Characterization of the 
Omega3/LHC1 
silicon pixel detector

Tessel Hester Chimwemwe Jarigsma

High energy physics chair
Solid state physics department
Applied physics faculty
University of Twente

Graduation committee:
Prof. Dr. C. Daum
Dr. Ir. H.H.J. ten Kate
Dr. Ir. H.J.W. Zandvliet
Dr. Ing. B. van Eijk
Drs. E.J. Buis
## Contents

1 Particle physics .................................. 5
   1.1 Standard model ................................. 5
       1.1.1 Higgs mechanism .......................... 7
   1.2 Experimental high energy physics ............. 9
       1.2.1 Production of particles .................. 9
       1.2.2 Detection of particles ................... 10
   1.3 The Large Hadron Collider .................... 11
   1.4 ATLAS ........................................ 13

2 Silicon as a detector material .................. 17
   2.1 Energy loss of charged particles ............... 17
       2.1.1 Thin absorbers ............................ 18
   2.2 Semiconductor physics ........................ 20
       2.2.1 Energy gap ................................ 20
       2.2.2 Charge carriers ............................ 22
       2.2.3 Doping .................................... 22
       2.2.4 P-N junction ............................... 23
   2.3 Principle of detection ........................ 25
   2.4 Noise in Silicon detectors ..................... 27
   2.5 Types of Silicon particle detectors .......... 28
       2.5.1 Micro strip detectors ..................... 29
       2.5.2 CCD detectors .............................. 30
       2.5.3 Pixel detectors ............................. 31

3 Silicon pixel detectors .......................... 33
   3.1 Integration of the detector and the electronics 33
       3.1.1 Monolithic integration .................... 34
       3.1.2 Silicon on insulator technique ............ 35
CONTENTS

3.1.3 Hybrid integration ............................................. 35
3.2 Fabrication of the detector ........................................ 35
3.3 The LHC1/Omega3 detector ....................................... 37
  3.3.1 Requirements .................................................. 37
  3.3.2 Read-out electronics ........................................... 40
  3.3.3 Sensor .......................................................... 42
  3.3.4 Bump bonding for the LHC1/Omega3 detector ............... 43

4 Measurements using the NIKHEF set up 47
  4.1 Set up ............................................................. 48
    4.1.1 Hardware .................................................... 48
    4.1.2 Software ..................................................... 49
  4.2 Electrical measurements ........................................ 51
    4.2.1 Detector response ............................................ 52
    4.2.2 Calibration .................................................. 53
    4.2.3 Temperature dependence of the readout electronics ...... 56
    4.2.4 Threshold variation and uniformity ......................... 57
  4.2.5 Noise ......................................................... 58
    4.2.6 Detector offset .............................................. 59

5 Test beam measurements 67
  5.1 Set up ............................................................. 67
  5.2 Results .......................................................... 69
    5.2.1 Calibration with pion beam ................................ 69
    5.2.2 Landau distribution ......................................... 70
    5.2.3 Effect of the bias voltage on the efficiency ............. 72
    5.2.4 Cluster size ................................................ 73
    5.2.5 Spatial resolution .......................................... 74

6 Discussion and conclusions 77
  6.1 Conclusion ...................................................... 77
  6.2 Suggestions for the future developments ....................... 80
Introduction

Experimental research in the field of elementary particle physics requires a continuous improvement of detectors and accelerators. At CERN near Geneva the Large Hadron Collider (LHC) is constructed where protons are brought into head on collision. At four points the particle beams collide and large detectors are constructed to study the results of these collisions. The ATLAS detector is a general purpose detector, placed at one of the interaction points. The pixel barrel is one of the most challenging parts of ATLAS. The inner layers are placed only 4 cm from the collisions point. The operating conditions for the pixel system are very severe. Since the pixels will be used as precise vertex and tracking device, the spatial resolution has to be very good, the noise has to be minimal to get a good signal to noise ratio. The bunch crossing frequency of 40 MHz requires fast electronics that can handle a large number of channels, since the total surface area is about 2 m². The radiation is the most intense close to the interaction point, thus the detector material has to be highly radiation tolerant.

