expected to hit the muon chambers during lead-lead events.

The tracking system makes use of cathode-pad chambers filled with an argon carbon dioxide mixture, arranged in five stations of which two are before, one is inside and two are located after the dipole magnet. Each of these stations has two chamber planes which collect the hit information with a granularity ranging from 4.2×6.3 mm\(^2\) for the innermost pads to 5×100 mm\(^2\) for the pads the furthest from the beamline. The granularity of the muon tracking chambers was chosen such that the occupancy of the tracking chambers is kept at approximately 5\%, which resulted in a total number of channels of about one million.

On average for central lead-lead collisions, eight low-\(p_t\) muons from pion and kaon decays are expected in the spectrometer. To reduce the probability of triggering on the events where these muons are not accompanied by the high-\(p_t\) muons originating from the decay of heavy quarkonia, a \(p_t\) cut is necessary at the trigger level for each separate muon in the spectrometer. This is achieved through a pair of programmable \(p_t\) cuts which are performed at the trigger level and which can be set in the range from \(\approx 0.5\) to \(\approx 2\) GeV/c. These thresholds are chosen as a compromise between background rejection and signal detection efficiency in the mass regions of the \(J/\Psi\) and \(\Upsilon\) resonances.

To achieve the \(p_t\) selection, a trigger detector with space resolution no worse than 1 cm is necessary. In the muon spectrometer, this is achieved through resistive plate chambers (RPCs), operated in streamer mode. The trigger system contains four RPC planes in two stations, separated by 1 meter, which are located behind the muon filter. Each plane has 18 low resistivity (3 G\(\Omega\) cm) Bakelite electrodes measuring 70 by 300 cm, which are read out through segmented strips with length and pitch that increase with the distance to the beam axis.

In order to add to the information gathered from the muon spectrometer, a new electromagnetic calorimeter at very forward angles is proposed at ALICE (see figure 1.2). With a very high granularity and a large depth in \(X_0\), this detector will be able separate close-lying electromagnetic showers and reconstruct their direction with high accuracy. A detector at this location will give data complementing that produced by the muon arm, which will give new insights into low-x physics. The depth of the detector and its sampling frequency will give it a reasonable energy resolution, which combined with its high granularity is expected give a very good separating power between prompt photons and photons from \(\pi^0\) decays. Because
CHAPTER 1. INTRODUCTION

Figure 1.2: The proposed location of both parts of FoCal in the ALICE experiment. It will be placed directly opposite the muon arm, due to the space already being taken up by the muon spectrometer (the conical structure on the right). The discussion of FoCal will only examine the electromagnetic section of FoCal (FoCal-E), which will be located at a distance of 700 cm. This thesis will ignore the hadronic section (FoCal-H), planned at 730 cm, since it is not the topic of this thesis.

of its location (at very forward angles) and function (measuring the energy of particles), the proposed detector will be called the Forward Calorimeter, or FoCal [8].

Because of the high requirements on positional resolution, a sampling calorimeter solution is chosen to allow for the use of silicon sensors. These sensors are then "sandwiched" between layers of very high density absorber material which is very efficient in absorbing high energy particles. The silicon sensors will then be able to sample the development of the interactions the particles will have with the absorber and from this information on the direction and momentum of the particles can be derived.

A number of the sensors will need to have a very high positional resolution to be able to measure the direction of the particles. The sensors used could be silicon strip or pixel sensors. The remainder would then be silicon pad sensors, measuring the energy deposited with good accuracy, but not with the positional resolution of the pixel sensors. The absorber material should be a high density and high atomic number element, such as tungsten or lead, in order to maximize its ability to stop high energy particles. This would then be made into slabs of sufficient thickness to allow the particles to interact. The complete detector would then consist of a large number (at least 20-30) of these alternating layers to contain particles of energies in excess of 100 GeV.

Knowledge on the behaviour of such a Silicon-Tungsten calorimeter in general and on the precise description of showers in it are crucial for this upgrade project. To perform the corresponding general research and development a high granularity prototype calorimeter has been built. The construction and first measurements made with this prototype are the subject of this thesis.
1.3 Summary of Chapters

Chapter 2 aims to give the reader a good understanding of the fundamental processes governing the development of electromagnetic showers. It also aims to explain how the different choices in detector construction in combination with these processes affect the measurements of particles.

The FoCal prototype is the subject of chapter 3. The choice of detector components is explained as well as the working of these components.

This is followed by the explanation of the software in chapter 4. The different steps in both data processing and analysis are examined piece by piece and should give a prospective user of this software a good understanding of the underlying principles.

Chapter 5 will discuss the simulation software used and the additions made to this software to fully model the behaviour of the sensors used in the prototype.

Chapter 6 will discuss the results of several analyses done on the data obtained from beamtests at both DESY and CERN, as well as compare these results with simulations done. This will test both the validity of the simulations as the quality of the beamtest results.

Finally, chapter 7 will compile the conclusions drawn from chapters 2 to 6 and give a final impression based on all results. It will also give a number of suggestions for future improvements to the prototype and detectors derived from the prototype.
Chapter 2

Principles of Calorimetry

In particle physics, calorimeters are devices which measure the energy of particles. This is usually done by measuring the energy deposited by the particle in a medium as the particle is stopped by it. This gives the calorimeter two functions it needs to perform. The calorimeter needs to cause the particle to lose energy to the calorimeter, and this energy needs to be measured in some manner. The medium causing the loss of energy is called the absorber and the medium measuring the energy the sensor.

There are two main types of calorimeter in high energy particle physics. Hadronic calorimeters are intended to measure the energy of hadrons such as pions, protons and neutrons, electromagnetic calorimeters the energy of electrons and photons.

There are significant differences in the design requirements between these two types. One of these is that in general, hadronic calorimeters need to be physically larger than electromagnetic calorimeters. This is because the strong interaction is shorter ranged than the electromagnetic interaction, resulting in longer path lengths.

Since the subject of this thesis is an electromagnetic calorimeter, this chapter will focus on the principles which govern the working of this type of calorimeter. The first section will explain the manner in which the particles will deposit energy, and how this influences their measurement. The second section explains how different design choices influence the performance of the calorimeter. From this point onward, when calorimeters are mentioned, electromagnetic calorimeters are implied, unless specified otherwise. In this chapter the description of Wigmans’ publication [9] on calorimetry is followed.

2.1 Electromagnetic Showers

Electromagnetic calorimeters are built to measure the energies of electrons, positrons and photons. These particles lose their energy in a so-called electromagnetic cascade or shower.

The main property of the shower is that it is composed of a number of particles, each losing energy. Some of this energy is lost in the form of new particles contributing to the shower, which increases the total energy deposition. This continues until the energy of the particles drops to the level where their energy available is insufficient to create more particles. The final result is a longitudinal distribution of energy deposition, which first increases, reaches a maximum where the number of particles is at its peak, and then decreases.
The shower is a collection of energy loss processes, each with its own influence on the location and amount of deposited energy. Therefore, in order to have a sufficient understanding of the energy deposition in a shower, an understanding of these processes is required.

The deviations from the generalized shower distributions depend on the distribution of charge. These material effects will also be explored, in addition to the average longitudinal and transverse shower distributions.

### 2.1.1 Electromagnetic Shower Fundamental Interaction Processes

Shower particles can deposit their energy through several processes.

Charged particles, which in showers are mainly electrons and positrons, interact in the following ways:

- at high energies, Bremsstrahlung is produced,
- the particles can ionize atoms, producing energetic electrons,
- particles may excite the electrons of the atoms of the medium to excited states without ionization, the de-excitation will create scintillation photons,
- charged particles travelling faster than the speed of light in the medium lose energy by radiating Cherenkov photons,
- and at the interfaces of different materials transition radiation is produced.

Photons interact through the following processes:

- pair production: a photon is converted into an electron and a positron in the vicinity of the electric field of an atomic nucleus,
Figure 2.2: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Bremsstrahlung is strongly dominant from energies of 10 MeV, whereas ionization losses are much more important at lower energies. Taken from [13] (fig. 32.11, pg. 404).

- Compton scattering: a photon is scattered off an electron in an atom, liberating the electron,
- the photoelectric effect: an atom absorbs a photon and an electron is emitted,
- and Rayleigh scattering: which does not change the energy of the photons.

The processes are examined in descending order of the energy at which they are influential. The changes in the contributions of these effects as the energy of the particles changes is the main focus of this section. The differences in fractional energy between the different processes for electrons and positrons is shown in figure 2.2, while the interaction length for photons is shown in figure 2.3.
CHAPTER 2. PRINCIPLES OF CALORIMETRY

Figure 2.3: Interaction length for photons in a number of materials. The independence of the interaction length for energies above $\approx 100$ MeV can be seen. Taken from [13] (fig. 32.16).

Pair production

Pair production contributes for all photons with an energy larger than twice the electron restmass. Above this energy any photon in the electric field of a charged particle may convert into an electron-positron pair.

In calorimeters, this means the electric field of an atomic nucleus. For nuclei in matter, this electric field is partially screened by the electrons making up the atoms. The effect of screening becomes more important for increasing energies. In the paper by Bethe [10], the cross sections for these processes are calculated to be:

\begin{align}
\Phi_{pair} &= r_e^2 \frac{Z^2}{\alpha} \left( \frac{28}{9} \log \frac{2h\nu}{m_e c^2} - \frac{218}{27} \right) \quad m_e c^2 \ll h\nu \ll Z^{-\frac{1}{3}} m_e c^2 / \alpha \\
\Phi_{pair} &= r_e^2 \frac{Z^2}{\alpha} \left( \frac{28}{9} \log 183 Z^{1/3} - \frac{2}{27} \right) \quad h\nu \gg Z^{-\frac{1}{3}} m_e c^2 / \alpha
\end{align}

with $Z$ the nuclear charge of the atom, $h$ Planck’s constant, $\nu$ the frequency of the photon, $\alpha$ the fine structure constant and $r_e = e^2 / m_e c^2$ the classical electron radius.

An important consequence of this relation is that the saturation of this cross-section occurs more quickly for higher $Z$ materials. This, together with the squared dependence on $Z$ of the pair production cross-section, has the effect that pair production becomes dominant at lower energies as the nuclear charge of the material increases.
This interaction process is dominant at energies much larger than the rest mass of the electron. At these energies, the electron and positron are created both with momenta mostly in the same direction as the original photon as a consequence of momentum conservation. The end result is that most shower particles will continue to travel in the general direction of the primary particle until the momentum becomes too low to retain the directional information of the particles. Because of this, pair production is very important in the early stages of an electromagnetic shower, where the particles are all concentrated in a small transverse region.

**Bremsstrahlung**

When an electron passes through the electric field of a nucleus, it can be decelerated, thereby losing energy. One possible mode of interaction is shown in figure 2.5, note the similarity to the pair production diagram (fig. 2.4). The energy lost is emitted in the form of a photon, which is called Bremsstrahlung.

Any charged particle decelerating in vacuum radiates electromagnetic energy according to the Larmor formula for non-relativistic particles, and its relativistic generalizations. The total radiated power follows:

\[
P = \frac{q^2 \gamma^4}{6\pi\varepsilon_0 c} \left( \hat{\beta}^2 + \frac{(\hat{\beta} \cdot \hat{\beta})}{1 - \beta^2} \right) = \frac{q^2 \gamma^6}{6\pi\varepsilon_0 c} \left( \hat{\beta}^2 - (\hat{\beta} \times \hat{\beta})^2 \right),
\]

with \( q \) the particle charge, \( \gamma \) the Lorentz factor and \( \beta \) the speed of the particle as a fraction of the speed of light. This gives the following limiting cases:

\[
P_{\hat{\beta} \parallel v} = \frac{q^2 \beta^2 \gamma^6}{6\pi\varepsilon_0 c^3}, \tag{2.4}
\]

\[
P_{\hat{\beta} \perp v} = \frac{q^2 \beta^2 \gamma^4}{6\pi\varepsilon_0 c^3}. \tag{2.5}
\]

This shows that the radiated power scales at least as \( \gamma^4 \) and at most as \( \gamma^6 \).

In the interaction between a moving charged particle (in our case almost exclusively electrons and positrons) and a stationary charge \( Z \) (mostly nuclei), the deceleration is not uniform through the total interaction time, which causes the production of a Bremsstrahlung spectrum.

The typical interaction time follows from the impact parameter \( b \) and the speed of the electron. From this also follows the cut-off frequency \( \omega_c = b/v \). The natural cut-off frequency follows from the absolute distance of closest approach \( b_0 = (e^2/4\pi\varepsilon_0)(Z^2/m_e c^2 v_0^2) \). The final form of the spectrum is:

\[
P(\omega) = \frac{16}{3} \frac{Z^2 e^6}{(4\pi\varepsilon_0)^3 m_e^2 c^5 v} \left\{ \begin{array}{ll} \ln \left( \frac{200\omega}{\gamma^2 \omega_c} \right) & \text{for } \omega \ll \omega_c \\ \frac{\pi}{2} e^{-2b_0 \omega/v} & \text{for } \omega \gg \omega_c \end{array} \right., \tag{2.6}
\]

with \( \Gamma = 1.7811 \ldots \). The energy emitted per unit frequency can be expected to be approximately independent of \( \omega \) for frequencies below the cut-off frequency, to diminish around it, and to be negligible above it.
The angular distribution of Bremsstrahlung follows:

\[
\frac{dP}{d\Omega} = \frac{q^2}{16\pi^2\varepsilon_0 c} \left| \hat{n} \times ((\hat{n} - \hat{\beta}) \times \dot{\hat{\beta}}) \right|^2 \frac{(1 - \hat{n} \cdot \hat{\beta})^5}{(1 - \hat{n} \cdot \hat{\beta})^5}.
\] (2.7)

Due to the \((1 - \hat{n} \cdot \hat{\beta})^5\) term in the angular distribution, the radiation is very strongly concentrated in the direction of travel of the particle, which only increases with its speed.

Bremsstrahlung has a continuous spectrum, which falls off as \(e^{-\omega}\), so most energy is lost through comparatively low energy photons, which, due to their low momentum, quickly lose their directional information through interactions.

**Compton scattering**

In Compton scattering a photon scatters off a free charged particle (which in a material means an electron), resulting in the decrease of the wavelength of the photon and the increase of the energy of the particle. This is illustrated in figure 2.6. Free in this case means that the energy of the photon is so large that any binding energy effects of the electrons in the material can be ignored.

With \(\zeta = E_\gamma/m_e c^2\), the relation between the scattering angles of the electron \(\phi\) and the photon \(\theta\) relative to the direction of the incoming photon follows:

\[
\cot \phi = (1 + \zeta) \tan \frac{\theta}{2}.
\] (2.8)

In nearly all but the highest \(Z\) materials Compton scattering becomes the dominant scattering mechanism for energies from a few hundred keV up to a few MeV. Since photons of these energies are responsible for the largest part of energy deposition of showers of multi-GeV/c particles, understanding this process is very important.

The differential cross section for Compton scattering follows from the Klein-Nishina relation calculated using QED:

\[
\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} \frac{1 + \cos^2 \theta}{(1 + \zeta(1 + \cos^2 \theta))^2} \left[ 1 + \frac{\zeta^2(1 + \cos \theta)^2}{(1 + \cos^2 \theta)(1 + \zeta(1 - \cos \theta))} \right],
\] (2.9)

with \(r_e\) the reduced Compton wavelength of the electron (0.38616 pm). For energies where Compton scattering is a process of interest this cross section becomes almost flat in the backward direction \((\theta > 90)\), and increases to its maximum at \(\theta = 0\). The angular distribution of the recoil electrons has a preference for the direction of the incoming photon and because of energy and momentum conservation no electrons are scattered backwards. Also, the distribution of recoil electrons becomes more "forward" as the energy of the photon increases.

The energy lost per interaction is:

\[
E_{\text{lost}} = E_\gamma \frac{\zeta(1 - \cos \theta)}{1 + \zeta(1 - \cos \theta)}.
\] (2.10)
For MeV photons, this means that after the first few interactions, the original direction of the photon is still somewhat conserved. However, since the energy loss process of photons of these energies takes a large number of interactions, it is most likely that the energy lost to a large number of low-energy electrons spread isotropically in the direction perpendicular to the photon, rather than a single electron with a high energy and a large variation of angles.

The dependence of the cross section of Compton scattering on $Z$ is almost proportional, i.e. the cross section scales with the number of electrons in an atom, as one would expect. Similar to the photoelectric effect, the cross section of the Compton effect also depends on the photon energy, but only as $E^{-1}$. This causes Compton scattering to become a more likely process than the photoelectric effect above a certain threshold energy.

**Delta rays**

Delta rays, also called "knock-on electrons", are produced when a charged particle transfers enough energy to an electron in the medium to free it from its atom. If this electron then has enough energy to ionize other atoms in the medium it is called a delta ray. This process is illustrated in diagram 2.7.

Theoretically, delta rays can have energies up to the energy of the particle that produced it, minus the binding energy, however most delta rays have energies in the keV range. The main effects of delta rays are the scattering of shower photons through the liberation of atomic electrons.

**Photoelectric effect**

The photoelectric effect, where an atom absorbs a photon and emits an electron, is dominant for low energies. The resulting ion then returns to a neutral state after emitting Auger electrons or x-rays. The photoelectric effect is very dependant on the number of electrons available, and thus depends strongly on the $Z$ value of the material. The nature of this process is almost exactly the same as that of delta rays, and differs only in the energy of the electrons produced.

The dependence of the cross section on $Z$ scales with $Z^n$ with $n$ between 4 and 5, while the energy dependence of the cross section scales with $E^{-3}$. This extreme dependence on the values of $Z$ and $E$ results in the photoelectric effect being dominant in iron up to 100 keV, while in uranium it is dominant up to 700 keV.

This process mainly results in a low to medium energy photon being converted into an electron of slightly lower energy.

**Rayleigh scattering**

Rayleigh scattering is a process where the photon is elastically scattered off electrons in a medium. Since the energy of the electrons is unchanged and there are no other particles produced, as opposed to the photoelectric effect, this process has no part in the amplification of electromagnetic showers. However, since the photons are scattered isotropically, the angular distribution of the photons is changed.
Cherenkov effect

The Cherenkov effect occurs when charged particles travel faster than the phase velocity of light in a dielectric medium. The field from the passing particle displaces the electrons in the medium. When these electrons return to their equilibrium positions, the energy stored is released in the form of Cherenkov photons.

For example, take an electron travelling through water. Water has a refractive index of 1.33 at 20°C, therefore the electron will cause Cherenkov radiation if it travels at speeds larger than \( \beta > \frac{1}{n} = 0.75 \), which equates to energies larger than 261.6 keV.

The disruption of the dielectric medium has a characteristic cone shape following from the relation between the speed of the particle, and the speed of the transmission of the electric field in the medium. The opening angle of the cone \( \theta \) follows:

\[
\cos \theta = \frac{1}{n \beta},
\]

with \( n \) the refractive index of the material and \( \beta \) the velocity of the particle.

The spectrum of Cherenkov radiation follows the Frank-Tamm formula, which in the visible part of the spectrum is approximately proportional to the frequency of the radiation. Therefore, to the human eye, Cherenkov radiation appears blue. Cherenkov radiation is only of importance in calorimeters which use media which are transparent to it, which is not the case for FoCal.

Scintillation

Scintillation occurs when a particle loses energy in a medium through collisions with atomic electrons, and excites these atomic electrons to higher energy levels, losing energy in the process.

Since the energy levels are atomic, most transitions have energies up to several 10s of eV, resulting in scintillation up to the UV region. While scintillation photons have major use in particle detectors in indicating the passage of a particle, only photons from a frequency range where the prototype is transparent can be used. The prototype, which is opaque to photons in the energy range of eVs, is not sensitive to them to any significant degree.

Ionization

Moderately relativistic charged particles other than electrons mainly lose their energy through ionization. This process involves the particle losing its energy mainly through a succession of many smaller interactions, rather than one large interaction.

The main cause behind this is the difference in mass between the travelling particle and the particles in the medium\(^1\). Because of conservation of momentum, the electrons in the medium can only receive a small fraction of the particle’s momentum.

The energy loss through ionization follows the Bethe-Bloch formula:

\[
-\frac{dE}{dx} = z^2 \frac{K Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_\text{e} c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \delta \right],
\]

where \( dx \) has the dimension of g/cm\(^2\), \( K/A = 0.307 \text{gMeV/cm}^2 \) for \( A = 1 \text{g/mol} \), \( I \) is the mean excitation energy of the medium in eV and \( \delta \) is the density correction.

\(^1\) Muons are the lightest kind of particle after electrons with \( m_\mu/m_\text{e} = 206.85 \).
2.1. ELECTROMAGNETIC SHOWERS

\( T_{\text{max}} \) is the maximum energy lost to an electron in a single interaction, and it follows:

\[
T_{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2},
\]

with \( M \) the heavier particle’s mass. The mean excitation energies of all elements are tabulated by [11], but for all materials with \( Z \) equal to or higher than Argon (\( Z = 18 \)) these fall within a band with \( I = 10 \pm 1 \text{eV} \).

The density effect attempts to account for the fact that as the particle energy increases, its electric field flattens and extends. Real media, due to their polarizability, resist this, and effectively truncate this rise. At very high energies this approaches:

\[
\delta/2 \approx \ln(\hbar \omega_p/I) + \ln(\beta \gamma) - 1/2,
\]

here \( \hbar \omega_p \) is the plasma energy which follows:

\[
\hbar \omega_p = \sqrt{4\pi N_e r_e^3} = 28.816 \sqrt{\rho \langle Z/A \rangle} \text{ eV},
\]

with \( \rho \) the density of the medium in \( \text{g/cm}^3 \).

The Bethe-Bloch equation quite accurately describes the energy loss for values of \( \beta \gamma \) between 0.1 and 60. In this range, the energy loss function has a minimum at \( \beta \gamma \approx 3 \) and particles with momenta close to this minimum can stay there for quite some time, since they are not losing much energy.

Particles with these momenta are called \textit{minimum ionizing particles} or \textit{MIPs} for short. These particles, especially cosmic muons, are a reliable source of reproducible energy depositions in detectors. One of their uses in the prototype was as a source of calibration signals.

2.1.2 Critical Energy

The original definition of the critical energy (\( \epsilon_c \)) is the energy at which the average energy losses from radiation processes (mainly Bremsstrahlung) equal those from ionization. The processes depend mainly on the electron density of the medium, which follows the average \( Z \). These result in values of \( \epsilon_c \) of 95 MeV for carbon, 28 MeV for iron and 9 MeV for uranium.

An alternative definition of the critical energy by Rossi [12], followed by the Particle data group ([13] p.331) states that the critical energy is where the energy loss through ionization per radiation length is equal to the electron energy:

\[
[\Delta E]_{\text{ion}} = \left[ \frac{dE}{dx} \right]_{\text{ion}} X_0 = E.
\]

Both definitions would be equivalent if the energy loss through Bremsstrahlung would follow:

\[
\left[ \frac{dE}{dx} \right]_B = \frac{E}{X_0}.
\]

While this is the case in the limit of very high energy, reducing the contribution of ionization effects, it is only an approximation in the region of energies of \( \epsilon_c \). Using the alternative definition by Rossi, the PDG has fitted the following functions to experimental data [13] p.261:

for solids and liquids: \( \epsilon_c = \frac{610 \text{MeV}}{Z+1.24} \),

for gases: \( \epsilon_c = \frac{710 \text{MeV}}{Z+0.92} \).
These follow the tabulated values to within 4% with the largest deviations occurring for the highest $Z$ values.

The critical energy is an indication of the energy down to which particles will shower in a material. Equation 2.18 shows that showers in higher $Z$ materials continue to develop down to lower energies. This has important consequences for the development of these showers, since lower energy particles interact differently with the materials. Section 2.1.4 will go into these effects further.

### 2.1.3 Shower Anatomy

A typical electromagnetic shower starts with a multi-GeV electron or photon. The main mode of energy loss for electrons with these energies is Bremsstrahlung. Most of the photons radiated by the primary electron have relatively low energies and are absorbed through Compton scattering and the photoelectric effect.

The photons with energies in excess of 5-10MeV lose their energy through pair production. If the energy of the photon is high enough, the electron and positron produced have sufficient energy to produce more showering particles through Bremsstrahlung leading to more pair production. Due to this multiplication of showering particles an *electromagnetic cascade* is started. This is the part called the *shower core*.

As the shower develops, the average energy of the particles drops, until it is too low for shower development. The point where this occurs is called the *shower maximum*, and particles beyond this point are more likely to lose their energy to through other processes than pair production.

After reaching the shower maximum, the energy and the number of particles in the shower decreases until no significant energy deposition by the particles occurs. This part of the shower gives rise to the *shower halo*.

Since the energy deposition is caused by ionization processes, the total energy deposited closely follows the number of particles in the shower, rather than the energy of the particles themselves.

The typical interaction lengths of most processes contributing to the electromagnetic showers scale with either the nuclear charge or the electron density of the material. The nuclear charge density per unit volume and therefore the electron density are closely linked to the density of the material, since each electron is associated on average with one proton and one to one and a half neutrons:

$$\rho_{e^-} = \frac{Q_{med}}{\rho_M} \cdot \rho_{med} = (2.4\ldots3.3) \cdot 10^{23} \frac{e^-}{g} \cdot \rho_{med}$$

with $\rho_{med}$ the density of the medium, $Q_{med}$ the number of electrons per mole, and for all elements except hydrogen.

This causes that, while showers in different materials might develop differently in absolute sense, the developments are comparable to a large degree in terms of material dependent scaling constants. These scaling constants are:

- the radiation length $X_0$ for longitudinal shower development,
- and the Moliere radius $R_M$ for transverse shower development.
2.1. ELECTROMAGNETIC SHOWERS

Average Particle Energy:

Figure 2.8: The anatomy of a shower, black arrows represent photons, green electrons, red positrons. Before shower maximum, a strong multiplication of shower particles is seen, and a large number of positrons. After shower maximum, the number of particles starts to decrease.

We can convert the shower coordinates to these scaled variables:

\[
\text{longitudinal} : \quad t = \frac{x}{X_0}, \quad (2.21) \\
\text{transverse} : \quad y = \frac{R}{R_M}. \quad (2.22)
\]

Definitions of \(X_0\) and \(R_M\) will be given in section 2.1.4. After scaling the shower by these quantities, the average longitudinal energy deposition follows a gamma distribution with reasonable accuracy ([14]):

\[
\frac{dE}{dt} = E_0 b (bt)^{a-1} e^{-bt} \frac{1}{\Gamma(a)}, \quad (2.23)
\]

where \(a\) and \(b\) are dimensionless parameters scaled in such a way that the shower maximum occurs at \(T_{max} = \frac{(a-1)}{b}\). The parameters are determined by assuming \(b \approx 0.5\) and deriving \(a\). The result is a logarithmic relation between the primary energy and the depth of shower maximum:

\[
T_{max} = \ln \left( \frac{E}{E_c} \right) \begin{cases} -0.5 & \text{for electrons}, \\ +0.5 & \text{for photons}. \end{cases} \quad (2.24)
\]

According to Wigmans ([9] p.46) the transverse shower development can be described by the sum of two exponential distributions which contribute differently as a function of the shower depth. In terms of \(R_M\) the first exponential function has a decay length of 0.2 \(R_M\), this is the core term. The second function has a decay length of 1.5 \(R_M\), and is the halo.

Before shower maximum, the shower core is the dominant component of the lateral shower distribution. The core becomes less significant with increasing depth, and at greater depths than shower maximum the halo dominates the lateral distribution.
2.1.4 Material Effects on Shower Development

Different materials have different effects on the composition and propagation of showers. One of the causes of the differences in shower composition is that pair production is the dominant mode of interaction down to much lower energies for higher $Z$ materials.

In this section the differences caused by the differences in interaction energy scales and relative cross sections is examined.

Radiation Length

The radiation length ($X_0$) is defined as the distance in a material in which a high energy (GeV/c range) electron or positron will lose on average $1 - e^{-1} = 63.2\%$ of its energy. For example, on average a 100 GeV/c electron traversing 88.97 mm of aluminium will lose the same amount of energy traversing 5.612 mm of lead.

By describing the absorbing properties of an electromagnetic calorimeter in terms of radiation lengths, material-dependant effects can be ignored to first approximation.

The radiation length of a chemical compound or a finely grained mixture of different elements is calculated through the addition of interaction probabilities. Since the interaction probability $P_i$ in a material is the inverse of the radiation length, the contributions of the radiation lengths are added in inverse:

$$P_{tot} = \sum_i P_i = \sum_i l_i / X_i, \quad (2.25)$$

where $l_i$ is the length and $X_i$ the radiation length of material $i$ in the compound. This equation can be rewritten, using the constraint that the distributions of the different materials in the lateral directions are isotropic, as:

$$X_{tot}/V_{tot} = \left( \sum_i V_i X_i \right)^{-1}. \quad (2.26)$$

Take for example a detector consisting of alternating 3 mm slabs of tungsten ($X_0 = 3.504\) and 1 mm slabs of silicon ($X_0 = 93.7\) mm). This results in the following expression for the radiation length:

$$X_0 = (0.75/3.504 + 0.25/93.7)^{-1} = 4.614 \text{ mm}, \quad (2.27)$$

which differs less than 2% from the radiation length of 3 mm of tungsten and 1 mm of vacuum:

$$X_0 = (0.75/3.504 + 0.25/\infty)^{-1} = 4.672 \text{ mm}, \quad (2.28)$$

showing the large contribution of the tungsten to the total radiation length.

Moliere Radius

While this quantity does not have the same rigorous physics definition as the radiation length, it does have utility similar to the radiation length in calorimetric applications.

The Moliere radius $R_M$ depends on $X_0$ and $c$ as:

$$R_M = E_s X_0 / \epsilon_c, \quad (2.29)$$
where the scale energy \( E_s \), defined as \( m_e c^2 \sqrt{4\pi/\alpha} \), is equal to 21.2 MeV.

The Moliere radius is used to describe the lateral development scale of showers. On average 90\% of the energy contained in an electromagnetic shower is deposited within 1 \( R_M \) radius around the axis of the shower, and 99\% within 3.5 \( R_M \). This is useful because a calorimeter where the showers are constrained to smaller volumes has a much larger capacity for separating them at smaller distances.

The Moliere radius of compound substances is calculated in the same manner as their radiation length. The contributions per volume are added to create a "compound" Moliere radius. This means that creating a compound by adding an element that is "bad" at containing showers to an element that is "good" at it, is effectively "diluting" the effect of the "good" element.

The \( Z \)-dependence of \( R_M \) is much less pronounced than it is in \( X_0 \). \( X_0 \) scales with \( A/Z^2 \) to first order, and for most elements \( A/Z \) lies within a rather narrow range. From this it follows that \( X_0 \) in units of g cm\(^{-2}\) scales with \( Z^{-1} \) to first order. That same scaling with \( Z^{-1} \) holds for \( \epsilon_e \). Since \( R_M \) is the ratio between \( X_0 \) and \( \epsilon_e \) both dependences on \( Z \) cancel out to first order.

As an example, copper, with a density of 8.96 g/cm\(^3\), and lead, with a density of 11.35 g/cm\(^3\), are very similar in their densities. The strong dependence of the radiation length on \( Z \) is reflected in their respective radiation lengths, 14.3 mm for copper and 5.6 mm for lead. However, their values of \( R_M \) reflect their similarities, 15.2 mm for copper and 16.0 mm for lead. Therefore, while the electromagnetic showers take more than twice as much depth to develop to the same extent in copper as in lead, their lateral dimensions will be the same to first order.

### 2.1.5 Longitudinal Shower Profiles

As explained in 2.1.3, the development of showers are to a large degree comparable when viewed in terms of \( X_0 \) and \( R_M \). There are, however, some differences between materials.

The main differences are:

- with increasing \( Z \), the depth at which the shower is at its highest intensity increases,
- and, with increasing \( Z \), the shower decays more slowly beyond its maximum.

This results in higher \( Z \) absorbers requiring a larger depth of \( X_0 \) to contain the same energy of showers. However, this mostly does not result in larger absolute depth of absorbers because of the much smaller radiation lengths for the higher \( Z \) materials.

The depth of material required to contain a shower scales with the logarithm of the energy of the shower. This can be inferred from the fact that a photon travels on average \( 9/7 X_0 \) before converting into an electron-positron pair of each half its energy. Because of this, an increase by that amount of depth of the detector will contain the same fraction of energy on average. For the same reason the depth at which the shower is at its maximum development also scales with the logarithm of its energy.

The differences between the shower developments in low-\( Z \) and high-\( Z \) materials are caused by the different contributions of the processes which give rise to the shower and their different dependences on energy. Since pair production continues down to much lower energies for higher-\( Z \) materials than for lower-\( Z \) materials, the multiplication of the number of particles will continue down to much lower energies as well.
The net result of this is that since the shower will continue to multiply down to much lower energies in higher-Z materials, the shower maximum will occur at greater depths in higher-Z materials. This also means that in higher-Z materials showers deposit a smaller fraction of their energy per radiation length unit depth.

After shower maximum the particles in the shower will produce less than one particle per interaction on average, and the lower the energy of the particles, the more likely it is that they will be absorbed completely by the medium. For higher-Z materials the average number of particles produced per interaction drops off more slowly than for lower-Z materials, resulting in the shower propagating deeper into the material.

### 2.1.6 Transverse Shower Profiles

The shower profile perpendicular to the direction of travel is caused by a number of processes. Bremsstrahlung and pair production are of importance at high energies, Compton scattering at intermediate energies and the photoelectric effect and multiple scattering at low energies. All types of effects cause particles to move away from the main shower axis but they have different contributions which depend on the stage of its the shower is in.

Since the particles that have the lowest energies are the ones that are deflected the most from the original shower axis, due to their lower momentum, the way they interact with the material has a lot of influence on the transverse shower profile.

One cause of the differences in transverse shower profiles is the difference in the mean free path of electrons in the MeV range. This goes from 1.6-1.8 $R_M$ for Al-Cu to 1.0 $R_M$ for Pb. This means that the particles which are deflected significantly from the shower axis travel further before interacting in low-Z materials, which results in a wider transverse distribution.

Another cause is that the absorption of low energy photons requires more interactions in lower-Z materials. The energies at which the photo-electric effect can absorb the products of Compton scattering are lower for lower-Z materials. Therefore, more scatterings are required to bring down the energy, and further travel into the material by low energy photons is the result.

### 2.1.7 Fluctuations in Shower Development

The main starting point of calorimeter design is the average shower development. While as a starting point this is sufficient, at least as much attention needs to be paid to the fluctuations around this average.

High energy particles, which are those in the starting stages of the shower, have an equal probability of interacting with the material each unit of length. This gives rise to an exponential distribution of the depth between interactions:

$$\Delta = X_0 e^{-x/X_0}.$$ (2.30)

This discrete nature of the energy process results in a Poissonian distribution for the number of interactions after a certain depth of detector material, shown in table 2.1.

Since the number of interactions per unit depth has this distribution, the development of each shower at has a certain variation the same depth. This is by itself a source of measurement uncertainty.
Table 2.1: the probability of different numbers of interactions having occurred as a function of the depth of material traversed.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Number of interactions</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 2 4 6 8 10</td>
<td></td>
</tr>
<tr>
<td>X/X₀</td>
<td>0.135 0.271 0.090 0.012 0.001 &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.018 0.147 0.195 0.104 0.030 0.005</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.002 0.045 0.134 0.161 0.103 0.041</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>&lt; 0.001 0.011 0.057 0.122 0.140 0.099</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>&lt; 0.001 0.002 0.019 0.063 0.113 0.125</td>
<td></td>
</tr>
</tbody>
</table>

The number of interactions before a shower reaches shower maximum also varies between showers. Combining all these effects results in a large spread in the depths at which shower maximum is observed, and also in the development of the shower at different depths.

The average number of interactions required to reach the shower maximum scales with the logarithm of the energy. Because the absolute width of the Poissonian distribution increases with increasing mean, the spread in the depths at which the shower maximum occurs will only increase as a function of the energy.

As no detector can be of infinite size, a fraction of energy will escape unmeasured from the detector. The fraction of energy that escapes depends on the evolution of the shower. If a shower develops earlier, less escapes, if it develops later, more escapes. This is a source of measurement uncertainty which increases with energy, even though the relative statistical fluctuations decrease with energy.

2.2 Principles behind Calorimeter Functionality

A calorimeter needs to absorb the energy of a particle and convert the deposited energy to a signal which can be processed. Therefore a calorimeter should have these two main properties at least:

- it should be able to contain most of the shower energy,
- and it should have a material which gives a signal if energy is deposited.

The section of the calorimeter responsible for the interaction is called the absorber, while the section from which the deposited energy can be obtained is called the sensor. All elementary particle calorimeters contain these two basic elements, while the details of their make-up and construction might vary between implementations.

The depth of absorber should be several radiation lengths, if the calorimeter needs to be able to contain the energy of particles with energies of several GeV. Analysis of the signals is significantly simplified if it is proportional to the energy deposited. Therefore the linearity of the active material is also of interest.
2.2.1 Differences between Signals of Homogeneous vs. Sampling Calorimeters

The distribution of the sensor and absorber materials in the calorimeter gives the main separation in designs. Designs where the same material functions as both sensor and absorber are called homogeneous calorimeters, after their homogeneous construction. Designs where the absorber and active material are physically separate, are called sampling calorimeters. This is due to the fact that they do not perform a continuous measurement of the shower, but sample it at a number of locations. This sampling generally leads to worse energy resolution when compared to homogeneous calorimeters.

Homogeneous calorimeters, being constructed out of a single material place multiple demands on this material. Because the material needs to be efficient at both stopping high energy particles, while at the same time converting the energy deposited by these particles into measurable signals, the number of materials suitable for both goals at the same time is very limited.

An example of a homogeneous calorimeter is PHOS, the Photon Spectrometer in the ALICE experiment at CERN. PHOS is constructed from very high density Lead Tungstate crystals, where the crystal functions as both the absorber and scintillator\(^2\).

Sampling calorimeters have the advantage of being constructed out of separate sensor and absorber sections, where each section is tailored to its own function. This allows for a wider selection of materials and lower costs. The absorber sections are made out of materials with very short radiation lengths in order to most efficiently stop the particles. The absorber materials usually have very high densities, such as metals like lead or tungsten, or even uranium.

The active sections are made of materials chosen both for their efficiency of converting the deposited energy into signals and for the ease of extraction of these signals. Some examples of different active media:

- a gas, such as Argon (with a small addition of CF\(_4\) and butane) in the MICROMEGAS sensors proposed for the CALICE project [15] p.5,
- a liquid, such as the Argon in ATLAS’s calorimeter [16] p.110,
- or a solid, such as the Polystyrene in LHCb’s ECAL [17] p.98.

In the case of scintillation or Cherenkov detectors, the signals are photons which are converted to electric signals in photomultiplier tubes. In ATLAS’s calorimeter the signals are charges which are amplified to give electric signals of a useful amplitude. The electric signals are then passed on for recording and analysis.

The relative advantages of each design should be quite apparent. While the homogeneous calorimeter takes its signal from the entire detector volume, the sampling calorimeter takes its signal from only the small fraction of active material.

The signals from a sampling calorimeter are therefore much smaller and have much greater fluctuations than those from a homogeneous calorimeter. On the other hand, the sampling calorimeter has absorber and active materials each tailored to their own tasks. Given a similar cost and/or size, a sampling calorimeter can outperform a homogeneous calorimeter with respect to some of its properties.

\(^2\)PHOS is very similar to CMS’s ECAL in construction and functionality.
2.2. PRINCIPLES BEHIND CALORIMETER FUNCTIONALITY

2.2.2 Calorimeter Response

The response $R$ of a calorimeter is defined here as: the average calorimeter signal divided by the deposited energy. Since the signal $S$ produced can be different for the same amount of deposited energy, we talk about the average signal:

$$R(E) = \overline{S}(E)/E.$$

(2.31)

So a detector for which the signal is proportional to the energy of the particle causing the signal has a response which does not depend on the energy. While this is the ideal result for a calorimeter, there are a number of effects which will influence the response of the calorimeter in such a way that it will no longer be proportional. The way in which the proportionality of the signal depends on the energy is called the linearity of the detector.

Any sensor will generate signals in the absence of a stimulus, this is called noise and will produce a limit on the accuracy of the detector even if all other components operate perfectly. The effect of the noise on the response of the calorimeter is most pronounced when the signals have the smallest amplitude, since the noise is independent of the signals.

Saturation of the sensor elements is another source of alinearity in the detector. It is defined as the effects that cause the signal of the sensor elements to no longer increase proportionally.

Saturation can be caused by sensor or readout chain elements whose response drops off with increasing energy. Another cause of saturation can be sensor or readout chain elements which require a recovery time after giving off a signal. This will result in a reduction or loss of signals with increasing stimulus rate or magnitude.

Shower leakage can also be a source of alinearity. Leakage is the propagation of particles into regions of the calorimeter where they no longer cause showers or signals. It can be separated into two categories, transverse and longitudinal.

Transverse leakage is caused by the propagation of shower particles in directions perpendicular to the primary vector. They then "escape" the calorimeter and no longer contribute to signals. Transverse leakage is usually caused by restrictions on the size of the calorimeter.

Transverse leakage is of importance for particles which hit the edge of sensitive elements of the detector. Part of the shower caused by these particles will not be registered and cause a reduction in the response of the detector for these regions.

This form of leakage is mostly energy independent, since the transverse scale of a shower is defined by $R_M$, which does not significantly depend on the energy of the shower for a large range of energies.

Longitudinal leakage is caused by the finite depth of the calorimeter. Statistically, a particle can travel an infinite depth of the calorimeter before interacting. So, to completely absorb the energy of all particles of a given energy, a calorimeter of infinite depth is required. Obviously, this is a physical impossibility, and therefore any calorimeter will not be able to measure a fraction of the energy.

As the energy of the shower increases, the fraction of energy deposited deeper in the calorimeter increases, and a larger fraction of the shower energy leaks out of the calorimeter. This causes a reduction in the response of the calorimeter for higher energies.

**Sampling Calorimeters**

The main defining property of the response of a sampling calorimeter is the sampling fraction $f_{samp}$. The sampling fraction is defined as the fraction of the energy deposited in the active
material of the calorimeter compared to the total energy loss across the whole detector by a minimum ionizing particle:

$$f_{samp} = \frac{\Delta E_{active}}{\Delta E_{total}} .$$

While the calculation of this property is rather straightforward, its connection to experimental data is not. First, for each material only a very specific value of $\beta \gamma$ will give the minimum energy loss for particles. This value differs between elements, but is in the range of $3 \ldots 4$. For electrons this means momenta in the range $1.5-2 \text{MeV}/c$.

While the dependence of the energy loss for higher values of $\beta \gamma$ is not very strong, it increases sharply for lower values. The particles making up the shower have a large spread of energies, mostly below this MIP value. This causes the energy deposition to rise above the value expected for minimum ionizing particles.

Also, the active materials in the calorimeter can respond differently to the particles making up a shower as compared to a minimum ionizing particle. Since a large part of the initial shower development is the production of large numbers of low energy (< 1 MeV) Bremsstrahlung photons, their interactions with the detector are very important.

The dominant interaction for photons of these energies is the photo-electric effect whose cross-section scales with $Z^\alpha$ with $\alpha$ between 4 and 5. It follows that the photons produced in the shower are much more likely to interact with the absorber layers, than the active layers. For example, the photo-electric cross section for lead ($Z = 82$) is larger by a factor of at least 20000 than the photo-electric cross section of silicon ($Z = 14$).

The electrons produced through the photo-electric effect have very short interaction lengths in the absorber material, much shorter than the typical absorber layer thicknesses (0.67 mm for 1 MeV $e^-$ in lead). This means that only photoelectrons produced very close to the boundaries between the layers will contribute to the signal.

This will reduce the relative response, called the $\gamma/mip$ ratio, which relates the average signal from photons compared to those from minimum ionizing particles. This ratio makes the response of the calorimeter even smaller than would be expected based on the sampling fraction alone.

Another important consequence is that sampling a very small fraction of the shower emphasizes the local fluctuations in the showers. With the prototype detector the sampling layers are very thin, which only increases the observed fluctuations.

**Particle Counting Calorimeters**

Because the energy at which the shower development stops does not depend on the shower energy, but only on the material properties, the number of particles in a shower depositing energy is approximately proportional to the energy of the shower.

This gives a new approach in measuring the energy of the shower: particle counting calorimetry. This is different from ordinary sampling calorimetry in that it does not sample the energy deposition of the particle, but that it samples the shower development by counting the number of particles.

With particles of energies of hundreds of GeV and critical energies around several MeV, the number of particles around shower maximum should range into the several tens of thousands. Combined with the lateral size of the shower defined by the Moliere radius which is on the order of centimetres this results in particle fluxes of at least $10^4 \text{cm}^2$. Even higher numbers can be expected in the core of the shower due to the radial shower profile. Due to the nature
of showers, local fluctuations in shower development will increase these numbers even further. Because the concept of particle counting relies entirely on the accurate measurement of the number of particles in the shower, the granularity of the detector should be adequate as well.

This means that the sensitive elements of the calorimeter should at most be of the size $10^{-4}\text{cm}^2$, and preferably much smaller. Separate elements, each with their own amplifiers, connections, and other logistics are technically not feasible at this granularity.

The advantage of the particle counting method is that the calorimeter only needs to record whether or not a particle passed through a sensitive element, and therefore a digital solution with only 1 bit per element can suffice. Integrated circuitry is a solution, as it allows the in-sensor amplification and digitization of the received signals. The trade-off is the increased power consumption in the sensors themselves, which might increase noise.

The sensor selected for use in the prototype is the MIMOSA Phase 2 produced by IPHC in Strasbourg. This sensor has pixels of $30\times30\mu\text{m}^2$ and a sensitive layer $15\mu\text{m}$ thick and a resolution of 1 bit per pixel.

### 2.2.3 Fluctuations of Signals in Sampling Calorimetry

The resolution of a calorimeter $r(E)$, which is the power to distinguish between two signals of different energies, is defined as the relative magnitude of the spread of the signals:

$$r(E) = \frac{\sigma(E)}{E}. \quad (2.33)$$

The energy resolution in a sampling calorimeter is mainly determined by the following factors:

- Shower fluctuations,
- Sampling fraction,
- and Sampling frequency.

Shower fluctuations contribute to the resolution because the shower is sampled only at certain points in its development. Because the energy deposition is approximately proportional to the number of particles, this effect contributes about the same to the effective resolution of the calorimeter whether it is counting particles or measuring energy deposition.

Since the observed fluctuations are Poissonian in nature, their contribution to the energy resolution will follow $N^{-1/2}$. And because the number of particles is approximately proportional to the energy of the shower, this gives the following expression for the resolution:

$$r(E) = \frac{\sigma}{E_{\text{samp}}} \propto \frac{1}{\sqrt{E}}. \quad (2.34)$$

As explained before, a large fraction of the energy in showers is deposited by particles which travel only small distances from where they are produced in absorbers. The main approach in improving the resolution is having more of these particles reaching the sensitive layers.

Having more particles reach the sensitive layers is achieved by increasing the number of sensitive layers. If the thickness of a layer is $d$, and the total depth of the sensitive layers
in the calorimeter is \( D \), then the total number of times the shower is sampled goes as \( D/d \). This gives the following expression for the resolution:

\[
\frac{\sigma}{E} \propto \sqrt{\frac{d}{D}} \cdot \sqrt{\frac{1}{E}}.
\]

(2.35)

What needs to be remembered is that the sensitive layers in the calorimeter come with logistics such as cables, support structures and/or cooling elements. While these do not contribute to sampling the particles in the shower, their fraction in the calorimeter scales linearly with the sampling frequency. Their main effect on the performance of the calorimeter is the increase of \( R_M \) since they effectively "dilute" the absorber material in the calorimeter volume. At the same time, the total depth of the calorimeter in \( X_0 \) will need to be kept the same to have it be effective for the same ranges of particle energies.

The sensitive layers of the calorimeter will also need to have sufficient thickness to generate signals of large enough magnitude. At the same time the layers need to be thin enough to not "dilute" the absorber sections of the calorimeter and thereby increasing \( R_M \) and therefore the shower size.

The energy resolution of a calorimeter can be broken up into these three main contributing factors:

- a constant term, caused by the construction of the calorimeter itself,
- a stochastic term, caused by the fluctuations in the development of the shower,
- and a noise term, caused by the noise of the sensor elements in the calorimeter.

The constant term \( (a) \) incorporates effects such as calorimeter non-uniformity. These effects will be present at all energies and contribute the same amount to calorimeter performance, they therefore have a linear dependence on \( E \).

The stochastic term \( (b) \) accounts for the fluctuations in shower development, the number of particles generated and the energy they deposit in the calorimeter’s sensors. Since these processes follow a Poissonian distribution, they have a dependence on \( \sqrt{E} \).

The noise term \( (c) \) contains the effects of noise collected by the sensors in the calorimeter. Since the noise does not depend on the energy of the showers, this will be independent of \( E \). Since the sources of fluctuations are uncorrelated they are added quadratically:

\[
\sigma(E) = \sqrt{a^2 E^2 + b^2 E + c^2},
\]

(2.36)

which results in the following expression which the resolution is expected to follow:

\[
r(E) = \sqrt{\frac{a^2 + b^2}{E} + \frac{c^2}{E^2}}.
\]

(2.37)

The main requirements that can be taken from the preceding considerations are:

- the highest possible sampling fraction, to maximize signals received,
- the highest possible sampling frequency, to optimize resolution,
- the lowest possible sampling fraction, to minimize \( R_M \),
- and the lowest possible sampling frequency, to reduce logistics required thereby reducing \( R_M \).

These requirements are in conflict, and any sampling calorimeter requires a delicate balance between these requirements.
2.2.4 Calorimeter Calibration

There are two types of calibration that have to be done with a calorimeter. The first is absolute calibration, the second is relative calibration.

Absolute calibration relates signals to particle energy. This is done by sending particles of a known energy into a detector and measuring the signal. From this the signal as a function of the particle species and energy will be calculated. Similarly, the energy resolution and linearity are derived from the same measurements.

Relative calibration corrects the differences in responses of sensitive elements of the detector, so that after relative calibration the same amount of energy gives the same signal in all layers. One type of relative calibration used for the prototype is the minimum ionizing particle method. It uses the signals from minimum ionizing particles to determine the relative responses of the different sensor elements. Another method of relative calibration minimizes the observed differences and fluctuations in sensor response, thereby improving the consistency of response, resulting in an improved detector energy resolution.

Minimum ionizing particles do not create showers in matter, and the average amount of energy deposited is predictable. Therefore, the responses of all elements in the detector can be adjusted until they give the same average signal for the same average energy deposition. The most readily available type of minimum ionizing particle are atmospheric muons produced through the interaction of cosmic rays with the Earth’s atmosphere. These muons give a very predictable energy deposition and are available without the need for any accelerators and other complex equipment.

The calibration methods used in this work are explained in more detail in section 4.2.3.

2.3 Current EM Calorimeter Designs

To determine whether technologies being used at experiments already have the capabilities necessary for the proposed forward calorimeter, the following devices being used at the experiments at the forefront of high energy particle physics research will be compared:

- ATLAS’s Forward Calorimeters (FCal), a detector using copper and tungsten as absorber and argon as the sampling material,
- CMS’s ECAL, which is constructed from very dense lead tungstate crystals,
- ALICE’s EMCal is a lead-scintillator calorimeter which is read out using wavelength-shifting optical fibres in a ”shashlik” geometry,
- LHCb’s ECAL, which also uses a ”shashlik” geometry,
- and the electromagnetic calorimeter used by the PAMELA experiment to measure cosmic rays on a satellite in earth orbit.

2.3.1 FCal at ATLAS

One of the foremost objectives of ATLAS is to investigate the Higgs boson, a missing piece of the Standard Model. The Higgs mechanism, which includes the Higgs boson, is hypothesized to give mass to elementary particles. This gives rise to the differences between the weak and electromagnetic forces in turn by giving the W and Z bosons mass while leaving the photon
CHAPTER 2. PRINCIPLES OF CALORIMETRY

Figure 2.9: A front view of ATLAS’s FCAL (left), and a single liquid argon unit cell (right). The PEEK fibres (in red in the schematic), which maintain the distance between the inner and outer electrodes can be seen sticking out at the detector surface. The charge deposited in the liquid Ar in this gap is a measure of the energy. Taken from [19].

massless. The main physics requirement of the forward calorimeters at ATLAS is to measure missing transverse energy of particles and to perform jet reconstruction.

ATLAS’s forward calorimeters ([16] p.129-133) are split into three 45 cm deep modules, one forward electromagnetic calorimeter, and 2 rear hadronic calorimeters. The electromagnetic calorimeters use copper as their absorber, for reasons of resolution and heat removal. The hadronic calorimeters use tungsten as the absorber material. Only the electromagnetic calorimeter is of interest for the purposes of this thesis, so when FCal is referenced, the electromagnetic part (FCal1) is implied.

An FCal module is a stack of plates of absorber, into which 12260 holes have been drilled parallel to the beam axis, into which the sampling electrodes have been inserted [18]. The sampling electrodes consist of a concentric copper rod and tube which are kept physically separated by a radiation resistant plastic sheath. The electromagnetic showers are sampled by 250µm of liquid argon which are directly read out by the rods.

The FCal has a coverage of $3.1 < |\eta| < 4.9$ and a granularity of $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$. The total depth of FCal is 27.6 radiation lengths, while the Molière radius is slightly larger than twice the distance between two sampling electrodes (19 mm).

The energy resolution of the first module of FCal was measured to be $28.5\% / \sqrt{E/\text{GeV}} \oplus 3.5\%$. These results were obtained during two FCal stand-alone testbeam periods at SPS, once in 1998 and once in 2003 [20, 21].

2.3.2 Electromagnetic Calorimeters at CMS

The main goals of CMS are to explore physics at the TeV scale, to study the properties of the recently found Higgs boson, to look for evidence of physics beyond the standard model, such as supersymmetry, or extra dimensions and to study aspects of heavy ion collisions. These
goals are similar to those of the ATLAS experiment, on the other side of the LHC. One of the main physics requirements in the design of CMS’s electromagnetic calorimeter was its capability to detect the decay of the postulated Higgs boson to two photons. A homogeneous crystal calorimeter enhances this capability through the good energy resolution it provides.

The electromagnetic calorimeter at CMS consists of 61200 lead tungstate crystals in the barrel section and 7324 crystals in each endcap [22] p. 90-121. Lead tungstate is a very high density (8.28 g/cm³) material which functions both as the absorber and the sensor at the same time.

Lead tungstate has a short radiation length of 0.89 cm and a Moliere radius of 2.2 cm. With this material a finely grained calorimeter can be achieved. However, the signal produced is rather small at 4.5 photoelectrons per MeV deposited at 18 °C, with 80 % of the light being generated within 25 ns. The photons emitted by the crystals are received by avalanche photodiodes in the barrel section and vacuum phototriodes in the endcaps. These photons are guided to the collection points by being reflected along the inside of the crystals. This internal reflection is achieved by the very high index of refraction of the crystals (n = 2.29) and polishing the crystals after they have been machined into their appropriate shapes.

CMS’s electromagnetic calorimeter barrel section covers the range of |η| < 1.47. It is divided into 360 sections in the radial direction and 2 × 85 divisions in pseudorapidity. The crystals are shaped such that there are no cracks in the calorimeter geometry while keeping a constant coverage in η − φ of 0.0174 × 0.0174. The crystal length is 230 mm corresponding to 25.8 radiation lengths in depth.

CMS’s endcap electromagnetic calorimeters cover the range of 1.47 < |η| < 3.0. The crystals in the endcaps have a length of 220 mm, which amounts to 24.7 radiation lengths of depth. The layout of the endcaps is chosen such that the crystal are pointing to a focus 1300 mm beyond the interaction point, allowing for off-pointing angles of 2 to 8 degrees.

Since the signal produced by the signal and the amplification of the avalanche diodes has a temperature dependence of −3.6±0.4%/°C, the operating temperature of CMS’s electromagnetic calorimeters is kept at 18 °C. This is achieved through a cooling system which runs water through a thermal screen which is placed in front of the crystals, decoupling them from the silicon tracker, and through pipes embedded in the aluminium grid.

The energy resolution of a fully equipped barrel supermodule was tested in the CERN H4 beam in 2004 with electron beams of energies from 20 GeV/c to 250 GeV/c. The energy resolution obtained using only electrons in a 4× 4 mm² was found to follow $2.8%/\sqrt{E/\text{GeV}} \oplus 0.12%/\text{E/GeV} \oplus 0.30%$ [24].

The PHOS detector at ALICE has a similar construction to that of the electromagnetic calorimeters at CMS. PHOS provides limited coverage in the central-rapidity domain and is used to provide data to test the thermal and dynamical properties of the initial state of the collision.
2.3.3 ALICE’s EMCal

The objective of ALICE is to explore the physics of jet quenching in heavy-ion collisions at the LHC. The geometry of EMCal was chosen to match the physics requirements of the goals of high-$p_t$ research [7] p.92-102. EMCal is located adjacent to ALICE’s magnet coil at a radius of $\approx 4.5$ m from the beam line, and is located approximately opposite in azimuth to PHOS, ALICE’s high precision photon spectrometer. The physical dimensions and mass of EMCal are constrained by the maximum weight that can be supported by the L3 magnet and the available free space.

EMCal is constructed from 12288 towers which are approximately projective in $\eta$ and $\phi$ relative to the interaction vertex. Combined with coverage in rapidity of $|\eta| < 0.7$, and a radial coverage of $\Delta \phi = 107^\circ$ gives EMCal a granularity of $\Delta \eta \times \Delta \phi = 0.0143 \times 0.0143$.

ALICE’s calorimeter is a sampling calorimeter with 76 alternating layers of 1.44 mm lead absorber and 77 layers of 1.76 mm polystyrene base scintillator. This gives it a depth of 20.1 radiation lengths and an effective Moliere radius of of 3.2 cm. The scintillation photons produced in each tower module are captured by 36 wavelength-shifting fibres which are arranged longitudinally. The fibres terminate in a mirror at the front of the tower, reflecting the light back to a Hamamatsu S8664-55 avalanche photodiode at the tower’s rear. Testbeam measurements have indicated the signal to be approximately 5 photo-electrons per MeV.

Based on the annual yield of photons and pions at high transverse momentum, the full scale energy range of EMCAL was chosen to be 250 GeV. This gives a maximum resolving power of 250 MeV given a 10 bit DAC. Simulations and test-beam measurements have given that the EMCal’s final resolution will not be worse than $10%/\sqrt{E}$.

2.3.4 ECAL at LHCb

LHCb is dedicated to the exploration of heavy flavour physics at the LHC. Its main goal is to look for signals which hint to new physics through the exploration of CP violation and rare decays of beauty and charm hadrons. ECAL assists in this by selection transverse energy hadron, electron and photon candidates for the first level trigger. It also identifies hadrons, electrons and photons as well as measuring their energy. The requirement of good background rejection, while retaining reasonable efficiency for B decays puts significant constraints on the performance of ECAL with regards to resolution and shower separation.

ECAL is located 12.5 meters from the interaction point and occupies a region with $0.025 < \theta_x < 0.3$ and $0.025 < \theta_y < 0.25$. Since the hit density is strongly dependant on the angle to the interaction point, ECAL is divided into an inner section with $40.4 \times 40.4 \text{ mm}^2$ cells, a
middle section with $60.6 \times 60.6 \text{mm}^2$ cells and an outer section with $121.2 \times 121.2 \text{mm}^2$ cells [17] p.103.

ECAL uses a "shashlik" construction which is similar to that of ALICE’s EMCal. It is constructed using alternating layers of 2 mm of lead absorber, 120 µm of TYVEK paper reflective material and 4 mm thick scintillator tiles which are mainly polystyrene. In depth, 66 such layers are combined into a 42 cm thick stack with $R_M$ of 3.5 cm and 25 $X_0$ total depth. The stack is wrapped in black paper and then sealed inside 100 µm steel foil to ensure light-tightness. The light from the scintillator layers is carried by 1.2 mm diameter wavelength-shifting Kuraray fibres to Hamamatsu R7899-20 phototubes, where it is converted to electric signals.

The energy resolution aimed for in the design was to be at least $10\% / \sqrt{E} \oplus 1\%$ (with E in GeV). The results from beamtests have indicated that the energy resolutions obtained were measured to be 8.5 to 9.5%/$\sqrt{E} \oplus 0.8\%$ (with E in GeV), exceeding the design specifications.

Figure 2.12: Three LHCb ECAL modules. The difference in cell size from inner section modules (top), middle section modules (bottom right) and outer section modules (bottom left) is clearly visible by the number of wavelength shifting fibres. Taken from [25] p.4 fig.2.

2.3.5 PAMELA

PAMELA [26] is an experiment dedicated to the measurement of cosmic rays, and especially their antimatter component. It is mounted on a Russian Resurs-DK1 earth observation satellite which is in a low earth orbit between 350 and 610 km. PAMELA’s calorimeter has a number of properties which make it similar to the proposed FoCal calorimeter, and the choices made in its design are therefore very important to examine.

PAMELA’s calorimeter is a sampling calorimeter which uses silicon sensors and tungsten absorber plates. There are 22 layers which contain one 2.6 mm layer of tungsten each, amounting to a total depth of 16.3 radiation lengths.

The absorbers are sandwiched between two PCB’s on which the sensor elements, front end electronics and ADC’s are mounted. This detector architecture results in a Moliere radius of 2.04 cm [27] p. 13.

The silicon sensors have a surface area of $8 \times 8 \text{cm}^2$ and are arranged in a 3 by 3 matrix. These sensors are subdivided into 32 readout strips 2.4 mm wide which are then connected to the matching strip on the neighbouring sensor, resulting in a silicon strip detector with 24 cm long strips. The strips on longitudinally adjacent sensors are at right angles, thereby giving an accurate measurement of the location of the particles.

The calorimeter front-end is constructed around the CR1.4P ASIC. This chip can support up to 16 channels, meaning that 6 chips are needed per layer of sensors. The outputs of a single layer of CR1.4P chips are multiplexed into a single 16-bit ADC. The complete detector contains 44 ADC’s whose data is processed by 4 DSP boards which send the data across a
serial link to the data acquisition system.

The constant term of PAMELA’s energy resolution has been measured to be \( \approx 5.5\% \) for electromagnetic showers.

### 2.3.6 Comparison of Calorimeter Performance

The high pseudorapidity region where FoCal is expected to work, will require an ability to separate electromagnetic showers which are located no more than 1 cm apart to identify high energy neutral pions. ATLAS’s FCal, CMS’s endcaps or LHCb’s ECAL cannot separate close-by showers well enough to allow a satisfactory discrimination of \( \pi^0 \) from direct photons at high energy due to their insufficient granularity. While the very high positional and angular resolution can be achieved through the use of high granularity silicon strip layers such those used in PAMELA’s calorimeter, another option is to evolve PAMELA’s design and use very high granularity silicon pixel sensors.

Table 2.2: A comparison of the material composition, depth, Moliere radius, granularity and resolution of the electromagnetic calorimeters at ATLAS, CMS, ALICE, LHCb and PAMELA.

<table>
<thead>
<tr>
<th>Materials used</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ALICE</th>
<th>LHCb</th>
<th>PAMELA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Depth ((X_0))</td>
<td>Cu-LAr</td>
<td>PbWO(_4)</td>
<td>Pb-PS</td>
<td>Pb-PS</td>
<td>W-Si</td>
</tr>
<tr>
<td>27.6</td>
<td>25.8</td>
<td>20.1</td>
<td>25</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>(R_M) (cm)</td>
<td>1.9</td>
<td>2.2</td>
<td>3.2</td>
<td>3.5</td>
<td>2.02</td>
</tr>
<tr>
<td>Granularity (cm)</td>
<td>3.0</td>
<td>2.2</td>
<td>6.0</td>
<td>2.02</td>
<td>0.24</td>
</tr>
<tr>
<td>Designed Resolution ((%/\sqrt{E}))</td>
<td>28.5</td>
<td>2.8</td>
<td>10</td>
<td>10</td>
<td>5.5</td>
</tr>
</tbody>
</table>

While the energy resolution is an important requirement in the design of FoCal, it is of secondary importance compared to the positional resolution. This is caused by the differences in the contribution to the total error of from the accuracies in measurement of the energy and angle. Because the \( p_T \) of a particle can be expressed as a function of its momentum \( p \) and angle \( \theta \) in the following way:

\[
p_T = p \cdot \sin \theta , \tag{2.38}
\]

the error in \( p_T \) of the particle depends in the following way on the experimental observables:

\[
\left( \frac{\sigma_{p_T}}{p_T} \right)^2 = \left( \frac{\sigma_p}{p} \right)^2 + \left( \frac{\sigma_\theta}{\tan \theta} \right)^2. \tag{2.39}
\]

Due to the very strong dependence on the angle of the \(1/\tan \theta\) term in the region \( \theta \approx 0 \), the contribution of the error in the measurement of the angle is greatly enhanced. For example, take a particle with \( p_T = 5 \text{ GeV} \) at \( \eta = 4 \), which correspond to \( p = 135 \text{ GeV}/c \) and \( \theta = 0.037 \). In determining the error on the measurement on \( p_T \), a resolution on the energy measurement of \( 20\%/\sqrt{E} \) will give a contribution of 1.7\%. To achieve the same contribution
to the error on the measurement on $p_T$, the error on the measurement of the angle will need to be $\sigma_\theta = 6 \cdot 10^{-4}$, which at a distance of 5 m means a positional resolution of a few mm.

Silicon pixel sensors with a granularity of 30µm are already being manufactured, and finer granularities are expected with future technologies. Because a detector with these sensors will be able to follow the development of the electromagnetic showers at a very small scale, the high granularity should also allow the detector to be much more effective at determining the energies of showers that are separated less than a Moliere radius from each other.

### 2.4 The FoCal detector in ALICE

As discussed in sections 2.3 and 1.2, the proposed design for FoCal will need to have a very high lateral segmentation of the electromagnetic section of the calorimeter. The high lateral segmentation is necessary to be able to discriminate between the large number of particles incident on the detector, and specifically to discriminate between $\gamma$’s and $\pi^0$’s.

The electromagnetic calorimeter section of FoCal will require a small shower size to minimize the effects of occupancy and to optimize the ability of the calorimeter to separate photon showers. The absorber material of choice is Tungsten, due to its small Moliere radius of 9 mm and radiation length of 3.5 mm. For the prototype design other absorber materials were considered, however for reasons explained in section 3.1, these were not chosen. Silicon was chosen as the sensor material. Due to the energy resolution requirement being not as stringent as the granularity, a sampling layer thickness of $\approx 1X_0$ has been chosen to reduce costs.

Through simulations a transverse positional resolution down to 1 mm was been shown to still be useful in identifying $\pi^0$’s. At the same time this positional resolution will enhance the capability of the calorimeter to resolve hits in a high multiplicity environment. Requiring this positional resolution for all layers will lead to a prohibitively large increase in the cost and the volume of data collected however. As longitudinal segmentation also allows for particle identification and background rejection, the design agreed upon will use longitudinal segments with moderate granularity summed longitudinally, interspersed with layers of high granularity.

The concept for the electromagnetic section of FoCal is shown in figure 2.13. The detector will contain alternating layers of absorber and sensors. Sampling the shower development will be done approximately once per radiation length. Thus to allow for accurate measurement of energies up to a few 100 GeV, at least 20 layers will be needed.

To reduce the complexity and cost of the data acquisition system the signals from the low granularity layers will be summed across a number of layers. The majority of the sensor layers will have low granularity ($\approx 1$ cm), with a few layers having high granularity ($< 1$ mm). The main function of the high granularity layers will be to determine the location of the particles, rather than to sample the energy of the showers. Since the width of a shower will grow as it develops and since the depth of shower maximum depends on the shower energy, a single layer of high granularity sensors may not be sufficient for FoCal.

The sensors of interest for the high granularity layers are monolithic active pixel sensors (MAPS). Based on CMOS technology, they are relatively cheap and allow for binary signals from pixels of a size down to $20 \times 20 \mu m^2$. In the current design on-chip summing of the signals from the binary pixels to virtual macro-pixels of $1 \times 1$ mm$^2$ is envisioned. These macro-pixels will reduce the data volume and will be used as the effective signals from the high granularity
layers. Since the MAPS rolling-shutter readout is intrinsically slow (≈5 µs) and non self-triggering, some pile-up will be expected in p-p events. This can be disentangled by matching to clusters in the low granularity layers.

The low granularity layers will be using conventional silicon pad sensors, which will be summed at the same transverse location for a number of layers to create a number of segments several layers deep. These layers will also provide triggering information for the high granularity layers.

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3Long term evolution: ALICE ITS Upgrade project aims at <30 µs [28].
2.4. THE FOCAL DETECTOR IN ALICE

Figure 2.13: The concept for the FoCal detector. (below) Absorbers (blue) will be approximately 1 $X_0$ of depth, with low granularity (red) and high granularity (green) sensor layers inserted between them. Independent readout units are indicated by numbers, with the low granularity layers being summed 4 to 5 layers deep, and the high granularity layers being read out independently. (above) Illustration of the difference in granularity of the low and high granularity cells.
Chapter 3

Detector Prototype

This chapter will go into the choices of the different components of the prototype and their function. Lastly this chapter will examine the differences in the relative setups between different beamtests.

3.1 General Construction

A sampling calorimeter consists of alternating layers of absorber and detector elements. In a sampling calorimeter the choice of thicknesses, lateral dimensions and materials depends on the particles and energy ranges to be measured. The objective of the prototype is to measure particles of a few GeV/c to several hundreds of GeV/c interacting mainly electromagnetically.

The longitudinal size of the prototype follows from the shower profile, which is described by equation 2.23. From this it is calculate that for showers up to 500 GeV/c, 20 radiation lengths contain on average 94.6% of the energy deposited by the shower.

The lateral size of the prototype is determined by the Moliere radius, since the prototype should be able to contain most of the energy in the shower to be able to accurately measure it. Therefore the lateral size of the prototype should be at least several Moliere radii.

The choice of absorber material in the prototype is mainly determined by these quantities. Smaller Moliere radii mean that shower particles travel less in the transverse direction when compared to materials with a larger Moliere radius. A smaller Moliere radius therefore allows the prototype to have a better spatial separation of simultaneous showers. It also means that the prototype can be physically smaller to contain the same fraction of the shower energy, reducing cost.

A small radiation length is also preferable since the physical depth of the prototype depends linearly on it. Because there are restrictions on the physical dimensions of the prototype, a small radiation length gives the advantage of being able to build a thinner calorimeter.

Since the optimal position for the high granularity layers of the final design for FoCal have not yet been determined, all sensors in the prototype will be of the high granularity type. This should allow for the determination of the layers which have the most effect. The sensor elements chosen for use in the prototype are the MIMOSA sensors [29], made by IPHC1.

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These sensors are active components which consume power, and the heat generated by the sensors will need to be removed from them. In order to do this, the absorber material will be used as a heatsink for the sensor elements.

Because of the heating of the sensors the last criterion for the choice of absorber material is the thermal conductivity $\lambda$. The thermal conductivity relates the temperature gradient per unit length of material to the amount of power applied to it. Doubling the thermal conductivity means that the difference in temperatures to sustain the transfer of a certain amount of power is halved.

A number of possible choices of absorber material is listed in table 3.1 with their relevant material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ g/cm$^3$</th>
<th>$X_0$ cm</th>
<th>$R_M$ cm</th>
<th>$\lambda$ W/Km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>7.87</td>
<td>1.757</td>
<td>1.719</td>
<td>80</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>1.436</td>
<td>1.568</td>
<td>400</td>
</tr>
<tr>
<td>W</td>
<td>19.3</td>
<td>0.3504</td>
<td>0.9327</td>
<td>173</td>
</tr>
<tr>
<td>Pb</td>
<td>11.4</td>
<td>0.5612</td>
<td>1.602</td>
<td>35</td>
</tr>
<tr>
<td>U</td>
<td>19.0</td>
<td>0.3166</td>
<td>1.009</td>
<td>28</td>
</tr>
</tbody>
</table>

Iron is very cheap and easy to work with. However, its radiation length and Moliere radius are not nearly as good as the other absorber materials in this list, making it less suitable.

Copper has a very high thermal conductivity and is very easy to work into complex shapes, which increases its suitability as an absorber from a mechanical standpoint. Its large radiation length and Moliere radius make it unsuitable for use in the prototype.

An absorber material often used is lead, since it has a short radiation length while at the same time being easy to work into shapes due to its good malleability.

Uranium is in many ways similar to tungsten; it has approximately the same density, radiation length and Moliere radius. One major difference between this and other possible absorbers is its natural radioactivity which causes severe complications in handling and transportation. This natural radioactivity also causes intrinsic noise in the prototype.

Tungsten is a material with a very short radiation length, a good thermal conductivity and the best Moliere radius of all materials under consideration.

The deciding factor between all materials considered is the Moliere radius, and for this reason tungsten was chosen as the material for the absorber.

Since this will be a sampling calorimeter, there is another parameter: the sampling frequency. Since the average length between interactions is not larger than the radiation length for showering particles, the sampling should be done at least that often during the stage where the shower has the most particles. This means a sampling of at least once per radiation length at shower maximum. This also gives the prototype a distinct segmentation in identical units of absorber and active material, who get stacked together into the entire detector.

The main properties of each layer are:

- the lateral size should be more than two Moliere radii large, to reduce lateral leakage as much as possible,
3.1. GENERAL CONSTRUCTION

Figure 3.1: The proposed prototype. Shown here as well are the PCBs which mount the sensors in brown and pink, the tungsten absorbers are shown in light grey while the sensors are shown in black. The copper heatsinks will touching the absorbers at the bottom and top of the prototype. A large amount of space on both the left and right side will be required to route all the cables from the prototype to the data acquisition hardware.

- the sampling should be done at least once per radiation length at shower maximum, to accurately determine the number of particles in the shower,

- the depth of the detector should be at least 20 radiation lengths deep, in order to contain a significant fraction of the energy of the shower.

The first point results in a lateral size larger than 2 cm from the centre of the prototype. The MIMOSA sensors also factor into this size, since the lateral dimensions of a layer will be a multiple of the sensor size, assuming no major overlaps between sensors in the same layer.

The second point results in the layers at shower maximum containing at most 3.5 mm tungsten. This can be tuned for ease of construction. More frequent sampling of the shower will increase the energy response and improve the resolution. It will also require a larger number of channels of data which must be handled, which will increase the complexity and cost of the data acquisition system. The combination of these considerations gives the number and location of the active layers in the detector.

The third point gives a total depth of absorber in the prototype of no less than 70 mm of tungsten.

After having taken all these requirements into account, the design was based around identical half-layer modules containing the main absorber plates, the sensors and their mounting PCBs. A rendering of the prototype concept is shown in figure 3.1.

The layers of the prototype are stacked with the modules ending up in a zig-zag fashion. Each module in the prototype also has a reference corner, and each MIMOSA sensor’s position is measured relative to this reference. During the assembly of the entire prototype, all
reference corners of the modules are then aligned, defining the locations of the sensors in the prototype.

### 3.2 Prototype Construction

The schematic of the half-layer module, as described in section 3.1 is shown in figure 3.3. The specific sensor chosen for the prototype is the PHASE2/MIMOSA23, whose operational properties will be explained in more detail in section 3.3. It is a silicon pixel sensor which was chosen for its small pixel size, allowing for high positional resolution, and its integrated digital readout circuitry.

A calorimeter with tungsten absorbers of dimensions matching the sensor (19.52×20.93 mm$^2$) is too small to effectively contain showers laterally, which is why each prototype layer contains 2 by 2 sensors. This design allows showers which strike in the centre region of the prototype to be fully contained and sampled.

The absorbers are tungsten plates of 50×49.85 mm$^2$ and 1.5 mm thickness. The sensors are bonded to PCB’s which are then mounted on the absorber plates. This allows for the prototype to be constructed from mechanically stable ensembles, which simplifies the relative alignment of the sensors.

Each sensor is mounted on its own individual PCB, which functions as a mechanical support for the MIMOSA sensor and its connections. Because the bondwires connecting the sensor to the PCB are very fragile, they are coated in an epoxy. The PCB also functions as a heatsink for the MIMOSA sensor. This is achieved by having a very large number of copper vias in the part of the PCB the sensor is mounted on. This construction should strongly aid in conducting heat away from the sensors, thereby reducing the noise in the sensor.

Because the sensors are very fragile and their surfaces extremely vulnerable, they can not simply be stacked between layers of tungsten. To work around this issue, each module has two stainless steel spacers. When the prototype is assembled, the two modules which make up a single layer rest on top of these spacers, which prevents physical damage to the sensors.

The space left between the sensor and the absorber plate of the opposite module in the same layer will degrade the lateral shower containment, since this effectively "dilutes" the absorber across a larger volume.
3.2. PROTOTYPE CONSTRUCTION

To this end the gap is filled with tungsten filler plates. The thickness is chosen such that the sensors are protected from physical damage. The resulting half-layer module is shown in figure 3.3.

Each layer takes up 3.97 mm in thickness, of which 3.38 mm is taken up by the tungsten absorber plates. The prototype contains 24 such layers. This gives the prototype an effective depth of 22.6 radiation lengths from the tungsten absorber. Adding to this the total 7.2 mm of tungsten filler plates, and 5 mm of copper in the PCBs, give the prototype layers an effective depth of 23.4 radiation lengths.

Figure 3.2 shows the different stages of the assembly of the prototype. The first layer of sensors is placed between both heatsinks, which at the same time function as supports for aligning the sensor modules. During the entire assembly process, the positions of the modules are recorded. According to these measurements, the sensors are positioned to within 200 µm of their planned positions.

Table 3.2: The constituents of a single layer of the prototype, sorted by total contribution to the prototype thickness. By adding the contributions of the constituents in inverse and by their fraction to the total contribution, the total Moliere radius and radiation length are calculated.

<table>
<thead>
<tr>
<th>Material</th>
<th>$X_0$ cm</th>
<th>$R_M$ cm</th>
<th>Thickness mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>0.35</td>
<td>0.9</td>
<td>3.38</td>
</tr>
<tr>
<td>Air</td>
<td>30390</td>
<td>7330.0</td>
<td>0.23</td>
</tr>
<tr>
<td>Si</td>
<td>9</td>
<td>4.9</td>
<td>0.12</td>
</tr>
<tr>
<td>G10</td>
<td>2</td>
<td>33</td>
<td>0.102</td>
</tr>
<tr>
<td>Cu</td>
<td>1.4</td>
<td>1.6</td>
<td>0.058</td>
</tr>
<tr>
<td>Epoxy</td>
<td>1</td>
<td>36</td>
<td>0.04</td>
</tr>
<tr>
<td>Ag</td>
<td>1.2</td>
<td>1</td>
<td>0.04</td>
</tr>
<tr>
<td>Total Layer</td>
<td>0.404</td>
<td>1.028</td>
<td>3.97</td>
</tr>
</tbody>
</table>
As the assembly of the prototype proceeds, the modules are fixed by clamping the mounting PCB’s between two rubber strips on both sides. This allows both to secure the position of the modules and the sensors mounted on them, while at the same time protecting them from damage. Lastly both heatsinks are fixed in position with a number of screws, which at the same also fixes the modules in the lateral direction of the heatsinks.

3.3 The MIMOSA sensor

The main difference of the MAPS [29] sensors when compared to conventional (analogue) sensors is the use of CMOS structures with an epitaxial layer of high resistivity material. These structures can simultaneously collect the charge generated in the high resistivity layer and amplify the collected charge.

This technology allows the combination of both sensor and front-end electronics on the same wafer, but it has the disadvantage that it does not allow the application of a bias voltage on the sensor layer, which would increase the signals collected. Instead, the collection diodes rely on the diffusion of charge generated in the epitaxial layer.

The prototype is constructed out of 19 sensors with 14µm of low-resistivity (10Ω/cm), 46 sensors with 15µm and 31 sensors with 20µm of high-resistivity (400Ω/cm) epitaxial silicon. The expectation is that the higher resistivity will result in less recombination of generated charges, increasing the amount of charge collected thereby increasing signal to noise ratios. The exploration of this effect was beyond the scope of the thesis, however.

The basic design of the sensor is shown in figure 3.4. Of the sensors’ $19.52 \times 20.93 \text{ mm}^2$ surface, $19.2 \times 19.2 \text{ mm}^2$ is taken up by the pixel matrix. The rest handles logistical and signal processing tasks.

The smallest element of the pixel matrix is the pixel. The main features of the pixel are the charge collection diode and the built in amplifier. Keeping the amplifier close to the point of generation of the signals reduces noise picked up by transmission lines and reduces the impedance from the sensor to the amplifier. The trade-off is increased complexity of the circuitry combined with increased power consumption.

The equivalent electronic circuit of a pixel is shown in figure 3.5, it contains a collection diode, an amplifier, two capacitors and a number of MOSFET switches. During the charge collection phase, the charges flowing from the diode are amplified and stored in one capacitor. During the calibration phase, the voltage across the diode is switched off and the noise from the amplifier is stored.

When a line of pixels is being read out, the charges from the pixels are converted to digital signals. This is done by a number of offset-compensated column-level discriminators a schematic of which is in figure 3.6. These discriminators take the signals from the pixels and compare them to the threshold voltages $V_{\text{ref1}}$ and $V_{\text{ref2}}$, which give the binary value of the pixel. The thresholds are set through a JTAG command, and are 8 bit values. $V_{\text{ref1}}$ determines the threshold for collected charge, while $V_{\text{ref2}}$ corrects for the positional dependence of the threshold.

During the first stage of the pixel readout phase, switches indicated by $\phi_1$ are closed, this discharges the capacitor in the pixel through the differential amplifier $G_0$. The difference generated by $G_0$ is capacitively coupled to amplifier $G_1$. In the next step switches $\phi_1$ are opened and $\phi_2$ are closed. The calibration charge is fed into $G_0$, which due to the capacitive coupling is effectively subtracted from the pixel charge result. When enough time has passed
3.3. THE MIMOSA SENSOR

Figure 3.4: The basic layout of a MIMOSA sensor. Through the line selection logic (not to scale), one line of pixels is connected to the discriminators, whose results are sent by the digital circuitry across one of four connections to the FPGA.

to discharge the capacitor, the result of the comparison is latched, fixing the readout of the pixel to a binary value. This readout process takes 1 µs. The pixel will now continue to collect charge until the next readout.

The discriminators are grouped in the manner shown in figure 3.7. This allows the readout of the sensor to work at a higher speed than that of the discriminators. The discriminators are first multiplexed in groups of 40 to intermediate data streams at 40 MHz. These intermediate data streams are then multiplexed into a single data stream of 160 MHz. These extra levels of multiplexing need to be removed to recover the original data streams (see section 4.1.1).

The MIMOSA has enough discriminators to handle the pixels of a single line. Because of this, all lines are read out one after the other, giving a sequential line readout or rolling shutter. The time structure of the readout has a number of consequences. To collect all signals generated by one particle, a full readout cycle has to be completed after the passage. Also, for every particle the relative time of passing may vary to such a degree that the readout cycle starts at different locations in the sensor. In addition, the duration of the readout cycle is also the integration time, so care should be taken to avoid pile-up during this period.

When the readout of the sensor reaches the end of the pixel matrix, a number of diagnostic signals can be sent across the data channels. There can be no diagnostic sent, a pattern called the checkerboard pattern, or the checkerboard pattern and a user defined testpattern. In the prototype both patterns are used to identify the end of the frame in each data channel. After
CHAPTER 3. DETECTOR PROTOTYPE

Figure 3.5: The basic circuit of a MIMOSA pixel taken from [31]. While the integration circuit is powered (PWR_ON), the charge collected by the pixel is amplified and stored by a capacitor until readout. After readout and calibration, the voltages on the pixel and capacitor are reset for the next readout cycle.

Figure 3.6: The MIMOSA offset-compensated discriminator, $\phi_1$ is active during pixel readout, $\phi_2$ during offset determination, $\phi_3$ during result storage, taken from [31].

Sending the testpatterns, the MIMOSA sensor then waits for the frame start command before starting readout anew.

The checkerboard pattern is a sequence of 160 alternating ones and zeroes, which will be sent by each channel of a MIMOSA sensor. The testpattern is different from the checkerboard in that the pattern sent can be loaded onto the sensor at start-up. This enables us to distinguish between different channels by identifying the pattern sent.
Figure 3.7: The MIMOSA channel multiplexers, inspired by [29]. 40 discriminators are multiplexed into an intermediate data stream, 4 of these intermediate data streams are then multiplexed onto a single data channel which connects to the FPGAs.

Table 3.3: The main specifications of the PHASE2/MIMOSA23 digital pixel sensors used in the prototype.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size</td>
<td>$30 \times 30 \mu m^2$</td>
</tr>
<tr>
<td>Charge Collection Time</td>
<td>642 $\mu s$</td>
</tr>
<tr>
<td>Sensor Refresh Rate</td>
<td>1.558 kHz</td>
</tr>
<tr>
<td>Sensitive Layer</td>
<td>19 sensors of 14$\mu m$ at 10$\Omega$/cm</td>
</tr>
<tr>
<td></td>
<td>46 sensors of 15$\mu m$ at 400$\Omega$/cm</td>
</tr>
<tr>
<td></td>
<td>31 sensors of 20$\mu m$ at 400$\Omega$/cm</td>
</tr>
</tbody>
</table>
3.4 FoCal Coordinate System

The sensors in the FoCal prototype are arranged in a regular pattern which makes calculating the location of a pixel in the detector straightforward. The initial assumptions used in the calculation of the pixel coordinates are shown in figure 3.8.

There are a number of limitations to these calculations. The first is that the gaps between the active areas of the sensors in the y-direction and the overlap between the sensors in the x-direction have not been taken into account.

The second is that any misalignments due to the limitations of the manufacturing and assembly processes have not been taken into account either, since these are not yet known. These quantities can be calculated through the use of the alignment algorithm (section 4.2.4).

![Figure 3.8: The manner in which the location of the pixels is calculated. Knowing the quadrant Q of the sensor and the line L and column C of the pixel allows us to calculate its coordinates.](image)

3.5 Data Acquisition System

Since each sensor generates 640 Mbps of data, the prototype of 96 sensors equates to 61.44 Gbps. This data rate is too high for most computers to handle directly. Another issue is the total number of connections required. With each sensor having 4 data connections, the sensors alone would require 384 connections to the computer which would be responsible for recording the data.

In addition to the control signals, additional connections are required for data recorded from the trigger system. Therefore an interface between the sensors and the computer is required, the Data Acquisition System. This system consists of the following:

- The trigger system indicates when a particle goes through certain regions near the prototype
- The distribution crate, which handles the connections between the MIMOSA sensors and the FPGA boxes as well as the power distribution to the sensors
- Two FPGA boxes with the following tasks:
  - interfacing between sensors, trigger logic and computer,
  - buffering the data stream,
  - and selecting and transferring a subset of this stream to the computer.
3.5. DATA ACQUISITION SYSTEM

3.5.1 Trigger system

In a conventional detector, the function of a trigger system is to initiate the read out of data from the detector when certain conditions are met. In the prototype, the sensors are being read out continuously and have a window of sensitivity due to the rolling shutter (p. 51).

Thus, the trigger system functions in a different way when compared to conventional detectors. It indicates which parts of the continuously generated data stream need to be examined for interesting signals.

The trigger system uses up to 5 scintillators to indicate when a particle is passing through certain regions in the neighbourhood of the prototype.

The Presence scintillator consists of 110 mm by 110 mm by 10 mm of NE102a plastic, and indicates particles entering the detector. It is used as a gating signal for all other scintillators in the trigger logic.

The two finger scintillators are called Horizontal and Vertical and have a thickness of 5 mm in the direction of the beam. The horizontal scintillator has its long axis in the x-direction and is 40 mm by 10 mm, while the vertical scintillator has its long axis in the y-direction and has dimensions 20 mm by 10 mm. These two scintillators together delimit an area of 10 mm by 10 mm in the centre of the prototype.

The Front scintillator consists of 40 mm by 40 mm by 10 mm of NE102a scintillator. The front scintillator indicates particles entering the front of the prototype. The Back scintillator, which has the same dimensions as Front, indicates particles leaving the detector. This might be the case with minimum ionizing particles or showering particles of very high energies.

Each of these scintillators has its own photomultiplier tube, which converts the light generated by the particles passing through them into electrical pulses.

Trigger Logic

The trigger logic converts the analog electrical pulses into digital signals that can be handled by the FPGA boxes. The trigger logic supplies up to 15 different bits to the FPGA boxes, of which 5 are trigger state bits, and 10 are trigger counter bits. A generalized trigger logic schematic is shown in figure 3.9.

The signals from the PMTs are very short analog pulses, which are converted by a number of discriminators and pulse shapers to the correct digital signals which can be processed by the rest of the trigger logic.

All signals from the PMTs are gated by a signal from the presence (P) scintillator in front of the prototype. This removes any false triggers caused by noise in the photomultipliers or by particles not travelling in the axial direction of the prototype.

The digital signals derived from the photomultipliers are combined into logic conditions and sent to the FPGA boxes, these are then called trigger bits. All trigger bits also link to a 10 bit ripple counter which generates a unique identifying code for each trigger. The bits from this ripple counter are also sent to the FPGA boxes.

Lastly there is a data taking enable (also called spill) signal which is not generated by any PMT. The spill signal indicates to the data acquisition system that it is allowed to record data.
3.5.2 Distribution crate

The distribution of power to and signals to and from the MIMOSA sensors is performed by dedicated printed circuit boards (PCBs) housed in the distribution crate.

On the side of the crate there are the bus bars handling the power supply to the MIMOSA sensors, as well as several large buffering capacitors for handling surges in current draw. The distribution crate contains a total of 24 PCBs as the ones in figure 3.10 for handling the connections to the MIMOSA sensors.

Each PCB handles the supply of current and the distribution of control signals of a single layer in the prototype. The transmission of control and clock signals to individual sensors can be interrupted through software or jumpers on the PCB. This allows for flexibility in routing the control signals if a single sensor in the layer is malfunctioning.

3.5.3 FPGA box

The distribution crate connects the chips to the FPGA box which is the interface between the sensors and the computer [30]. The main functions of the FPGA box, as shown in figure 3.11, are:

- connections to and from the PCBs in the distribution crate,
- buffering the data from the sensors until collection,
- storing the trigger information,
- communicating with the computer,
3.5. DATA ACQUISITION SYSTEM

Figure 3.10: A photo (left) and schematic drawing (right) of a FoCal PCB. The schematic indicates elements: a: the RJ45 connectors to the FPGA box, b: the connectors to the sensors, c: power regulators, d: status LEDs, e: power connector.

- and clock generation and synchronization.

The FPGA box has two main levels of components. The first level is the Spartan FPGA, which handles the connections to the chips and sends the data streams to the second level. The second level is the Virtex FPGA which handles the buffering and communication with the data acquisition computer.

**Spartan FPGA**

The two Spartan6 XC6SLX150 FPGAs in the FPGA box function as a fan-in for the main Virtex FPGA. At the same time the Spartan checks the data streams coming from the distribution box for the testpatterns sent by the MIMOSA sensors as well as for the end of frame readout and connection integrity.

Each Spartan FPGA handles the signals for 24 sensors, linked through a 500 pin Searay connector, and offers the 96 bits sampled each clock pulse to a 128 bit FIFO buffer in the Virtex FPGA. When the buffers are full, 256 bits are written to memory, in the manner shown in figure 3.12. This adds another level of complexity to the data stream which needs to be removed before the detector state can be reconstructed.

The Spartans’ last function is to sample the 10-bit counter from the external trigger logic. Trigger bits are written to the trigger stream when one of these bits has a rising flank.

**Virtex FPGA**

The Xilinx Virtex 6 XC6VLX240T FPGA is the main interface between the trigger system, the data coming from the MIMOSA sensors and the computer recording the data.

The Virtex runs a lightweight PetaLinux operating system, which is externally accessible using SSH. The programs which tell the Virtex when to write data to the 2GB of buffer ram and when to send which part of the data stored to the recording PC run under PetaLinux.
Figure 3.11: A photo (left) and schematic drawing (right) of an FPGA box. The schematic indicates the following elements: a. RJ45 connectors to sensors, b. Spartan PCB, c. Virtex PCB, d. power supply units, e. power, network and USB connections.

Figure 3.12: The FIFO buffer’s 128 bits are written to memory 3 times in the time it takes to sample 96 channels 4 times. This gives rise to an extra structure of the data recorded.

The pixel stream, the data sent to the FIFO by the Spartan FPGAs, is only written to memory when enabled by the data acquisition program. If the Virtex is recording the pixel stream, it will at the same time also be recording a trigger stream in memory. Trigger bits will be written to the trigger stream either when the Spartan FPGAs signal that the MIMOSA sensors have reached their end of frame readout, or when any of the five trigger lines supplied to the Virtex has a rising flank.

When the trigger bits are written to the trigger stream, they consist of the following:

- 10 bits from the ripple counter,
- 5 externally supplied trigger bits,
- 1 internally generated frame synchronization bit, indicating the end of frame readout,
- 24 bits generated by an internal clock running at 10 MHz, this allows the exact reconstruction of where in the readout cycle a trigger happened,
- and 16 internal status bits indicating the synchronization status of the chips of both Spartans and the buffer overflow status.
These triggers will be used to identify which parts of the pixel stream will be used in analysis, and which parts of the streams of different FPGA boxes should be combined to fully reconstruct the status of the prototype.

Data Transfer

The pixel stream comprises the data from 48 sensors per FPGA box, each sending data at 640 Mbps, resulting in a data rate of 30.72 Gbps. The trigger stream will take up a negligible amount of memory compared to the pixel stream, usually kilobytes for a pixel stream of gigabytes. This results in the Virtex being able to record data for a maximum of 0.521 s.

When the buffer is filled, the data can be sent to the recording PC or discarded, according to the settings of the program storing the data. When the data is to be sent, PetaLinux will open a socket connection to the recording computer and start sending the data. In this the DAQ system is hampered by the limitations of the PetaLinux operating system which can only generate transfer speeds on the order of 100 Mbps. This means that after taking data for 0.5 s the DAQ system will spend around 2 min sending the data to the recording computer. This very low duty cycle means that the moment at which to start recording data is very important.

The prototype’s DAQ system has 2 FPGA boxes in a master-slave relationship, where the storage of data in memory by the slave unit will only begin after being sent the datataking enable signal from the master unit. This signal is sent over a twinning cable which links both FPGA boxes. The server determines the master and slave status of an FPGA box by the IP address it is assigned during configuration.

3.6 Cooling

Since each MIMOSA sensor produces around 450 mW of heat, adding up to over 40 W for the whole prototype, the interior of the prototype will significantly heat up, unless it is cooled. An increase in temperature will mean an increase in thermal noise and therefore a reduction in the signal to noise ratio.

During testing, it was observed that the MIMOSA sensors measure more noise as the temperature increases and that reliable operation ceases at temperatures in excess of 50 °C. Cooling is therefore necessary for the correct and accurate operation of the prototype.

Heat transport off the sensors is done via the mounting PCBs of the modules, the tungsten absorber plates and a pair of heat exchangers connected to a water based cooling apparatus as shown in figure 3.13.

In the design of the PCBs care has been taken to minimize the thermal resistance as much as possible. The PCBs are much thinner in the region the sensor is mounted on, and this region has a large number of copper filled vias, further reducing thermal resistance.

The PCBs are mounted on the tungsten absorber plates using silver glue, which is another measure to reduce thermal resistance. The thermal conductivity of the absorbers is sufficient to transport the heat from the sensors to their sides. Here a pair of large copper heat exchangers kept at 17 °C by the water chiller\(^2\) remove the heat, keeping the sensors at temperatures of around 27 °C. From calculations the total thermal resistance from the diode on the MIMOSA to the cooling water is then 22 K/W.

\(^2\)The water chiller used is a Lauda Compact-Kältethermostate, type RCS 6.
Lastly, the cooling system incorporates a thermal cutout. This device disables the power to the sensors if the measured temperature of the sampled sensor rises above a threshold. The sampled sensor is the one which is expected to have the highest temperature out of all sensors in the detector, which is the centremost sensor. The thermal cutoff threshold is set to 35°C, which should prevent the temperatures of the sensors in the detector reaching a level impairing their function or causing damage.

In the case of a loss of power, the box will also be latched off at the resumption of power. This is to prevent data taking when the sensors or the rest of the prototype are not yet correctly initialized.

### 3.7 DESY beamtest setup

From March 12th to March 19th of 2012 the prototype was set up at testbeamline T22 at DESYII of the Deutsche Elektronen Synchrotron (DESY) in Hamburg. This beamline produces test beams of up to 1000 particles per square centimetre per second of momenta ranging from 1 GeV/c up to 6 GeV/c. The two energies that were used to take data are 2 GeV/c and 5 GeV/c, since the yield at 6 GeV/c was found to be too low to be useful. This accelerator produces bunches of particles every 80 ms, resulting in a bunch frequency of 12.5 Hz.

The prototype itself consisted of 24 layers with 4 sensors each. As shown in table 7.1, the 4 rearmost layers were not connected. This was caused by a lack of working sensors before going to beamtest.

Since the periodicity of the beam at DESY is much shorter than the time it takes to fill
3.8 SPS beamtest setup

The prototype was set up at beamline H2 in the North Area of CERN. Here the protons from the SPS are made to collide with a stationary target to produce a secondary beam of mainly pions. The neutral pions decay into photons, which are then converted into electrons by another target, which does not significantly interfere with the charged pions.

It was observed in the data that the beam has a high admixture of hadrons and is thus not a pure leptonic beam as expected from this setup. Apparently, the beam settings were not fully correct.

The complete setup of the trigger system is shown in figure 3.17. The main difference between the DESY and SPS trigger setup is the manner in which the trigger for recording data is generated. The beam structure at SPS is very different from that at DESY. The H2 beamline receives an extraction of 9.69 s every 43.2 s. This necessitates a change in the way the FPGA boxes trigger their buffering. The H2 beamline has a beam extraction trigger.
indicating an imminent extraction. By delaying this trigger by the correct amount, the FPGA boxes will start recording during the correct part of the extraction cycle.

When the buffers are filled, shipping of the data will commence, which will take several extraction cycles. During these cycles, the FPGA boxes will ignore any triggers until shipping is completed. This will result in a reduced duty cycle when compared to the setup at DESY, since the FPGA boxes will spend some of their time waiting for a new extraction and not shipping data.

The prototype was also redesigned between the beamtests at DESY and SPS. The main change was the addition of enough sensors to have all layers operational, increasing the total signal obtained from the prototype. Another change to the prototype was the addition of a 2 cm thick block of tungsten between layers 21 and 22, bringing the total depth to 28 $X_0$. This extra absorber should stop most shower particles, while not significantly influencing MIPs, which then should allow for increased discrimination between MIPs and showering particles.

Both design changes should be of importance with the higher energies and changes in the beam composition at the SPS, when compared with DESY.
3.8. **SPS BEAMTEST SETUP**

Figure 3.16: A picture of the beamtest setup at SPS. The beampipe is visible at the extreme left, with the vacuum tube connected to it. The calorimeter proper is not visible, it is hidden behind the square P scintillator and the PMT of the F scintillator.

Figure 3.17: The setup of the trigger scintillators (not to scale) at SPS, with distances to the front of the calorimeter in mm. The addition of extra absorber increases the power to distinguish between showers and tracks.
Chapter 4

Software

The software written for the FoCal prototype has two main functions. The first is data processing, which contains all steps going from data stored in the buffer of the FPGAs to the status of the pixels in the prototype at a certain point in time.

The second is data analysis, whose task is to derive information from the processed data. Each of these will be explained in detail in the following sections.

4.1 Data Processing

The data recorded by the FPGA boxes consists of two distinct data types. The pixel stream contains the data taken from the sensors, whereas the trigger stream contains the data taken from the external trigger channels and the internally generated triggers. Data processing derives the status of all pixels in the prototype using the data from both the pixel and trigger streams. To do this, three processing steps need to be done on the data:

- the data, as it is recorded in the buffer memory of the FPGA, has several levels of multiplexing applied to it. Transforming this data into a sequential data format is called the Demultiplexing step.

- The FPGA boxes are not synchronized, so any external triggers they have recorded are used to correct any differences in clock speeds and clock starting times.

- When the data from both boxes has been converted to the sequential format and the differences between both FPGAs’ clocks have been determined, the signals produced during the integration window following those clock values can be combined into a complete frame.

Each of these steps will be explained in more detail in the following subsections.

4.1.1 Demultiplexing

Due to the architecture of the MIMOSA sensors, two layers of multiplexing are applied to the data recorded by the sensor as explained in section 3.3. The information is then sent to a FPGA box. Another level of multiplexing is then introduced by the way the Virtex FPGA
takens the data from the Spartan FPGAs and writes it to memory, as explained in section 3.5.3.

Combining all levels of multiplexing results in a lookup table which gives the repeating pattern in which the bits from the connections of the sensors are written to the memory of the DAQ computer. Using this lookup table the pixel streams can be processed.

Each sensor has 4 connections to the FPGA box, which are called channels from here onwards. The demultiplexing goes through the following steps for each channel:

- finding the checkerboard pattern for rough alignment,
- finding the testpatterns for fine alignment,
- and removing the sensor level multiplexing and writing the data in a sequential format.

The MIMOSA sensors send two types of diagnostic information at the end of frame readout. The first is the checkerboard pattern. It is a sequence of 160 alternating ones and zeroes. This is not useful for alignment on the bit level, because the addition of a single one following a zero will make the location of the entire pattern ambiguous. The second is the testpattern. This is a sequence of bits that can be set by the user through JTAG during the configuration of the MIMOSA sensors. This is what will be used to find the end of frame of each channel.

The FPGA multiplexing is first removed using a lookup table and each channel will be read as the sequence of bits as they were sampled by the FPGA. Having this sequence of bits, the checkerboard is searched for in the first 5 frames of readout of the channel, a total of \(5 \cdot 642 \cdot 160 = 513600\) bits\(^1\).

If the checkerboard cannot be found in this range of bits, the channel is determined to be inactive and it will not be demultiplexed further. If it is found, the search for the testpatterns will be started around the location of the checkerboard plus the length of the checkerboard (160 bits).

In a range of 5 bits surrounding the expected start location of the testpattern, as derived from the checkerboard pattern, the testpattern is searched for. Since the testpattern is a semirandom pattern of bits, which is different for each channel on a chip, any shift from the location of the pattern in the channel will make around 50% of the bits no longer match.

At least 155 out of 160 bits have to match the testpattern, for that location in the bit stream to become the starting location of the new frame. If less than 155 out of 160 bits are matching the testpattern, then the next bit offset is examined for the number of matching bits. The number of 155 matching bits was chosen to allow for a small number of missing bits to cause the software to be unable to identify the start of a new frame. Since the testpattern is a semi-random pattern of bits, attempting to match them at offsets in the datastream will cause a significantly larger number of the bits to not match.

If all possible testpattern locations in the search range are exhausted, then the expected location of the next testpattern is shifted by 1 frame of bits (642 lines per frame times 160 bits per channel per frame = 102720 bits per frame per channel). The difference between 642 lines of data per frame and 640 lines of pixels originates from the 2 lines of diagnostic data which are sent at the end of each frame readout. If the testpattern is found, the expected location of the next testpattern is 1 frame of bits after this location. The search is then started with in a range of 5 bits around this location. The locations at which the testpatterns were found

---

\(^1\)Each channel sends 160 bits per line read out, and each sensor sends 640 lines of data and 2 lines of diagnostic information per frame.
will be stored as synchronization points (short *syncpoint*), and used in the demultiplexing process.

With the syncpoints indicating the end of frame readout of that channel, each channel will be run through again. The levels of multiplexing created by the sensors is now removed, and all data is written in a sequential format to a new container. After 160 bits a new line of data is started. Either when 642 lines have been demultiplexed and no syncpoint will occur within 3 lines, or the channel reaches a syncpoint, a new frame is started. This is done so that a new frame is started at its expected starting location in the stream, even if one of the testpatterns was not reconstructed correctly from the pixel stream.

### 4.1.2 Trigger Stream Alignment

For a single FPGA box finding the point in the pixel stream corresponding to a certain clock value is simple using the frame synchronization markers. The main issue is to find how the clock values of one FPGA box are related to those of another FPGA box. Having this relation is required to accurately reconstruct the status of the entire prototype at a certain time.

Ideally the clocks of both FPGA boxes will start at exactly the same moment and run at exactly the same speed. This is not necessarily the case however. The clocks might start at slightly different times, giving rise to an offset ∆t₁−₂. The clocks might also run at different frequencies ν₁ and ν₂, causing a clock drift. Disregarding any effects such as jitter or other higher order contributions, the relations between both clock values can be expressed as:

\[
C₂ = ν₂ (C₁/ν₁ + ∆t₁−₂) .
\]  

(4.1)

The bits of the trigger counter can advance slightly asynchronously to the trigger bits being sampled by the FPGA box. When this happens, the old value of the trigger counter might still be on the counter, when the new trigger is being sampled. This means that two triggers with the same trigger number, but at two different times, will be present in the trigger stream. Since this is observed in the trigger streams during the beamtests, simply matching up triggers by their trigger number from the different FPGA boxes could connect the wrong times in the different trigger streams. This would then result in an incorrect detector status being reconstructed from the pixel streams.

The information from the trigger streams is used to determine the differences in clock speeds and clock offsets to prevent this from occurring. Only triggers which are generated by the PMTs connected to the trigger system, and not those generated at the end of frame readout, are used to determine the difference between the clocks. These should not be affected by any clock issues of the FPGA.

First the average and spread of the clock offset are determined. The clock difference between both FPGAs of all triggers with the same trigger status and trigger number is calculated. This will give the average and spread of the differences.

The end result is a collection of clock values in all FPGA boxes corresponding to the same points in time. The values of equation 4.1 are then derived from this collection. When a trigger in one FPGA is then to be matched to one in another FPGA, the clock difference equation is used to extrapolate which triggers with certain clock values belong together.
Figure 4.1: The hatched areas indicate parts of the data possibly containing data from a trigger. The frame belonging to trigger T1 can be read out successfully, while triggers T2 and T3 have an overlap, indicated by the double hatched area, where the data read out from the sensor could have been generated by either trigger.

### 4.1.3 Frame Selection

Due to the integration time inherent to the design of the MIMOSA sensor one can only be certain that all charge generated at a certain moment in time will be read out after the integration time has passed. This window of time following an event is called the frame belonging to this event.

Take for instance an electron depositing energy in the epitaxial layer of a MIMOSA at \( t = 0 \mu s \), also take the readout of said MIMOSA to start a new readout at this time. If this electron deposited the energy at line 20, then its signal will be read out after just 20\( \mu s \). However, if the energy is deposited at the very edge of the MIMOSA, line 639, then its signal will only be available after 639\( \mu s \).

Following from this, one can only be certain that all signals that might have been produced at a certain time have been read out after the integration time. This gives rise to the frame belonging to that event. Since the MIMOSA sensors themselves do not indicate when a particle enter the detector, the external trigger system is used to determine at which times signals may be produced.

Each trigger is then used to create a frame which contains all the data produced at the time interval belonging to that event. The frame is then stored in a format which contains the entire state of the detector belonging to that time. This format contains the following three main sections:

- pixel information,
- trigger information,
- and diagnostic information.
4.2 DATA ANALYSIS

The pixel information contains the pixels which were over threshold during the integration window. Usually the noisy or unreliable pixels are masked out before being added, this is explained in further detail in section 4.2.1. These pixels have positional information which is used in the search for tracks of MIPs or to reconstruct the location of a shower in the prototype.

The trigger information is stored as well. This can then be used to select specific kinds of events from the pool of frames. It also contains the time between this event and the previous and next events, which is useful for past-future protection.

When two triggers occur between two readouts of the same pixel, the signals collected from the pixel could have been caused during either of the triggers, due to the integration time of the MIMOSA sensor. To account for this, the time between the current trigger and the previous one as well as the current trigger and the next is calculated. Using this past-future protection any triggers which might contain ambiguous data can be ignored in analysis.

Lastly, diagnostic information is stored. The diagnostic information records which channels were demultiplexed correctly during the readout of the frame. This is important during the analysis step, since the absence of a signal in some sensor might be caused by the insensitivity of the sensor, or by the sensor not transmitting its data correctly. Without this diagnostic information, this would not be known.

4.2 Data Analysis

The main tasks of the data analysis are the following:

- determination and elimination of fixed pattern noise, such as in shown in figure 4.3,
- pedestal estimation,
- track identification/reconstruction and sensor alignment,
- and sensor response calibration.

These tasks will be explained in more detail in the following sections.

4.2.1 Mask Creation

The goal of the detector is to measure charged particles passing through it. This is done by measuring the charge generated in the epitaxial layer of the sensors collected by the pixel circuitry, causing them to be read out as a digital one if enough charge was collected between two sequential readouts. This charge can be generated by sources external to the sensor, such as the charged particles that make up electromagnetic showers. Charge can also be generated by sources internal to the sensor. One of these sources is the thermal generation of electron-hole pairs which occurs in all semiconductors. Another important source is defects in the sensor material. Defects can have a strong influence because they might damage the pixel electronics or might make it much easier for electron-hole pairs to be formed spontaneously.

The signals caused by sources internal from the sensors are called noise, which can be split up into two main categories. Random or thermal noise is caused by randomly occurring electron-hole pairs. Non-random or fixed-pattern noise is associated with damaged or malfunctioning regions of the sensors.
The main method of suppressing thermal noise will be to increase the detection threshold of the sensors. While this will reduce the general sensitivity of the sensors, it will impact the thermal noise to a greater degree since this charge is generated over the entire surface of the sensor, whereas the charge generated by particles is localized in a region of a few pixels.

Increasing the detection threshold will only be effective up to a certain point, since the reduction in sensitivity will also reduce the signals received from particles passing through the sensors. Because of this, increasing the threshold only has limited success in reducing fixed-pattern noise, since the signals collected from defects in the sensors, can easily be much larger than those from particles.

If it can be assumed that the fixed-pattern noise is approximately constant in time and not influenced by the number of particles passing through the sensor, then the pixels which are contributing strongly to the fixed-pattern noise can be identified and ignored in analysis. For example: if 1% of the pixels is producing 99% of the noise, then by ignoring these pixels we can have a prototype which has just 1% of the noise while retaining 99% of sensor coverage.

The goal of the masking program is to determine which pixels to mask and which to allow through. This is done by masking noisy pixels starting with the ones producing the most noise until an acceptable level of noise is reached.

The program will use two thresholds to determine which pixels to mask and which not to. The first of these is the external noise threshold $P_e$, which is the same for all sensors in the prototype, and can be expressed as the average noise per pixel per frame. The external noise threshold defines the amount of noise $N_{tot}$ which is allowed "through" the mask on each readout, which for a sensor with $N_{pix}$ pixels follows:

$$N_{tot} = P_e \cdot N_{pix} \quad (4.2)$$

The second is the internal noise threshold $P_i$, which can be different for each sensor. The internal noise threshold is the average level of noise above which a pixel is masked, because it is contributing too much to the average noise of the sensor. So for a single sensor where the number of pixels with an average noise of $P_n$ follows $N(P_n)$, the internal noise threshold is calculated from:

$$P_e \cdot N_{pix} = \int_0^{P_i} N(P_n) \cdot P_n dP_n \quad (4.3)$$

The algorithm for calculating the internal noise threshold uses the following steps:
- compile signals from readouts without triggers, to determine $N(P_n)$ for each sensor,
- calculate $P_i$ using equation 4.3,
- determine which pixels to mask using $P_i$.

Usually the data for a pedestal will be taken when the detector is not likely to be hit by particles, this data set is called a pedestal run. For each pixel, the number of times it was read out as '1' as well as the total number of times it was read out are stored. From this $N(P_n)$ is calculated and the analysis is started.

$P_e$ is chosen to have an acceptable signal to noise ratio in a shower measurement. It follows from the number of pixels in the area of an electromagnetic shower compared to the signal expected from this area. A simplified model of an electromagnetic shower approximates it to a cylinder with a radius of $1 \, R_M$ and a height of 10 radiation lengths. In this volume the
4.2. DATA ANALYSIS

A prototype will have 10 layers of sensors with a pixel size of $30 \times 30 \mu\text{m}^2$. The total number of pixels $N_p$ in this volume will therefore follow:

$$N_p = \frac{A_{\text{shower}} \cdot N_{\text{layers}}}{A_{\text{pix}}} = \frac{10\pi R_M \cdot 2}{30 \times 30 \mu\text{m}^2} \quad (4.4)$$

The total noise remaining from these pixels should be less than the signals expected from the showering particles. Simulations indicated that at the low end of the detection range, $2\text{ GeV}/c$, the total number of particles that could be detected would be several hundreds. Taking $R_M$ as 1.2 cm, $N_p$ becomes 5 million pixels. The value chosen for $P_e$ in experiment was $10^{-5}$. This should result in a remaining noise of around 50 pixels per frame, which is always smaller than the signal from the shower area.

As a simplified example of the masking procedure, assume a sensor with $N_{\text{pix}} = 10^6$ and $P_e$ the same as in experiment and $N(P_n)$ following table 4.1. This means that, on average, a frame should have no more than 10 pixels read out as ‘1’ while there are no particles going through the detector.

The maximum frame noise of $10^{-5}$ used here is the same as used during the experiment. Since the prototype has $\approx 4 \cdot 10^7$ pixels, the maximum noise per pixel would then need to be $\approx 10^{-5}$ to have a signal to noise figure of $\propto 1$ at the lower end of the energies to be measured.

Table 4.1: The calculation deriving $P_i$ (eqn. 4.3). The total noise that would result from a noise threshold

<table>
<thead>
<tr>
<th>Prob. of noise</th>
<th>Total pixels $N(P_n)$</th>
<th>Contribution to total noise $N(P_n) \cdot P_n$</th>
<th>Integral of noise upto this threshold $\int_0^{P_n} N(P_x) \cdot P_x dP_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.0 \cdot 10^{-2}$</td>
<td>100</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$2.0 \cdot 10^{-2}$</td>
<td>100</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$3.0 \cdot 10^{-2}$</td>
<td>100</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$4.0 \cdot 10^{-2}$</td>
<td>100</td>
<td>4.0</td>
<td>10.0</td>
</tr>
<tr>
<td>$5.0 \cdot 10^{-2}$</td>
<td>100</td>
<td>5.0</td>
<td>15.0</td>
</tr>
<tr>
<td>$1.0 \cdot 10^{-1}$</td>
<td>200</td>
<td>20.0</td>
<td>35.0</td>
</tr>
<tr>
<td>1.0</td>
<td>1000</td>
<td>1000.0</td>
<td>1035</td>
</tr>
</tbody>
</table>

Setting $P_i$ to $1.0 \cdot 10^{-2}$ results in an average noise per frame of 1.0, with 1600 pixels masked. Since $P_e \cdot N_p$ has not yet been reached, $P_i$ can be increased. For this example this point lies between $4.0 \cdot 10^{-2}$ and $5.0 \cdot 10^{-2}$. This means masking all pixels with $P_n = 4 \cdot 10^{-2}$, equating to 1300 pixels or 0.13% of the sensor. The remaining noise in the sensor is caused by the pixels with an average noise below the internal noise threshold, this remaining noise is called the pedestal.

A number of sensors were damaged during the dicing process causing them to have higher noise levels, for some to the level that they would not be of any use in the prototype. The sensor in the example, number 34, was chosen because it is exhibiting noise at levels much higher than the average sensor, making the effect of the masking visually more pronounced. The result of this analysis method on the data produced by this sensor is shown in figures 4.2
Figure 4.2: The noise observed in sensor 34 connected to FPGA 0 (left) results in a noise spectrum (right) with a significant number of pixels which are on 100% of the time. This is caused by the hot pixels on the left edge of the sensor as well as hot lines and columns.

and 4.3. The main conclusion which is drawn from the example is that masking is working as expected in reducing the noise.
Figure 4.3: The mask resulting from the analysis of the noise observed in figure 4.2. Note the very strong correlations between the hot lines/columns and other broken pixels and the masked pixels, only pixels with a very low noise level are not masked. Through the use of this mask, the average residual noise of sensor 34 can be reduced to the external noise threshold.
CHAPTER 4. SOFTWARE

4.2.2 Tracker

Charged particles which do not create showers are expected to generate tracks, a collection of localized hits in each layer they cross. These tracks might only leave a few hits per layer, which may be difficult to discriminate from the expected noise which is set at $10^{-5}$ per pixel per frame.

Since a track leaves maybe 40 hits, compared to the $\approx 400$ hits from noise, it cannot be identified through statistical analysis alone. Another problem with the prototype in detecting MIPs is that at the sensitivity used, most sensors produce a few hits per MIP passing through, with a significant fraction of MIPs passing through a sensor without activating a pixel. Another method for finding these tracks is therefore required. While the efficiency for tracks is low, it is a consequence of the different demands placed on the sensors for a calorimeter compared to a tracker.

Since the main property of a track is that all hits lie on the same line, this property is exploited in the algorithm which searches for these tracks, the tracker. The tracker goes through the following steps to find a track contained in a readout of the prototype:

- Combine hits into tracklets,
- find a region of interest,
- calculate the number of other tracklets within 1 mm of each tracklet
- use the tracklet with the highest number of neighbouring tracklets as the seed for a proto-track,
- assign all hits that are closer than 1 mm to the seed line to the proto-track,
- if the proto-track has at least 24 hits assigned to it in at least 12 layers, promote it to a full track and remove all hits assigned to the track from the pool,
- start with combining tracklets again, repeat this process until no track can be created from the pool of available hits.

The tracker starts with the distribution of hits from a frame, each with their own coordinates, and ignores the masked hits. An extremely simplified detector status with only 5 hits is displayed in figure 4.4.

Using the unmasked hits a tracklet is calculated for each pair of hits which are not in the same layer of the prototype, the tracklet can be described by the following equation:

$$\vec{v}(a) = \vec{v}_1 + a \cdot (\vec{v}_2 - \vec{v}_1) \ ,$$  \hspace{1cm} (4.5)

with $\vec{v}_1$ the position of the first hit and $\vec{v}_2$ that of the second hit.

The result of using this first tracking step on figure 4.4 is shown in figure 4.5.

The intercepts of these lines with two planes at the top and bottom of the prototype are also calculated. These two planes represent the top and bottom scintillators of the prototype, and a track will have to trigger both of these to have been recorded.

If the locations of these intercepts fall outside the dimensions of the scintillators, no track could have caused the hits to fall on that line. These tracklets are called non-physical and are discarded in the following analysis.
4.2. DATA ANALYSIS

Figure 4.4: A simplified detector status, the black points belong to the track, the red one does not. The tracker should therefore only assign the black hits to the track.

Because the tracklets which are created from the hits from a track will all lie approximately on the same line, the locations where they intercept the top and bottom scintillators will be strongly correlated. The location of all intercepts in the 4-dimensional parameters space are put in a histogram and the region with the highest number of tracks in 1 mm is taken as the region of interest.

All tracklets in this region are assigned a score which is the number of other tracklets whose \( l \)-values (eqn. 4.6) are smaller than 1 mm. The tracklet with the highest score will be taken as the seed for the new track.

\[
l = \sqrt{(\vec{v}_{\text{front},a} - \vec{v}_{\text{front},b})^2 + (\vec{v}_{\text{back},a} - \vec{v}_{\text{back},b})^2}
\]  

(4.6)

All hits closer than 1 mm to the seed will be assigned to the track. If the conditions on page 74 are met, the track is passed to the straightening procedure which fits a line to all hits in the track. The square of the distance of a point to a line is, with \( \vec{a} \) and \( \vec{b} \) defining the line and \( \vec{v} \) as the location of the point:

\[
r^2 = \frac{|(\vec{a} - \vec{b}) \times (\vec{a} - \vec{v})|^2}{|\vec{a} - \vec{b}|^2}.
\]  

(4.7)
Figure 4.5: The tracklets are represented as lines. The black lines are tracklets created from hits from the track, the red lines with the non-track hit. All tracklets that belong to hits from the track pass through the same regions at the top and bottom of the calorimeter.

For a collection of points $\vec{v}_i$, this relation then becomes:

$$R^2 = \sum_i \frac{|(\vec{a} - \vec{b}) \times (\vec{a} - \vec{v}_i)|^2}{|\vec{a} - \vec{b}|^2}.$$ (4.8)

By minimizing this equation for $\vec{a}$ and $\vec{b}$, the line which passes closest to a collection of points can be found. For the prototype a number of assumptions can simplify this equation.

All tracks under examination will have triggered both top and bottom scintillator. Assuming that they are simple planes parallel to the planes of the detector, the $z$ parameters in $\vec{a}$ and $\vec{b}$ become fixed. This leaves only the $x$ and $y$ coordinates as parameters in the equation to be minimized.

All hits which are more than 1 mm from the optimal line fitted through all hits in the track are removed from the track. If any hits are removed during the track straightening, the line is fitted again, and the process is repeated until all hits are within 1 mm of the optimal line. The end result of this process is shown in figure 4.6, with the hit falling outside the 1 mm region in red.

Lastly, all hits which belong to this track are then removed from the pool of available hits and the tracker will again attempt to find a track, stopping when it can find no more.
4.2. DATA ANALYSIS

Figure 4.6: The final result of the tracker. Due to the correlations between the hits from the track, the red non-track hit is not included in the track.

4.2.3 Detector Calibration Methods

Since the prototype has a number of different sensor models and the sensors have different threshold settings, the signals for each sensor to the same particle passing through might be very different. These differences in sensitivity will increase the difficulty in determining the correct signal from the prototype, as this will vary according to the location in the prototype.

The objective of all methods of calibration is to improve the consistency of the signals of the prototype. This can be done through two main methods, the minimum ionizing particles method, and the resolution minimization method.

Both methods use the same procedure to determine the signals of the prototype. Assume a prototype consisting of sensors $[0 \cdots C]$, each with its own signals to a particle hitting the prototype $s_i$, then the total signal of the prototype will be the sum of these signals:

$$S_{\text{raw}} = \sum_{i=0}^{C} s_i .$$

(4.9)

By giving each sensor its own calibration factor $c_i$, the signal becomes:

$$S_{\text{corr}} = \sum_{i}^{C} s_i c_i .$$

(4.10)
The resolution of the prototype given by equation 4.11, which is derived from equation 2.33. Any non-uniformity in the prototype response will be visible in the obtained resolution, with more uniform signals giving a smaller spread in prototype signal and therefore a better resolution.

\[ r = \frac{\sigma_S}{S} = \sqrt{\frac{S^2 - S^2}{S^2}} = \sqrt{\frac{S^2}{S^2} - 1} \] (4.11)

The main difference between both optimization methods is the manner in which the calibration factors are determined.

The first method aims to use the signals from Minimum Ionizing Particles (MIPs) to find the calibration factors \( c_i \) such that the signals from the different sensor represent the same amount of energy deposited.

MIPs leave tracks of hits in the prototype. These tracks go through a number of sensors, depending on their direction, and leave a small signal in each. Since the average signal of a MIP is known, the number of hits per MIP can be converted to an energy, which then gives the inverse of the calibration factors of each sensor.

For this method we have used both 100 GeV pions taken at the SPS and cosmic muons. The tracker was then used to find the tracks created by the pions and muons. Then the average signal for each chip was calculated using these tracks. The main issue with this method is the question whether the signals from MIPs are related in a simple one-on-one manner to those from particles in a shower.

The second method aims to optimize the calibration factors of the sensors in such a way that the signal of the prototype for different triggers is the most uniform. It uses the prototype signals from a sample of showers, and optimizes the calibration factors in such a manner that the spread of the signals, as defined by equation 4.11, is minimized. Ideally the calibration factors should be independent of the calibration method, so these are also used as a check for the suitability of the MIP calibration method.

The signals for each shower of each chip first have their pedestal values subtracted and are added to equation 4.11. The calibration factors are then used as parameters and the resolution is minimized using these parameters.

By minimizing the spread of the signals for a given data set the optimal calibration factors for that data set are determined. Since the calibration factors are derived from one data set, their applicability to other data sets needs to be checked. This check can be done by comparing the resolution by using the calibration factors from similar but separate data sets.

4.2.4 Sensor Alignment

The calculation of the position of the pixels is based on a number of assumptions. The most important is that the pixel matrices of the different sensors are positioned in such a way that they are bordering on each other, but are not overlapping anywhere. While this is sufficient for a first approximation of the relative locations of the pixels, it does not account for the gap and overlap between the sensors or any shifts or rotations of the sensors from their expected positions. A more advanced calculation must therefore be used to correctly determine the locations of the pixels in the prototype.

Each sensor has 6 degrees of freedom to completely describe the positions of all pixels on the sensor, assuming that the sensors themselves are completely flat. These degrees are
two tilts of the sensor in its layer $\beta$ and $\gamma$ (2), equal to rotations around the x- and y-axis, a rotation around the axis perpendicular to the surface of the sensor $\alpha$ (1), equal to a rotation around the z-axis, and a displacement vector from the expected position $\vec{\Delta}$ (3), performed in that order.

By using these parameters, a full mapping from each pixel’s observed position to its real physical position can be made using equation 4.12.

$$
\vec{v}_{\text{real}} = \begin{pmatrix}
\cos \alpha & \sin \alpha & 0 \\
-\sin \alpha & \cos \alpha & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \beta & -\sin \beta \\
0 & \sin \beta & \cos \beta
\end{pmatrix}
\begin{pmatrix}
\cos \gamma & 0 & -\sin \gamma \\
0 & 1 & 0 \\
\sin \gamma & 0 & \cos \gamma
\end{pmatrix}
\vec{v}_{\text{obs}} + \vec{\Delta} \quad (4.12)
$$

The tracks are extrapolated and the points of intersection with the sensors are calculated. The positions where the track is observed can then be compared to the positions where the track is expected to be observed, based on the information from the other sensors in the prototype.

The square of the distance between the observed and the expected coordinates becomes a function of the alignment parameters:

$$
d_i^2 = \left| \vec{v}_{\text{cor}}(\vec{v}_{\text{obs}}, \alpha, \beta, \gamma, \vec{\Delta}) - \vec{v}_{\text{exp}} \right|^2 \quad (4.13)
$$

The optimum alignment parameter can be obtained by minimising the sum of these squared distances.

Several caveats should be given before going through this process:

1. since the geometry limits the movement of the sensors, some alignment parameters will be more important than others,

2. without a fixed reference point, the alignment parameters might start to "drift", never finding an optimal solution, this is caused by equation 4.13 finding a region of minima with equal values,

3. a large number of tracks are required for accurately finding the alignment parameters,

4. because all tracks travel through the prototype in a line approximately perpendicular to the surface of the sensors, most tracks will travel through a single quadrant of the prototype. "Linking" the different quadrants requires tracks which go from one quadrant to another,

5. and since $\vec{v}_{\text{exp}}$ depends on the positions of the hits in other layers, the result of the minimization will also depend on the alignment parameters of the other sensors.

Issue number 1 is partially solved by assuming all sensors are nearly parallel in their surface direction, thereby fixing the parameters $\beta$ and $\gamma$ to 0. The assumption that the longitudinal position of the sensor is defined with great accuracy similarly fixes the parameter $\Delta_z$ to 0. This leaves 3 degrees of freedom for each sensor.

Issue number 2 can be addressed by fixing the transformation parameters of one sensor. This will have the effect that this sensor will become the absolute reference point of the whole prototype. This problem will also become less likely to occur if the number of free parameters is reduced.
While the whole prototype after all these considerations still has \((96 - 1) \cdot 3 = 285\) degrees of freedom, the number of tracks required for accurate alignment is a multiple of this. This is caused by the relatively low occurrence of tracks which connect different quadrants. Also, a number of sensors in the prototype have a very low sensitivity, which reduces the numbers of datapoints which can be used in fitting the parameters of these sensors.

Because \(\vec{v}_{exp}\) of the track in a sensor is calculated from all hits of the track except the hits in the sensor under examination, the result of the calculation of the optimal alignment parameters of one sensor depends on the alignment parameters of a number of other sensors in the prototype. By going through the alignment procedure a number of times, the alignment parameters should converge to optimal values. These optimal values will then minimize the misalignments of all sensors.

The alignment algorithm was created by Hongkai Wang as a part of his PhD research [32], and for a more complete explanation the reader is referred to his future thesis. As an example of the power of his alignment algorithm, the distances between the observed x- and y-coordinates of a single sensor both before and after the alignment procedure are shown in figure 4.7. While this is a reduction of a 4-dimensional parameter space to a 2-dimensional plot, a number of interesting conclusions can already be derived from these results. The location of each sensor before alignment was taken to be set to \((x, y) = (0, 0)\) with the location of the pixel at line 0, column 0 as shown in figure 3.8 as reference.

By examining the fits to the distributions in figure 4.8, compiled in table 4.2, accurate conclusions can be drawn on the alignment of the sensors in the prototype.

The means of the distributions go from \(-106\)\(\mu\)m to 0.81\(\mu\)m in x and \(-148.8\)\(\mu\)m to \(-9.97\)\(\mu\)m in y. This indicates that the mean locations of the tracks are in much better agreement with the values expected from the data from the other layers in the prototype.

The widths of the distributions do not significantly change after using the alignment method, going from a width of 106.1\(\mu\)m to 105.2\(\mu\)m in x and 122.8\(\mu\)m to 108.1\(\mu\)m in y.
4.2. DATA ANALYSIS

<table>
<thead>
<tr>
<th>Direction</th>
<th>Corrected</th>
<th>$\mu$ $\mu$m</th>
<th>$\sigma$ $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>no</td>
<td>-106(1)</td>
<td>106.1(1.7)</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>-0.81(1.36)</td>
<td>105.2(1.5)</td>
</tr>
<tr>
<td>Y</td>
<td>no</td>
<td>-148.8(1.6)</td>
<td>122.8(1.7)</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>-9.97(1.45)</td>
<td>108.1(1.8)</td>
</tr>
</tbody>
</table>

Because the widths of these distributions are related to the positional resolution for tracks in the calorimeter, one would expect them to be comparable to the physical size of the sensor elements (30 $\mu$m).

Figure 4.9 shows the misalignments of all sensors obtained from the alignment algorithm. During assembly the sensors were placed with an accuracy of $\pm$ 200 $\mu$m. While a large variation of misalignments between different sensors can be seen, all but 6 sensors have misalignments which are smaller than 200 $\mu$m.

The sensor positions and orientations are adjusted using the measured alignment parameters. Applying the alignment algorithm once more yields the residuals as shown in figure 4.10. While the alignment algorithm still seems to be attempting to "shift" the sensors around, the residuals are much smaller than before alignment (less than 10 $\mu$m compared to 200 $\mu$m).

Another interesting result of the residual misalignments after the alignment procedure, as shown in figure 4.10, is that it can be explained through simple geometrical considerations.

Since the depth in the prototype approximately scales with the layer number, the almost linear dependence of both the residual X- and Y-misalignments on the depth in the prototype tells us that the alignment procedure is attempting to "skew" the entire prototype. This is caused by the fact that the degree of freedom of skewing of the prototype is not constrained by the alignment procedure. Because of this, the relative residual misalignments of the different layers might start to drift with a linear dependence on the depth in the prototype, as can be seen in figure 4.10. While this skew might become an issue if the number of alignment iterations becomes very large, it can be easily fixed by limiting the range of the misalignment parameters, since these were measured during construction and are known to fall within a small range of values $\pm$0.2 mm.

4.2.5 Shower Location

Because the shower occurring in the calorimeter passes through a number of sensors which do not have the same sensitivities to particles or which are even disabled, the number of hits in a shower depends not only on the energy of the shower but also on the location of the shower in the calorimeter. This gives rise to a position-dependent calorimeter response.

If the shower position $\vec{X}$ is calculated as the average of the positions of all hits $\vec{x}_i$ in the shower:

$$\vec{X} = \sum_{i} \vec{x}_i,$$

this creates a problem. Since the number of hits observed is larger in the more sensitive parts of the calorimeter for the same amount of energy deposited, showers which are distributed across multiple areas of the calorimeter will be "drawn" towards the more sensitive areas.
To work around this problem, the position of the shower is calculated as the mean of the locations of the hits in the first four layers of the calorimeter. This is chosen so that shower in those layers is still in the first phases of its development and therefore will not yet radially extend into other parts of the calorimeter. Thus, the different sensitivities of sensors will have a much smaller influence on the estimate of the position. However, this method can not yet completely remove this effect.
Figure 4.8: Fits to the x- (left) and y- values of figure 4.7 both before (top) and after alignment procedure (bottom). The smooth line indicates a Gaussian distribution fitted to each of the distributions. The distribution is not correctly described by the Gaussian function.
Figure 4.9: Misalignments of all sensors in the prototype, obtained from the alignment algorithm. Split up into X misalignments (top) and Y misalignments (bottom). The sensors of different quadrants in the prototype are indicated by different colours, black: quadrant 0, red: quadrant 1, green: quadrant 2, blue: quadrant 3.
Figure 4.10: Residual misalignments of all sensors in the prototype, obtained from the alignment algorithm. Split up into X misalignments (top) and Y misalignments (bottom). The sensors of different quadrants in the prototype are indicated by different colours, black: quadrant 0, red: quadrant 1, green: quadrant 2, blue: quadrant 3. The values are much smaller than those before the alignment procedure (4.9), but there seems to be a linear relation between misalignment and layer (depth).
4.3 Simulations

A number of simulations of the prototype have been done to examine the possibilities of this new technology. The first thing to be examined was the effect of the disabled and malfunctioning sensors on the prototype’s performance. Since non-functional sensors will not contribute to the signal retrieved from the calorimeter, their influence on the performance will be significant.

The second property of the prototype to be examined was the resolution which is obtainable using these sensors which are very thin when compared to those used in previous sampling calorimeters.

Lastly, the impact of charge sharing between the pixels of the prototype’s sensors was examined. To this end a new program was created which models the charge diffusion process in the sensor material.

The simulations start with the creation of the geometry to be simulated in the simulation software. This models the correct materials with the suitable shapes and densities in the right positions. The geometry module was created by P.J. Blenkers [33] specifically for simulations of the FoCal prototype.

When the geometry has been created to a high enough degree of accuracy, the passage of particles through it can be simulated. This is done using the GEANT3 simulation software, which tracks the different species of particles passing through the materials of the prototype. By calculating the cross-sections of the interaction processes, the movement of the particles through and the interactions of the particles with the materials can be simulated.

The effects of charge sharing are modelled using a different program which will be discussed in more detail in section 4.3.1.

The final step in simulations is to examine the results. This is done by analysing the number of hits generated in the materials which are designated as being sensitive detector materials by the geometry framework.

The simulations replicate the geometries of the prototype in use at both SPS and DESY and at the same time use the same beam composition and beam profile. This will give an accurate representation of the theoretical capabilities of the prototype, while at the same time giving indication of the causes of any reduced performance.

4.3.1 Charge Sharing

The charge sharing algorithm models the effect of the diffusion of free charge carriers in the sensor epitaxial layers. The MAPS has a very high granularity and a very low drift voltage. This results in a much larger distance travelled laterally than in normal sensors. Because of this, the effects of charge diffusion are much more significant than in analogue, high drift voltage sensors. To get the correct results these effects will also have to be modelled.

The assumption made is that the diffusion process occurs through random walks of the charge carriers in the semiconductor region. If a large number of interactions occur before the charge carriers are collected by the sensor, the resulting charge distribution can be assumed to be Gaussian.

From these assumptions the charge collected by an area of dimensions $S_x$, $S_y$, located $\Delta x$, $\Delta y$ from the centre of the distribution follows from:

$$ C(\Delta \vec{x}) = C_0 \int_{-S_x/2+\Delta x}^{S_x+\Delta x} \int_{-S_y/2+\Delta y}^{S_y+\Delta y} \frac{1}{2\pi \sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} dydx , \quad (4.15) $$
which results in:

\[ C(\Delta \vec{x}) = \frac{C_0}{4} D(\Delta x, S_x) D(\Delta y, S_y) \] (4.16)

with:

\[ D(\Delta, S) = \int_{-S/2+\Delta}^{S/2+\Delta} \frac{1}{\sigma \sqrt{2\pi}} e^{-\left( \frac{S^2}{2\sigma^2} \right)} dx = \frac{1}{2\sigma} \left( \text{erf} \left( \frac{S/2 + \Delta}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{-S/2 + \Delta}{\sqrt{2}\sigma} \right) \right) \] (4.17)

Next, assuming square pixels, the amount of charge collected by a pixel located \( i \) pixels in \( x \) and \( j \) pixels in \( y \) away from the pixel the hit is in, follows from the following equation:

\[ C_{i,j}(\Delta \vec{x}) = \frac{C_0}{4} D(\Delta x + iS, S) D(\Delta y + jS, S) \] (4.18)

which is a function depending only on \( i, j, \Delta_x \) and \( \Delta_y \). In order to save computing time the charge sharing algorithm now divides a pixel into 10 by 10 ”subpixels”, each with its own pre-calculated charge sharing matrix for a predetermined number of pixels surrounding the hit. One can ignore the charge deposition which occurs more than several diffusion radii away from the impact point, due to the fast drop-off of the Gaussian distribution.

The charge sharing algorithm goes through the following steps for each simulated hit:

- convert the deposited energy to a number of electrons,
- based on the location on the pixel where the hit occurred, take the charge sharing matrix belonging to the interval the location is in,
- distribute the electrons according to the charge sharing matrix on the pixels.

When all hits have been processed, the charges deposited are stored. During analysis of simulation results, these charges are then compared to a threshold to determine whether a pixel was above threshold or not.

The important parameters in this process are the diffusion radius \( \sigma \) and the detection threshold. From the data presented in [34], a diffusion radius of 15 \( \mu \text{m} \) is estimated. Because \( \sigma \) is of the same magnitude as the pixel size in the MAPS, charge sharing can be expected to contribute significantly to the response of the sensor.
Chapter 5

Experimental Results

The data taken at the accelerators with the setups discussed in sections 3.7 and 3.8 was analysed to determine the properties of the detector. The data sets used during analysis are summarized in table 5.1.

Table 5.1: Data sets measured with the prototype during the beamtests at the DESY and SPS. The numbers of triggers given is integrated over all particle species. There is an increasing pion component with increasing momentum for the SPS beam.

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Date</th>
<th>Momentum (GeV/c)</th>
<th>Triggers</th>
<th>Beam Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESY 03-2012</td>
<td>2</td>
<td>8736</td>
<td>e⁺</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2550</td>
<td>e⁺</td>
<td></td>
</tr>
<tr>
<td>SPS 09-2012</td>
<td>30</td>
<td>28132</td>
<td>e⁺</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>27425</td>
<td>e⁺</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>13974</td>
<td>e⁺ and π⁺</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>28185</td>
<td>mostly π⁺ and very few e⁺</td>
<td></td>
</tr>
</tbody>
</table>

The steps involved in analysing the data sets are:

- the noise levels and number of pixels masked out are examined, because masked out pixels influence the general and positional response of the prototype,

- the raw data from the prototype is examined and the sensors which produce the most consistent responses are determined,

- the results from simulations of the beamtests at DESY and SPS are shown, these are then compared to the raw data,

- two different calibration methods are compared:
  - calibration using Minimum Ionizing Particles,
  - calibration using the spread minimization method.
Figure 5.1: Typical events for 2 GeV/c (left) and 100 GeV/c positrons (right). The large difference in the number of hits in the detector is obvious, which is an aspect of the predicted theoretical shower development.

Each of these analyses will be examined in detail in the following sections.

Two examples of the results from the beamtest data sets are shown in figure 5.1. The left picture shows the result of a 2 GeV/c positron hitting the prototype, while the right shows the result of a 100 GeV/c positron hitting the detector. The large difference in the number of hits as predicted by theoretical calculations is apparent, as is the change in the depth of shower maximum.

Another thing that can be seen from the events shown in figure 5.1 are the large fluctuations in the showers from single particles. Clusters of hits, located more than 1 cm (> 1R_M) from the shower core indicate that some shower components deposit energy that far from the original axis of the primary particle. While analytical predictions of the shower development give smooth distributions, the events displayed show that in reality, this is far from the truth.

A number of the graphs shown in the following sections might display a non-integer number of sensors when showing them as a function of another observable, such as the residual noise in figure 5.2. This is caused by the averaging of the noise values over a number of runs and does not indicate that a fractional number of sensors could have been used.

### 5.1 Noise Levels

Using pedestal measurements, the pixels contributing to high noise levels were identified and masked to reach a noise level of 10^{-5}. Because the number and position of the pixels masked depend on the threshold settings of the sensors, they are different between the DESY and SPS data sets because different threshold settings were used.

The number of pixels ignored in analysis and the remaining noise for the DESY data set is shown in figure 5.2. At DESY the threshold levels were set at a very high level to suppress noise. Improved settings were derived by the time of data taking at SPS, which improved the sensitivity of the sensors while keeping the noise at an acceptable level, this is shown in figure 5.3.
5.1. NOISE LEVELS

Some sensors were completely disabled or were performing erratically, and are ignored during analysis. The number of disabled sensors is 30 at DESY and 34 at SPS (see section 7 for sensor numbers), which correspond to 31.3% and 35.4% of the total number of sensors. These sensors did not produce any data to base the masks on and are not included in figures 5.2 and 5.3. Since the number of disabled sensors and their locations varies from quadrant to quadrant, the response of the prototype will vary with the position at which the shower occurs.

It can be seen from both plots that a number of sensors in the prototype have distributions of noise which require that a significant fraction of the pixels need to be masked to reduce the noise to an average of $10^{-5}$ per pixel per frame. The average coverage for the active sensors was 99.0% at DESY and 98.2% at SPS, giving the prototype an overall coverage of 68.0% at DESY and 63.4% at SPS. The higher average coverage at DESY when compared to SPS is the result of the lower thresholds used at SPS, which require masking more pixels to achieve the same noise levels.

The remaining average noise of the sensors calculated using the masking analysis is taken as the pedestal and subtracted from the number of hits of the events in further analysis. The spread of the pedestal, which is the real noise on the signal is the Poissonian width of the pedestal for the DESY and SPS datasets is summarized in table 5.2.

When the total width of the distribution is compared to the contribution to it by the noise, it can be seen to be very small. For example, the total width of the distribution at 2 GeV is 87, while the noise is less than 11.7080. Since the different sources of the width of the distribution are added squared, the total contribution of the noise will follow:

$$11.7080^2/87^2 = 137.077/7569 = 1.81\%$$  (5.1)
Figure 5.3: The distribution of the remaining noise (left) and masked pixels (right) for the SPS data sets. There are less sensors with a very low number of masked pixels when compared to DESY. This is caused by the lowering of the sensor thresholds which increases sensitivity and noise, requiring more pixels to be masked out to reach the same sensor noise level.

Table 5.2: The average remaining noise per frame for the DESY and SPS datasets.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Pedestal</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESY</td>
<td>137.077</td>
<td>11.7080</td>
</tr>
<tr>
<td>SPS</td>
<td>219.7</td>
<td>14.82</td>
</tr>
</tbody>
</table>

Therefore ignoring the noise will cause the stochastic and constant terms to be estimated wrongly no more than approximately half this amount\(^1\), or less than 1% of their total value at 2 GeV, and less at higher energies.

5.2 Signal Distributions From Raw Data

Taking all triggered frames from the data collected at DESY and subtracting the pedestal, after masking of noisy pixels, results in the signal distributions shown in figure 5.4.

The signals from 2 and 5 GeV/c show broad distributions with a tail towards lower numbers of hits. Both distributions also have a tail at higher numbers of hits, where the tail to higher numbers of hits seems to be more pronounced at 2 GeV/c. The first thing that can be seen is that the number of hits grows with increasing energy, which is the behaviour looked for in a calorimeter. Gaussian functions were fitted to both distributions to determine their width and mean.

The large widths of the distributions are likely caused by the different sensitivities of the sensors and the different numbers of working sensors in each quadrant, causing a positional

\(^1\)Due to the approximation \(\sqrt{1 + x} \approx 1 + x/2\) for small \(x\).
5.2. SIGNAL DISTRIBUTIONS FROM RAW DATA

Figure 5.4: Raw distributions of the number of hit pixels with $e^+$ of 2 GeV/c (magenta) and 5 GeV/c (cyan) and Gaussian fits to the distributions (black), measured at DESY. The events with a negative number of hits are caused by subtracting the pedestal from a triggered frame containing no data, caused by the trigger PMTs giving a signal when there is no particle hitting the part of the detector which is read out.

dependence of the signals. After determining the position of the showers, using the method explained in section 4.2.5, the distributions of the number of hits for the 5 GeV/c measurements are split up according to the quadrant they occur in. The result is shown in figure 5.5, where quadrants 0 and 1 (black and red) have significantly higher responses to the same energy compared to quadrants 2 and 3 (blue and green).

The result of fitting Gaussian functions to the distributions obtained for both 2 and 5 GeV/c are summarized in table 5.3. This shows that quadrant 0 gives the best resolution at 5 GeV/c and the second best resolution at 2 GeV/c.

Table 5.3: The mean and width of the distributions of signals and the derived resolutions from the prototype, split into the different quadrants. These values were obtained by fitting Gaussian functions to the distributions.

<table>
<thead>
<tr>
<th>Momentum GeV/c</th>
<th>Quadrant</th>
<th>Mean</th>
<th>Sigma</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>2.42(3)·10^2</td>
<td>8.7(2)·10^1</td>
<td>0.359(9)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.86(2)·10^2</td>
<td>9.5(2)·10^1</td>
<td>0.332(8)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.71(2)·10^2</td>
<td>1.127(17)·10^2</td>
<td>0.415(7)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2151(19)·10^2</td>
<td>8.13(15)·10^1</td>
<td>0.378(8)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>8.63(9)·10^2</td>
<td>1.27(8)·10^2</td>
<td>0.148(9)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9.62(8)·10^2</td>
<td>1.55(8)·10^2</td>
<td>0.161(8)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.38(6)·10^2</td>
<td>1.84(5)·10^2</td>
<td>0.219(7)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.86(6)·10^2</td>
<td>1.40(6)·10^2</td>
<td>0.178(7)</td>
</tr>
</tbody>
</table>
To allow for the best performance of the prototype, based on table 5.3, only showers occurring in quadrant 0 are used for the analysis. This results in the following position cuts:

- x is between 0 and 1.92 cm,
- and y is between 0 and 1.92 cm.

Figure 5.6 shows the signal distributions using these cuts on the shower position. Just as in figure 5.4, Gaussian functions were fitted to these distributions. The parameters of these fits are summarised in table 5.4. This shows the effect of the positional cuts for the data taken at DESY. While the effect on the means of the distributions appears minimal, the widths and resolutions are much improved. Also the great majority of events at the very low end of the distribution is suppressed, which is shown in figure 5.6.

Table 5.4: Comparison between Gaussian fits to the distributions of hits obtained at DESY without positional cuts (fig. 5.4) and with positional cuts (fig. 5.6).

<table>
<thead>
<tr>
<th>Momentum GeV/c</th>
<th>Positional Cut</th>
<th>Mean</th>
<th>Sigma</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>No</td>
<td>2.640(12) \cdot 10^2</td>
<td>1.012(10) \cdot 10^2</td>
<td>0.383(4)</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>2.42(3) \cdot 10^2</td>
<td>8.7(2) \cdot 10^1</td>
<td>0.359(9)</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>8.50(4) \cdot 10^2</td>
<td>1.73(3) \cdot 10^2</td>
<td>0.204(4)</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>8.63(9) \cdot 10^2</td>
<td>1.27(8) \cdot 10^2</td>
<td>0.148(9)</td>
</tr>
</tbody>
</table>

The positional cuts on the DESY data seem to give a strong improvement on the resolutions obtained, especially for the 5 GeV/c events. Subsequent analyses of this data set will only use events which use the same positional cuts.

Figure 5.7 shows the distributions of the raw signals for the measurements at SPS. The distributions at all energies show peaks, but these have a very broad and non-Gaussian appearance. This means that Gaussian fits are not appropriate to derive the characteristic quantities from these distributions. There also appears to be an additional exponentially decreasing component in the distribution for the measurements at 100 GeV/c. The distribution of signals at 200 GeV/c is not shown, since the great majority of the particles in the beam at that energy are pions.

The exponentially decreasing component of the distribution is most likely caused by an admixture of pions in the beam, which most of the time will only deposit a fraction of their energy in the prototype. Tracks in the prototype created by these particles explain the large peaks at very low number of hits as well. The prototype is 0.86 hadronic interaction lengths deep. Because of this depth the number of hadrons which have not started to shower will remain approximately constant throughout the depth of the prototype.

The hadronic showers can therefore be seen as a combination of a number of tracks, which go over to showering at approximately random depths in the prototype. If the hadron has an interaction near the back of the prototype, the electromagnetic component of the shower will still be in its exponential growth stage, which gives rise to the lower end of the distribution seen in figure 5.7. However, if the hadronic shower starts near the front of the calorimeter, the number of hits it produces will be very similar to those of electromagnetic showers of the same energy.
5.2. SIGNAL DISTRIBUTIONS FROM RAW DATA

While cuts on the numbers of hits per event will enable a significant separating power between hadronic and electromagnetic showers; not all hadronic showers can be separated from the electromagnetic showers by a numerical alone. Also, basing the analysis solely on this cut may bias the response, and from this, the estimate of the resolution. Still, it can be used to look at the different components of the beam.

In the following analysis a distinction is made between "tracks", events with fewer than 1000 hit pixels, which are almost certainly caused by hadrons, and "showers", events with more than 15000 hits, which will mostly be caused by electromagnetic particles. By comparing the positions where tracks enter the prototype, as calculated from the direction of the track (section 4.2.2), with the locations of the showers, as based on the first four layers of the prototype (section 4.2.5), the picture in figure 5.8 appears.

The secondary and tertiary beams of the SPS at the North Area of CERN are produced by colliding protons with a converter target. This process produces a large amount of hadrons (mainly pions) at the same time. If these pions are not adequately removed by the beam optics, they will hit the prototype. Since there was insufficient online discrimination between hadrons and leptons during the beamtest at SPS, these hadrons will appear in the triggered events of the prototype.

In figure 5.8 we observe a "splitting" of the beam into a hadronic and leptonic component. It is not clear, how this appears in the test beam line, but with this knowledge, positional cuts can also be used to remove the pion contamination from the data set. The window which contains only showering particles and which is at least 0.3 cm removed from any edge is:

- x between 0.3 and 1.0 cm,
- y between 0.3 and 0.7 cm.

Applying those cuts results in signal distributions as shown in figure 5.9. The distributions are better shaped and the strong low-energy (pion) component has largely disappeared. Also, the peaks can be described reasonably well by Gaussians, which are then used for fitting.

The results of fitting a Gaussian distribution to the response curves with positional cuts are shown in table 5.5.

<table>
<thead>
<tr>
<th>Momentum GeV/c</th>
<th>Mean</th>
<th>Sigma</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.42(3) \times 10^{2}</td>
<td>8.7(2) \times 10^{1}</td>
<td>0.359(9)</td>
</tr>
<tr>
<td>5</td>
<td>8.63(9) \times 10^{2}</td>
<td>1.27(8) \times 10^{2}</td>
<td>0.148(9)</td>
</tr>
<tr>
<td>30</td>
<td>5.599(19) \times 10^{3}</td>
<td>4.65(15) \times 10^{2}</td>
<td>0.083(3)</td>
</tr>
<tr>
<td>50</td>
<td>9.600(4) \times 10^{3}</td>
<td>6.2(3) \times 10^{2}</td>
<td>0.065(3)</td>
</tr>
<tr>
<td>100</td>
<td>1.843(5) \times 10^{4}</td>
<td>1.05(4) \times 10^{3}</td>
<td>0.057(2)</td>
</tr>
</tbody>
</table>

The use of the positional cuts removed a large part of the hadronic component of the beam from the signals in the distribution. The result is that the widths of the distributions are much smaller when compared to those without positional cuts (figure 5.7).
CHAPTER 5. EXPERIMENTAL RESULTS

Figure 5.5: Raw distributions of the number of hit pixels with $5\text{ GeV}/c\ e^+$ measured at DESY, split up into different prototype quadrants. A large difference between the response of quadrants 1 (red) and 3 (blue) is shown, with quadrants 0 (black) and 2 (green) falling in between.
5.2. SIGNAL DISTRIBUTIONS FROM RAW DATA

Figure 5.6: The same as figure 5.4 with the additional restriction that the showers must start in quadrant 0.

Figure 5.7: Distribution of signals from all triggers and all quadrants for $e^+$ at 30 (red), 50 (green) and 100 GeV/$c$ (blue), as measured at SPS. The shape of the curves are obviously not Gaussian. Note the "shoulder" in the 50 GeV/$c$ distribution hinting at a combination of multiple Gaussians, and the long tail at 100 GeV/$c$, possibly caused by particles other than electrons.
CHAPTER 5. EXPERIMENTAL RESULTS

Figure 5.8: The distribution of the location of tracks (left) and the location of showers (right), a splitting of the beam into 2 types of interactions can be seen at data obtained at SPS at 100 GeV/c.

Figure 5.9: Distribution of hit pixels for $e^+$ at 30 GeV/c (red), 50 GeV/c (green) and 100 GeV/c (blue), as measured at SPS as in figure 5.7. In addition cuts on the shower position based on the results of the analysis of figure 5.8 are applied.
5.3 Simulation Results

Simulations of the prototype used at both DESY and SPS were done using the simulation framework. These simulations implemented the geometries of the prototype at both beamtests, and used the beam composition, position and profile that was derived from the data taken.

The simulations can not yet take the effects of masking pixels or position dependant sensitivity into account. After running the simulations and ignoring the signals from unreliable sensors, the spectra of the number of particles hitting the active sensors are shown in figure 5.10.

When the number of hits derived from simulations in figure 5.10, while taking into account that the pion contamination is not explicitly simulated, is compared with those from experiment in figures 5.6 and 5.9 shows a factor five difference between the number of hits from simulations and those from experiment.

The factor of five difference between the observed hits and the simulated hits might be accounted for if the response of the detector is not taken as the number of energy depositions, but as the number of pixels with a charge above a certain threshold if charge sharing is taken into account. With the charge sharing radius having a dimension (15µm) similar to the pixel pitch (30µm), enough charge could be shared between pixels to match the number of active pixels to the observed value. The method used in the simulations is explained in more detail in section 4.3.1.

The number of hits derived for a range of thresholds was compared to the number of hits observed in experiment. For the DESY simulations the threshold derived was found to be 800 eV above the noise, and for SPS to be 130 eV above the noise. These values depend on the charge sharing radius, with a larger radius meaning the charge is shared between more pixels which reduces the threshold.
Using these thresholds on the simulations with charge sharing, results in the responses shown in figure 5.11. When figure 5.11 is compared to figures 5.6 and 5.9, a much better agreement can be seen between the number of hits observed in simulations and experiment.

A multi-peaked structure appears, especially in the SPS simulations. This structure is caused by the different numbers of operational sensors in each quadrant. This is illustrated in figure 5.12.

Since each quadrant functions as its own calorimeter with its own response to particles of different energies, particles hitting these detector quadrants will cause these different responses to appear as a number of peaks at the responses. When the showers spill over into other quadrants, the response will be a sum of parts of responses from several quadrants, widening the observed peak for that quadrant.

This is observed in figure 5.11 for the SPS results (right panel), but not for the DESY results (left). It is very likely that the different responses of the quadrants do not lead to identifiable peak structures for the lower energies, where the relative width of the distribution (the resolution) is larger.

While this multiple peak structure is not observed in experiment to the degree as it is in simulations, some hints to it can be observed in the 50\(\text{GeV}/c\) spectrum in figure 5.7. There the spectrum has a ”shoulder” at the higher end, hinting at a multiple peak structure.

After using the same location cuts as used in the analysis of the beamtest data, the spectra in figure 5.13 are obtained.

When the exposure of the prototype is reduced to a single quadrant in both simulations (figure 5.13) and experiment (figures 5.6 and 5.9) the shapes of the responses and their average values agree to a much higher degree.

Another aspect in which simulation and experiment are similar is the disappearance of the dual peaked structure in the simulation and the ”shoulder” in the 50\(\text{GeV}/c\) SPS structure, indicating that the spread of showers to multiple quadrants is responsible for a large fraction of these effects. The results of Gaussian fits to these curves are summarized in table 5.6.
5.3. SIMULATION RESULTS

Table 5.6: Results from fits of Gaussian distributions on DESY (fig. 5.13 left) and SPS (fig. 5.13 right) simulated data with location cuts.

<table>
<thead>
<tr>
<th>Momentum GeV/c</th>
<th>Mean</th>
<th>Sigma</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$3.215(4) \times 10^2$</td>
<td>$4.30(3) \times 10^1$</td>
<td>$0.1338(10)$</td>
</tr>
<tr>
<td>5</td>
<td>$7.726(8) \times 10^2$</td>
<td>$7.31(7) \times 10^1$</td>
<td>$0.0947(9)$</td>
</tr>
<tr>
<td>30</td>
<td>$5.821(4) \times 10^3$</td>
<td>$2.379(3) \times 10^2$</td>
<td>$0.0409(6)$</td>
</tr>
<tr>
<td>50</td>
<td>$9.405(6) \times 10^3$</td>
<td>$3.19(5) \times 10^2$</td>
<td>$0.0339(5)$</td>
</tr>
<tr>
<td>100</td>
<td>$1.7819(4) \times 10^4$</td>
<td>$4.79(3) \times 10^2$</td>
<td>$0.02686(17)$</td>
</tr>
</tbody>
</table>

By choosing the correct threshold values, a detector response almost identical to that derived from the experimental data can be achieved. The width of the distributions derived from those responses is about half of those derived from the experimental data. For this there are a number of possible explanations:

- not taking into account differing sensitivities of sensors,
- incorrect assumptions on the charge diffusion mechanism,
- and differences in the inherent noise levels of the sensors.

All of these factors will contribute to an increase in the relative spread of responses and would move the values obtained from the simulations closer to those obtained from the experimental data. The differences in sensitivity can be corrected for in the experimental data by correct calibration of the prototype, the results of which will be discussed in the following sections.
Figure 5.12: Distributions of hit pixels over threshold with simulations of 30\,GeV/c positrons at SPS, split up into quadrants 0 (black), 1 (red), 2 (green) and 3 (blue). A large variation between the responses of the different quadrants can be observed, especially for quadrant 3.
Figure 5.13: Distribution of the number of pixels over threshold from Monte Carlo simulations for 2 GeV/c (magenta) and 5 GeV/c (cyan) (left), 30 GeV/c (red), 50 GeV/c (green) and 100 GeV/c (blue) (right). Additionally, the location cuts described in chapter 5.2 are used. The black lines show Gaussian fits to the distribution. The width of both distributions is visibly smaller, but a tail at a level of 10% of the peak still remains. This indicates that the positional cuts are not yet strict enough to prevent leakage of the showers to other quadrants.
Figure 5.14: The clustersize distributions of a "good" sensor (sensor 49) on the left, and a "bad" (sensor 85) sensor on the right obtained by examining the signals left 200 GeV/c pions at the SPS. The good sensor has an average clustersize of around 4, and will give a signal in over 80% of cases, while the bad sensor’s average clustersize is less than 0.5, and will give a signal in less than 25% of cases.

5.4 Calibration Using Pions

Since, on average, a minimum ionizing particle deposits the same amount of energy in the same thickness of material, the responses from these particles can be used as an absolute calibration tool. Since there is no pion or other MIP data with which to calibrate the data taken at DESY, the pion calibration method cannot be used on this data.

By examining the 200 GeV/c spectrum, it is concluded that non-showering particles compose the majority of the beam. By only selecting the events with fewer than 1000 hits in the detector, any particle which starts showering will be discarded. The events which are not discarded by this cut are then passed to the tracker which searches for any hits that belong to the track (see 4.2.2). The largest contiguous group of hits, a "cluster", is taken to be the signal from the track. Two examples of the distributions of clustersizes are shown in figure 5.14.

The large variation in responses to pions between the different sensors becomes obvious in figure 5.14. Some sensors generate signals to pions less than 50% of the time. This can be the result of wrong threshold settings. By changing the threshold settings for these sensors, the tracking efficiency of the prototype can be increased. The result of comparing the clustersizes from the different sensors is shown in figure 5.15.

The average clustersize is an indication of the sensitivity of the sensor, and it is calculated by including clusters of zero size. The clusters of zero size indicate that a track was expected to pass through a certain region of a sensor, but no hits were found. The inverse of the average clustersize will be used as the calibration factor for that sensor. Any sensors with an average response of less than 0.1 are ignored for being unreliable, with the calibrated signals shown in figure 5.16.

The results from the Gaussian fits are summarized in table 5.7.
5.4. CALIBRATION USING PIONS

Figure 5.15: The average clustersize as a response to 200\,GeV/c pions at the SPS as a function of sensor number. While most sensors have an average clustersize between 1 and 5, there are some sensors which have an average clustersize which is much lower. These are not used in the calibration process.

Table 5.7: Resolutions obtained from fitting Gaussian functions to the signals obtained at SPS after pion calibration and location cuts.

<table>
<thead>
<tr>
<th>Momentum GeV/c</th>
<th>Mean ( \times ) 10^3</th>
<th>Sigma ( \times ) 10^2</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.943(7) \times 10^3</td>
<td>1.58(6) \times 10^2</td>
<td>0.081(3)</td>
</tr>
<tr>
<td>50</td>
<td>3.332(12) \times 10^3</td>
<td>2.14(10) \times 10^2</td>
<td>0.064(3)</td>
</tr>
<tr>
<td>100</td>
<td>6.401(16) \times 10^3</td>
<td>3.68(16) \times 10^2</td>
<td>0.058(3)</td>
</tr>
</tbody>
</table>

Calibration with this method effectively leads to no improvement: the resolution is very similar to the one for the raw data. Possible explanations for the ineffectiveness of this method may be the differences in sensitivities of the sensors to showers and pions.
Figure 5.16: Distributions of the 30 GeV/c (red), 50 GeV/c (green) and 100 GeV/c (blue) shower responses at SPS, calibrated with pion responses.
5.5 Spread Minimization Method

The aim of the spread minimization method is to obtain the best resolution possible for a certain data set. This is achieved by multiplying the response of each sensor by its own calibration factor as in equation 4.10, and then minimizing the relative spread of the responses by varying these calibration factors.

This is a relative calibration method, since the obtained calibration factors minimize the relative spread. The response plots may therefore be scaled by an arbitrary factor to have the same significance.

By discarding the top and bottom 2.5% of the showers, determined by examining the spectrum of the number of hits, the effect of outlier datapoints is reduced. The end result is that the fitted curves follow the obtained distributions more closely.

The calibration parameters of the sensors have been limited to the range 0.001..1.0, in order to prevent the minimization method to attempt reducing the spread by setting all responses to 0. The sensors that were disabled during data taking have had their calibration parameters fixed to 0 during the minimization procedure.

The calibration factors obtained from the DESY data sets are shown in figure 5.17. While there are some differences between the factors obtained from the different DESY data sets, a lot of calibration factors obtained seem to converge to the same values. Sensors which have a large calibration factor at one energy are also very likely to have a large calibration factor at another energy. This, combined with the very similar resolution obtained by using the calibration factors from different energies on the data of the same energy (see table 5.8), indicates that this calibration method is reliable in improving the resolution.

The calibration factors obtained from the SPS data sets are shown in figure 5.18. The factors derived from the SPS data sets show a number of differences between the different energies, but most are very similar. Most sensors which have a smaller calibration factor in the 30 GeV/c data set, such as 48-51, also have a smaller calibration factor in the 50 GeV/c and 100 GeV/c data sets. There are large differences between the calibration factors
obtained from the DESY and SPS data sets for some sensors. There are a number of factors which can be responsible for this:

- the construction of the prototype is different (see chapters 3.7 and 3.8),
- differences in beam position and shower profile,
- and differences in the sensor thresholds settings (see chapter 7).

The result of using the calibration factors obtained from the 30 GeV/c data set is shown in figure 5.19. The responses have been multiplied by a factor chosen such that the mean responses of the prototype after calibration match those obtained before calibration.

The results of the Gaussian fits to the calibrated data are shown in table 5.8. The spread minimization method improves the obtained energy resolution in all cases. Also the best resolutions calculated using this method are very similar for different calibration data sets. This indicates that this method is reliable for different data sets.

The resolution obtained with the different methods is summarized in figure 5.20. The figure also shows fits of equation 2.37. The values of the parameters obtained are given in table 5.9.
5.5. **SPREAD MINIMIZATION METHOD**

![Graph showing number of hits and number of occurrences](image)

**Figure 5.19:** Responses from data taken at SPS calibrated with factors derived from 30 GeV/c data.

**Table 5.8:** Resolution obtained by using spread minimization on all data sets with position cuts, the calibrated responses have been scaled such that the mean response is the same as for the uncalibrated data.

<table>
<thead>
<tr>
<th>Data set GeV/c</th>
<th>Calibration Set GeV/c</th>
<th>Mean</th>
<th>Sigma</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>2.512(18)·10²</td>
<td>6.14(15)·10¹</td>
<td>0.245(6)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.85(3)·10²</td>
<td>8.8(2)·10¹</td>
<td>0.307(7)</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>6.97(8)·10²</td>
<td>1.19(7)·10²</td>
<td>0.171(10)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8.63(8)·10²</td>
<td>1.22(7)·10²</td>
<td>0.141(8)</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>5.735(15)·10³</td>
<td>3.56(13)·10²</td>
<td>0.062(2)</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5.657(18)·10³</td>
<td>4.40(15)·10²</td>
<td>0.078(3)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5.592(17)·10³</td>
<td>4.16(15)·10²</td>
<td>0.074(3)</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>9.60(3)·10³</td>
<td>4.9(3)·10²</td>
<td>0.051(3)</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>9.58(3)·10³</td>
<td>4.9(2)·10²</td>
<td>0.051(3)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>9.40(4)·10³</td>
<td>5.7(3)·10²</td>
<td>0.060(3)</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>1.899(4)·10⁴</td>
<td>8.4(3)·10²</td>
<td>0.0444(18)</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.952(4)·10⁴</td>
<td>8.9(4)·10²</td>
<td>0.0458(19)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1852(4)·10⁴</td>
<td>8.1(3)·10²</td>
<td>0.0438(18)</td>
</tr>
</tbody>
</table>
Figure 5.20: A comparison of resolutions obtained from both experiment and simulations. The dotted lines indicate fits of equation 2.37 to the uncalibrated and simulated data sets. The DESY sets were not fitted because there are too few datapoints to fit the function to give an accurate result.

Table 5.9: Results of fitting equation 2.37 to the points in figure 5.20. The noise term $c$ has been set to 0 since its contribution to the total noise is not constant across the entire range of datapoints.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Stochastic Term $b$ [GeV$^{1/2}$]</th>
<th>Constant Term $a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Data</td>
<td>0.445(10)</td>
<td>0.030(4)</td>
</tr>
<tr>
<td>Simulated Data</td>
<td>0.1943(12)</td>
<td>0.0188(4)</td>
</tr>
<tr>
<td>30 GeV/c Calibrated Data</td>
<td>0.28(2)</td>
<td>0.034(4)</td>
</tr>
<tr>
<td>Pion Calibrated Data</td>
<td>0.37(3)</td>
<td>0.043(6)</td>
</tr>
</tbody>
</table>
5.6 STRINGENT SENSOR SELECTION METHOD

The sensors in table 7.6 were found to have problems with the synchronization of one or more channels. These channels will have a negative effect on the observed resolution of the prototype by only contributing to the response when they are working, thereby widening it.

While disabling these sensors will leave the prototype with only 39 sensors which provide data, the concept of the stringent selection method is that the quality of this data is higher than the other sensors in the prototype. This should result in a more accurate response.

The result of this selection of sensors is shown in figure 5.21 and in comparison the result of simulations of the same sensors is shown in figure 5.22.

After fitting Gaussian functions to the distributions in figures 5.21 and 5.22 the obtained parameters are shown in table 5.10.

Table 5.10 shows that the resolution obtained using this method is worse for both experimental and simulated data. This is the consequence of having fewer samples of the shower’s development.

One would expect that the agreement between experimental data and simulation will be better after the more stringent selection. This is, however, not the case. At all energies the relative spread of the responses of experimental grows at least as much, if not more, than those from the simulated data.

The main conclusion that therefore can be drawn from table 5.10 is that the stringent selection method does not improve the relation between the simulated and experimental data or the resolution obtained. This method shall therefore be ignored in further comparisons of results.
Figure 5.22: Distributions of simulated signals of the setup of the prototype at the beamtest at SPS after only including the signals from the sensors which have functioned without problems, and showers which fall in the electron shower region.

Table 5.10: Results from the Gaussian fits to the experimental data in figure 5.21, to the simulated prototype in figure 5.22, compared with the results from the normal selections from tables 5.5 and 5.6.

<table>
<thead>
<tr>
<th>Data</th>
<th>Fit Parameters</th>
<th>Obtained Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Sigma</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p$ GeV/$c$</td>
<td>Source</td>
<td>Mean</td>
</tr>
<tr>
<td>30</td>
<td>simulation</td>
<td>4.492 (3) · 10$^3$</td>
</tr>
<tr>
<td>30</td>
<td>experiment</td>
<td>4.749 (17) · 10$^3$</td>
</tr>
<tr>
<td>50</td>
<td>simulation</td>
<td>7.228 (6) · 10$^3$</td>
</tr>
<tr>
<td>50</td>
<td>experiment</td>
<td>8.03 (4) · 10$^3$</td>
</tr>
<tr>
<td>100</td>
<td>simulation</td>
<td>1.3538 (3) · 10$^4$</td>
</tr>
<tr>
<td>100</td>
<td>experiment</td>
<td>1.500 (4) · 10$^4$</td>
</tr>
</tbody>
</table>
5.7 Linearity

As shown in section 2.2.2 the response per unit energy of a calorimeter is defined as:
\[ R(E) = \frac{\bar{S}(E)}{E} , \]  
with \( \bar{S}(E) \) being the signal at energy \( E \). Using the above equation we can calculate the alinearity of the prototype which is defined as how much the response per unit of energy deviates from one particle energy to another:
\[ A_{E_{\text{ref}}}(E) = \frac{R(E)}{R_{\text{ref}}} - 1.0 , \]
with \( E \) being the energy at which the linearity is being calculated and \( R_{\text{ref}} \) being the data-point whose response the linearity is relative to. A positive alinearity means that the response at that energy is higher than expected, extrapolating from the reference energy, while a negative alinearity means a lower response than expected.

Alinearity of a calorimeter can have a number of causes, such as:

(a) detection thresholds of the sensor elements,
(b) saturation effects on the sensor elements,
(c) charge sharing between pixels,
(d) and shower leakage.

Since we know the noise levels of the chips with significant accuracy due to the pedestal measurements, and have corrected the sensor responses accordingly, their effect on the prototype linearity will not reach any significant level. The pixels of the sensors used in the prototype have a detection threshold, which can influence the linearity as well.

Saturation effects are expected to occur when the average number of shower particles per surface area approaches the calorimeter granularity. At this point the probability of multiple hits per pixel becomes large enough, causing the sensor response to flatten off with an increasing number of particles. This should result in a negative alinearity for higher energies, as the number of particles in a shower has an approximately linear dependence on the shower energy.

Another contributing factor to alinearity is charge sharing between pixels. When the hit density in the sensor begins to increase, the amount of charge shared between the pixels also increases. Due to the detection threshold, this causes a positive alinearity for lower energies, because more pixels have enough charge. At higher shower energies, charge sharing contributes to a negative alinearity, as it then contributes to the saturation of the pixels.

Shower leakage becomes a problem when the shower occurs close to the edge of a calorimeter, because the particles which exit the calorimeter no longer contribute to its response. For instance, a shower which happens at the edge of the calorimeter can only be expected to have a fraction of the response when compared to one which happens in the centre. Because of this, shower leakage is expected to give a reduction in the response, which increases which the proximity of the shower to the edge of the calorimeter and a resulting negative alinearity. Since the prototype has the ability to determine the shower position with great accuracy,
any showers which occur less than 5 mm from its edges are ignored in the analysis, greatly reducing the effects of shower leakage.

Because the calorimeters used at DESY and SPS are different, comparing their responses can not be done directly. One method of accounting for the differences in response is by taking the response from the simulated SPS data at 30 GeV and scaling it down to the response which would be expected at 5 GeV. Dividing the expected response by the observed DESY response then gives the factor which all DESY data will need to scaled up by, as shown in equations 5.4 and 5.5:

\[ A_{corr} = \frac{S_{SPS}(30 \text{ GeV})}{S_{DESY}(5 \text{ GeV})} = 1.256, \quad (5.4) \]

\[ S_{corr}(E) = S_{DESY}(E) \times A_{corr}. \quad (5.5) \]

This correction factor is applied to the DESY data in figure 5.23, which shows the detector signal as a function of beam energy.

Apparently, the raw data shows reasonably linear behaviour already, as can be seen from the comparison to the linear fit shown in figure 5.23. The calibration with the spread minimisation seems to yield only minor modifications to this behaviour.

The data points using pion calibration are completely off, which was to be expected from the different response to pions as discussed earlier. One can look at details of the linearity behaviour by studying the response as shown in figure 5.24, or alternatively as the relative deviations from linearity (alinearity) in figure 5.25. Those deviations are in the order of 5% for most except for the DESY datapoints.

One possible explanation for the larger DESY alinearity is a reduction of the response for decreasing energies caused by the showers being sampled by fewer layers due to their smaller longitudinal size for lower energies. This can be seen in the experimental DESY as a much lower response for the 2 GeV data when compared to the 5 GeV data.

A contributing factor to the detector alinearity may come from variations in the longitudinal distribution, as is illustrated in figure 5.26. As the depth where shower maximum occurs is further in the detector with increasing energy, the relative contributions of the different layers, which may have different sensitivities, to the total response changes as well. The total response of the detector thus has a more complex relation to the particle energy than a simple linear relation.
Figure 5.23: A comparison of signals from DESY and SPS, after correcting for the different calorimeter constructions. The dotted line indicates a linear fit to the raw data points which passes through the origin.
Figure 5.24: A comparison of prototype responses. Note that the pion response is a factor of \( \approx 2.5 \) smaller due to the average number of hits per particle (\( \approx 2.5 \)). All other responses are very similar. The dotted line indicates a fit of a constant to the raw data responses. All responses are located very close to this line.
Figure 5.25: A comparison of a linearities derived from the responses in figure 5.24. $R_{ref}$ is the SPS 30 GeV datapoint. All calculated alinearities fall within 10%, except for the pion-calibrated datapoints, which were not analysed.
5.8 Shower profiles - an outlook

Longitudinal shower distributions at 30 and 100 GeV are shown in figure 5.26. A number of points that may be relevant for future development can be derived from them.

When looking at the uncalibrated profiles for 30 GeV showers, the first thing one can observe is that the prototype’s response to the electromagnetic shower is far from uniform. For instance, the average response of layer 9 is around 750, whereas layers 8 and 10 have responses of 290 and 150 respectively. Both are much lower than the average responses of layers 6 and 7 as well as layers 11 and 12, which are all around 400 hits.

The same observations can be made for the results for 100 GeV showers at layers 8, 9 and 10. Again the response of layer 9 seems to be significantly greater than those of the surrounding layers, and the responses of layers 8 and 10 seem to be significantly lower.

One explanation for the observed deviations in the prototype’s response is the difference in the sensitivities of the different layers to the shower particles. As discussed in section 2.2.2, the difference in sensitivities will also affect the prototype linearity and resolution, due to the enhancement of layer-independent fluctuations and energy-dependent layer contributions to the total response.

To more completely correct for these effects, additional analyses will still need to be done. Which will involve the use of transverse shower profiles, which can give the shower development on a per-layer basis with a spatial resolution better than 100 µm. Unfortunately, the development of these techniques is not a part of this thesis.
Chapter 6

Conclusions

This chapter will summarize the findings from the previous chapters and draw conclusions from these findings. Finally an outlook for the future of the pixel counting method in FoCal is given.

6.1 Prototype Design and Construction

The construction of the prototype has achieved a number of goals.

First is the alignment reached during construction. The need for precise alignment was taken into account from the beginning of prototype design, and the fact that all but 6 sensors were found to be placed with a precision better than 200µm (see fig. 4.9), shows that the method of aligning the sensors was successful.

Second is the creation of a cooling system which was able to remove the heat generated inside the prototype. While the cooling elements were located more than 2 cm from some parts of the sensors, the sensors were kept on average 10 °C above the temperature of the coolant. And while the threshold settings were not able to completely remove all noise from the readout, of which some could be expected to come from thermal sources, the use of the mask managed to keep it on an average level of 10^{-5} per pixel per frame.

Third, the data acquisition system is successful in transporting over 60 Gbps of data produced by the sensors outside the prototype. The data is then buffered by the Virtex system after which it is archived by the data-acquisition computer.

The prototype ran into several problems during construction which negatively affected its performance:

- a number of sensor chips were damaged during their separation from the die, reducing the number of functional chips available during construction,

- some of the sensor chips were not bonded successfully to the carrier circuit boards, further reducing the number of chips available,

- and there were a number of sensors which have one or more data channels that do not synchronize correctly.
CHAPTER 6. CONCLUSIONS

The first two issues can be partially addressed in following tests by the use of newly bonded chips. While the supply of new chips is limited, there are some left which can be bonded to circuit boards and used as a replacement for malfunctioning sensors.

Another possible solution to the problem can be new firmware for the Virtex and Spartan FPGAs. By taking different algorithms for determining the temporal alignment of the sensors connected, some of the problems with sensors not synchronizing correctly might be fixed.

The long term stability of the prototype was also found to be very good, with the noise level of the sensors in the prototype not changing over time.

6.2 Experimental Results

Examining the results of the analysis of the data obtained from beamtests and the comparison of the results of simulations with this data has provided a number of conclusions:

**Linearity**

From figure 5.25 the conclusion must be drawn that for both the experimental and the simulated data, the linearity of the prototype is very good with all values of the same datasets not differing more than 5% for the SPS datasets. This also indicates that saturation does not yet become a problem at the upper range of the energies explored.

The main issues with the linearity come from the experimental data collected at DESY. For this data sets are available with improved sensor thresholds, which were taken at DESY in 2014, the analysis of which is ongoing [32].

**Resolution**

As shown in table 5.9, the stochastic term obtained from the prototype after calibration is 0.28. This is not at the level indicated by simulations (0.1943). Similarly, the constant term obtained from the prototype after calibration is larger than that obtained from simulations (0.034 versus 0.0188).

Some of the differences between the experimental and simulated resolutions can be explained through the sub-optimal choice of sensor threshold reducing the prototype response and the simulations not modelling these effects correctly. These effects add up to the observed differences and require further analysis of the new experimental data and more accurate simulations. New datasets taken at DESY and the SPS...
with improved threshold settings will have improved values and will therefore be more in line
with the values obtained from simulations.

When these results are compared to other electromagnetic calorimeters, a more optimistic
picture emerges. The values obtained from the prototype, even in this sub-optimal form, are
very close to those obtained from ATLAS’s forward calorimeter, which has a stochastic term
of 0.285 and a constant term of 0.035 (table 2.2). The granularity of the prototype is a factor
100 smaller than that of ATLAS’s forward calorimeters (3.0 cm versus 30 µm).

The comparison of the prototype’s resolution with that of LHCb’s ECAL is not so good,
a stochastic term of 0.1 and a constant term of 0.01 at LHCb. These are much better than
that achieved by the prototype. But even here the detector granularity is much worse for
ECAL (2.02 cm).

Another aspect which must not be neglected in the comparisons with other detectors is
the Moliere radius, since this also strongly determines the separating power of the detector.
In this aspect, the prototype with its Moliere radius of 1.028 cm (table 3.2) has the advantage
when compared to ATLAS’s forward calorimeter (1.9 cm) and LHCb’s ECAL (3.5 cm).

Calibration

The main conclusion to be taken from the analysis of the different calibration methods is
that the calibration of the prototype is not yet fully understood.

One issue complicating a complete analysis of the different calibration methods is the
non-uniformity of the prototype response depending on the position on the prototype. While
a large part of the non-uniformity must be attributed to the different numbers of working
sensors in the separate quadrants, a part of it is caused by the differing sensitivities of the
sensors in the prototype. The effect of the different sensitivities of the sensors on the resolution
of the prototype and how to correct for it, is not yet fully understood.

While some improvement of the detector resolution was gained through the use of the
spread minimization method, the pion calibration method did not improve the resolution as
expected. Setting the sensor thresholds using cosmic muons was implemented for the data
collected during the 2014 beamtests which is being studied in an ongoing project [32].

Simulations

The results from the simulations have shown the same trend as those from experiment. While
the resolution obtained from the simulations is significantly better than that obtained from
the experimental data, the same kind of improvement with energy can be seen in figure 5.20.

The conclusions that can be drawn from the results of the simulations are limited by a
number of assumptions and uncertainties that have gone into the underlying calculations.
Better calculations will result in more accurate simulations.

The first main point of improvement of the simulations are the calculations going into
the processes that model the energy deposition by the shower particles in the calorimeter’s
sensor elements. GEANT3, the software suite responsible for these calculations, accurately
models the energy loss of particles down to 10 keV, but its accuracy drops below this energy.
An electromagnetic shower contains a large number of particles with energy below 10 keV.
Because the sensors are sensitive to deposited energies below 10 keV, a large number of hits
will be incorrectly interpreted or missed by the sensors.
The second point of improvement is the incorrect modelling of the electron diffusion and recombination in the sensor medium. The leakage of charge generated in one pixel to neighbouring pixels is taken to follow a Gaussian distribution, after assuming a random-walk model of charge flow (section 4.3.1). This neglects non-uniformity of the space-charge region, dependence on angle of incidence of the particles, and recombination losses, which one might consider to implement in an improved diffusion model.

Discussion

The main aspect in which the same conclusions can be drawn from the beamtest and simulated data is that the number of working sensors in a quadrant of the prototype has a very strong influence on the observed response from particles hitting that quadrant. The relative spread and therefore the observed resolution of the prototype will be influenced by the number of working sensors as well. When this is combined with the assumption of equal sensitivities of the sensors in the simulations, which is definitely not the case in the real prototype, the resolutions obtained from the simulations are a lower bound.

The limitations of the GEANT3 simulation software for very low energy particles might be an explanation for some of the observed discrepancies between the simulated and experimental data, especially with the detection threshold being 130 eV for the SPS simulations. The shorter range over which particles are propagated through the simulated materials will cause the results from simulations to underestimate the fluctuations and therefore give an overly optimistic estimate of the resolution.

6.3 Future Outlook

Another beamtest with the prototype was performed in February/March of 2014. The results of the analysis of this beamtest could not be completed for this thesis in time. While the experimental setup was largely the same, the settings of the sensors were tuned to generate a much more even response across the detector. By having this more even response, the effects of shower-to-shower fluctuations should become much less pronounced when compared to the DESY beamtest results of 2012. The end result should be a significantly smaller spread of responses from shower to shower and therefore a much better energy resolution.

The GEANT4 particle interaction package should give more reliable results. Efforts are currently under way to implement the detector geometry using GEANT4.

The MIMOSA sensors currently used in the prototype are not suitable for the calorimeter envisioned as an extension of the ALICE experiment after the Long Shutdown of LHC in 2018. The first reason for the unsuitability of the sensors is their long integration time, resulting in a maximum event rate before pile-up occurs. The reason is the low maximum event rate will become more severe after the Long Shutdown in 2018 when the event rate will increase to 50 kHz for lead-lead events.

Another cause of the unsuitability of the sensors for use in the new calorimeter is the amount of data produced. This amount is already quite large for a prototype which is several orders of magnitude smaller than the one imagined at the improved ALICE after LS2018.

The last main problem in using the current pixel sensors in a full-sized calorimeter is the detector integration required. Both the power consumed and the amount of data produced by the sensors in the prototype gives rise to a large number of cables. The cabling solution
used in prototype is not suitable for use in the full-sized calorimeter either and the issue of cabling will need a lot of attention.

Some of these issues, such as reducing the integration time and the data volume, will be solved by ongoing research and development in newer versions of the sensor chip. This will likely also alleviate the problems of cooling and cabling.
# Chapter 7

## Appendix

### 7.1 Sensor connection scheme

Table 7.1: Correspondence of sensor numbering scheme and actual location of sensors. The quadrants are following the numbering scheme of fig. 3.8 for both DESY and SPS.

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125
## 7.2 DESY sensor settings

Table 7.2: The settings of both MIMOSA sensor threshold DAC converters (ch.3.3) during data taking at DESY.

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7.2. DESY SENSOR SETTINGS

Table 7.3: Sensors which were not functional during data taking at DESY and the layers they were located in. A number were missing due to not being ready in time (N.C.), others were non-functional due to not synchronizing properly.

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## 7.3 SPS sensor settings

Table 7.4: The settings of both MIMOSA sensor threshold DAC converters (ch.3.3) during data taking at SPS.

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Table 7.5: Sensors which were not functional during data taking at SPS and the layers they were located in. A number were missing due to not being ready in time (N.C.), others were non-functional due to not synchronizing properly.

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7.4 Sensors Ignored After Stringent Selections

Table 7.6: Sensors ignored during processing of SPS data and the layers they are located in after stringent selection (ch. 5.6).

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Nederlandse Samenvatting

Inleiding
Het ALICE experiment bij de Large Hadron Collider (LHC) heeft als doel onderzoek te doen naar de eigenschappen van het Quark Gluon Plasma (QGP). Het QGP is een nieuwe vorm van materie die ontstaat wanneer de dichtheid van zowel energie als massa zo groot worden dat de quarks en gluonen waaruit de neutronen en protonen bestaan in elkaar "versmelten" tot een soort van nucleaire "soep". In het ALICE experiment komt het QGP tot stand in botsingen van atoomkernen bij extreem hoge energie.

Om eigenschappen van het QGP nauwkeurig te kunnen heeft ALICE een aantal detectoren tot haar beschikking die de energie en richting van de deeltjes die uit het QGP ontsnappen te kunnen meten. Deeltjes die zich voortbewegen in richtingen die overeenkomen met die van de deeltjesbundels die het QGP tot stand brengen heten in de terminologie van de deeltjesfysica "voorwaartse" deeltjes. Helaas is de dekking van deze detectoren bij ALICE voor voorwaartse deeltjes ontoereikend.

Om dit te verhelpen is bij de grote upgrade van ALICE een extra en voorwaartse deeltjesdetector (FoCal) voorgesteld. De speciale eisen die worden gesteld bij een detector op deze locatie en een prototype van een mogelijke oplossing zijn het onderwerp van dit proefschrift.

Calorimeters
FoCal is een electromagnetische calorimeter, een deeltjesdetector die de energie van deeltjes die erop vallen vaststelt. Electromagnetische calorimeters bepalen de energie van de deeltjes die hoofdzakelijk via de electromagnetische wisselwerking interacties hebben. Om een nauwkeurige beeld van de energie van het deeltje te krijgen moet een calorimeter meestal het overgrote deel van de energie van het deeltje absorberen. Dit gebeurt door het deeltje in een materiaal een "lawine" of "cascade" effect van andere deeltjes te laten beginnen, die elk afzonderlijk ook hetzelfde proces ondergaan.

Er zijn twee hoofdtypen electromagnetische calorimeters. De eerste zijn proportionele analoge calorimeters. Deze wekken een signaal op wat proportioneel is met de energie van het invallende deeltje. Door de aard van de uitlezing van dit soort detectoren is de maximale plaatsresolutie meestal niet beter dan een paar millimeter, aangezien elk afzonderlijk element zijn eigen uitleeskannels nodig heeft.

De tweede soort is een detector die de energie van het deeltje bepaalt aan de hand van het aantal deeltjes wat gezien is in het cascade effect. Omdat de aantallen geladen deeltjes de tienduizenden overschrijden bij de energie waar ALICE in geïnteresseerd is, en het oppervlak
waarover het proces zich uitspreid niet veel groter is dan een paar cm\(^2\), zijn uitlees elementen met een grootte kleiner dan 1000µm\(^2\) een vereiste. Dit heeft als gevolg dat de inherente plaatsresolutie van de detector beter is dan 15µm.

**Prototype**

Het prototype dat voorgesteld is voor FoCal bestaat uit platen wolfram waar de deeltjes in de cascade interacties mee moeten hebben. Er is gekozen voor wolfram vanwege de hoge dichtheid, dat weer een grotere kans van interactie met geladen tot gevolg heeft vergeleken met lichtere materialen. Dit resulteert in kleinere cascades, en dus een groter vermogen om twee cascades van elkaar te kunnen scheiden.

Als sensor elementen zijn silicium pixel sensoren van het type MIMOSA23 gekozen. Deze sensoren hebben een gevoelige laag van 1215µm dik en 640 bij 640 pixels van 30 bij 30µm\(^2\). Deze sensoren kunnen uitgelezen worden in 642µs. Elke laag van het prototype bevat 2 bij 2 van deze sensoren, wat een gevoelig gebied oplevert van ongeveer 2 bij 2 cm\(^2\). De sensoren van een laag hebben 2 wolfram platen van 1.5 mm aan elke kant zitten. Het prototype bevat 24 van dergelijke lagen.

De software van het prototype heeft drie hoofdrollen. De eerste is het nauwkeurig opnemen van de data. Hiervoor is het nodig om de data uit de verschillende kanalen van de sensoren in de correcte volgorde op te slaan, omdat door de opnamemethode van de sensoren de status pixels niet in een direct sequentiële volgorde wordt verzonden.

De tweede is het voorbereiden van de data voor analyse. Hiervoor moet de ruis die door willekeurige ladingsverplaatsingen of beschadigingen van de sensors ontstaat zoveel mogelijk worden onderdrukt, terwijl de nuttige informatie zoveel mogelijk beschermd blijft. De volgende stap is het selecteren van interessante delen van de data voor analyse als zogenaamde ”frames”. Omdat de data continu uit de sensors wordt opgenomen moeten de correcte delen van de data worden gecorrelleerd met data uit externe trigger sensoren.

De laatste rol van de software is het analyseren van de data. Dit kan het zoeken naar patronen in frames die kunnen wijzen naar sporen van deeltjes die niet sterk met het prototype wisselwerken. Dit zijn zogenaamde ”tracks” en kunnen gebruikt worden om de sensoren onderling uit te lijnen en de relatieve gevoeligheden van de sensoren te bepalen. Andere analyses hebben meer te maken met statistische analyses van electromagnetische cascades en de respons en resolutie die daaruit voorkomt.

De data gebruikt in dit proefschrift zijn opgenomen tijdens twee bundeltesten. De eerste bundeltest vond plaats in maart 2012 bij het DESY in Hamburg. Data zijn hier met deeltjes met een energie in het bereik van 2 tot 5 GeV opgenomen, hoewel het nuttige bereik van de versneller 1 tot 6 GeV was. De tweede bundeltest vond plaats bij het SPS van CERN in Geneve in september 2012. De deeltjes hadden hier een energie van 30 tot 200 GeV, hoewel het aandeel nuttige deeltjes in de bundel bij een energie boven de 100 GeV te verwaarlozen was.

**Resultaten**

Na het kiezen van de detectiedrempels van de sensoren en het onderdrukken van de ruis door middel van de software bleef er een gemiddelde ruis van ongeveer 4 pixels per sensor per frame over. Over een prototype van 96 sensors resulteerde dit in een ruissignaal van iets minder dan
400 pixels per frame. Omdat de ruis van alle sensoren onfhankelijk is kan verwacht worden dat deze ruis een Poissonverdeling volgt.

De energie waarbij voor het bepalen van de resolutie nuttige data is opgenomen was bij DESY 2 en 5 GeV, en bij het PS 30, 50 en 100 GeV. De resolutie van het prototype dat uit deze datapunten resulteerde was 5.7% bij 100 GeV. Hoewel dit meer dan een factor 2 slechter is dan wat volgens simulaties verwacht kan worden (2.686%), is dit een bemoedigend teken voor deze nieuwe technologie. De verwachte resultaten van een correct uitgevoerde digitale pixel calorimeter zullen omdat de prestaties van het prototype significant slechter uitpakten vanwege de defecten in de aangeleverde sensoren, en omdat de detectiedrempels van de sensoren voor de bundeltesten niet optimaal uitgekozen waren.

Het gebied waar het prototype echt de kracht van de nieuwe technologie heeft kunnen laten zien is in de combinatie van detectie van energie en plaats in dezelfde detector. Na uitlijning van de sensoren doormiddel van kosmische muonen werd de meetfout van de positie van de deeltjes die door sensor 11 heengingen van 106 naar 1 \( \mu \)m in de X-coordinaat en van 149 naar 10 \( \mu \)m in de Y-coordinaat teruggebracht.
De onzekerheid in de gemeten positie bleef voor beide coordinaten boven de 100µm. Het resultaat van sensor 11 was typisch voor het hele prototype. Aangezien dit significant groter is dan de afmetingen van de pixels op de sensoren is het duidelijk dat de uitlijning van de sensoren niet de enige factor was die bijdroeg aan de fout van het vaststellen van de positie.
Acknowledgements

This thesis is the result of 4 years of work at Utrecht University. I am very grateful to many people who helped me in creating this thesis. Some of these peoples’ assistance has been in a very direct form, while others have contributed in a more indirect manner.

First I would like to thank Prof. Thomas Peitzmann. His faith in my skills has allowed me the opportunity to perform this research and develop my skills as a programmer and a researcher. Thomas, even though I did not have a large amount of experience, you trusted me to develop the software for the FoCal prototype.

The next person I would like to thank is Dr. Gert-Jan Nooren. Your critical but fair examination of my results gave me good ideas on which direction to go next in the research. Also, your implacability on experimental results allowed me to discover new skills I did not think I had.

Marco, you were always ready to answer questions regarding ROOT and programming. No matter what the question was, or when I asked it, you were always there to give a hand. Without your assistance I think most PhDs would not have been able to solve many of the problems we encountered.

The assistance of Ton during the assembly of the prototype calorimeter and the beamtests can not be understated. Ton, together with Marcel, Arie, Gert-Jan en Kees created the prototype from scratch. Also, your contributions to the beamtests can not be underestimated.

This thesis is also dedicated to the memory of my mother, Margriet, who is no longer with us to share this achievement with me. My father Aarnout, my stepmother Sjoerdje, my sister Floor, Grandpa and Grandma, your support or just even having the opportunity to talk to you when things were rough, has helped me enormously. Not just during this research, but during the years running up to it as well.

Without Shiming, Kjetil, Dieter and the others from Norway’s Bergen University the prototype could also not have come together. Their work on the Virtex FPGAs which interface between the sensors and the data acquisition computer is very impressive.

Nikola, your time with us was not long, but I enjoyed your good humor and expert knowledge of Linux and ROOT, we are still using your installation of Scientific Linux on the DAQ computer!

With the addition of Elena, Chunhui and Hongkai to our team, it has grown to a real project which can continue into the future. I will miss your presence at my new working place, and hope to meet new colleagues who can give me the same feedback you have given me during our time working together.

Davide, You, Hongyan, Sandro, Andrea, Carlos, Alberto, I have immensely enjoyed your company at the Subatomic Physics group and I wish you all the best with your research.

Deepa, Raoul, Marek, Ermes, Martha, even though you left the subatomic physics group
some time ago, I will remember the time spent as fellow PhDs. And I especially hope that Raoul will become an even more valorous warrior.

My friends Jan, Joey, Egbert, Redmer, Edith, Maarten, Ellen, Rico and Xander, you were the people I went to when I needed to relax.
Curriculum Vitae

The author of this thesis was born on March 26th of 1982 in Groningen, the Netherlands. He finished his secondary education at the Stedelijk Gymnasium in Leeuwarden in 2000, after which he started his studies in physics at Groningen University. He obtained his bachelor’s degree in physics in 2007. He continued at Groningen University up to obtaining his master’s degree in Theoretical Physics with a thesis on 'Improving Neutrino Detection Through Neutron Capture' in 2009, supervised by Rob Timmermans.

From 2010 to 2016 the current PhD work was performed, under the supervision of prof. dr. Thomas Peitzmann and dr. Ir. Gert-Jan Nooren. The goal of the research was to examine the feasibility of a new type of electromagnetic calorimeter which is to be an upgrade for the ALICE experiment. Since the end of his contract at Utrecht University the author has been working at Luminext, while at the same time continuing his work on his PhD thesis.
Bibliography