The topic of this study is to compare the ATLAS specifications for the pixel system with the experimental specifications of the Omega3/LHC1 pixel detector. Chapter 1 is an introduction into particle physics and provides a description of the ATLAS detector. In chapter 2 the principle of Silicon as a detector material is described. Chapter 3 reviews the general features of silicon pixel detectors and the specific features of the Omega3/LHC1 detector. Chapter 4 concentrates on the measurements carried out with the NIKHEF test set up. Chapter 5 presents the measurements performed in the CERN SPS H6 test beam. Finally the conclusions of the measurements on the Omega3/LHC1 detector are presented in chapter 6.
Chapter 1

Particle physics

The basic question in elementary particle physics is: 'What is the world made of?'. Experimental research to answer this question is carried out with giant particle accelerators and huge particle detectors. The particle accelerators operate at very high energies (up to TeV), because of two reasons. The first is the very small scale of the particles (one requires radiation of the smallest possible wavelength), the second is the large mass of many of the fundamental constituents. During the last 30 years an enormous amount of unknown particles has been discovered. Happily these particles, who at first appeared unordered, can be organized in the Standard Model. Knowing these particles, the question concerning their interaction is rising immediately.

1.1 Standard model

In the current view matter is composed of elementary particles that are smaller than $10^{-15}$ cm and 4 fundamental forces are needed to keep the particles together. These particles, called fermions, all obey the Fermi-Dirac statistics and they have spin 1/2. Fermions can be divided in two groups: leptons, which are particles that may live freely in space, unlike the quarks that never occur singly and only occur in clusters named hadrons. The set of leptons and quarks is shown in table 1.1.

As shown in the table 1.1 the particles can be grouped into three families of increasing mass. The muon is a heavy copy of the electron, and the tau is
even more heavy. The neutrinos are generally assumed to be massless \([1]\). Only recently it was discovered that there are probably only three of such families\(^1\). Each of the 12 fermions has its own anti-fermion.

On the other hand, spin 1 particles exist, bosons, which are the quantum mechanical counterpart of the fermions and obey the Bose-Einstein statistics. Therefore they are called bosons. The photon is the most common of these bosons. The bosons are crucial for our understanding of the fundamental forces. We nowadays believe that there are four fundamental forces in na-
tecture: gravitational, electro-magnetic, weak and strong. The Standard model gives a quantum field description of three of these forces (electro-magnetic, weak and strong). The bosons carry the force between interacting particles. The four forces each have their own boson: the electro-magnetic force is carried by the photon, the weak nuclear force by the intermediate vector bosons $W^+$, $W^-$ and $Z^0$ and the strong nuclear force by the gluons.

<table>
<thead>
<tr>
<th>boson</th>
<th>mass</th>
<th>force</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (photon)</td>
<td>0 GeV</td>
<td>electro-magnetic</td>
</tr>
<tr>
<td>$W^+, W^-$</td>
<td>80.2 GeV</td>
<td>weak</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.2 GeV</td>
<td>weak</td>
</tr>
<tr>
<td>gluons</td>
<td>0 GeV</td>
<td>strong</td>
</tr>
</tbody>
</table>

Table 1.2: Summary of the bosons (except the graviton) with their mass and the force for which they are the mediator. The mass of weak gauge bosons can be explained by the Higgs mechanism.

The electro-magnetic force and the weak interaction are unified by a theory developed by Glashow, Weinberg and Salam [2] [3] [4] called Quantum Electrodynamics (QED). The strong interaction is described by Quantum Chromodynamics (QCD). These theories do not cover the mass of some of the bosons. On the other hand extraordinary cross-sections are predicted at high energies. Therefore a new mechanism is introduced: the Higgs mechanism. The electroweak theory together with this mechanism is called the Standard Model of Electroweak Interactions.

### 1.1.1 Higgs mechanism

A rather important symmetry in the electroweak theory is the local gauge invariance. The transformation

$$\psi(x) \rightarrow e^{i\alpha}\psi(x) \quad (1.2)$$

is a global transformation, since the $\alpha$ is not depending on the space. If it is, like in the following equation, one speaks about local transformations.

$$\psi(x) \rightarrow e^{i\alpha(x)}\psi(x) \quad (1.3)$$
By demanding local phase invariance, a vector field $A_a$ has to be introduced. The introduction of this field implies the gauge particles to be massless \[5\]. This however is not the case for the gauge particles of the weak interactions. An answer to this problem is found in introducing “spontaneous symmetry breaking”. Therefore a field potential is postulated, the potential is invariant under rotations, see figure 1.1:

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \lambda\phi^4$$  \hspace{1cm} (1.4)

The choice for $\mu$ is arbitrary, for $\mu^2 < 0$ the symmetry is broken, $\phi = \pm v$ with $v = \sqrt{-\mu^2/\lambda}$ describes a circle with an infinite number of minima. Since the scalar field has to couple to the $\bar{W}$, $\phi$ is an imaginary doublet, with four degrees of freedom. The solutions ($\phi_1, ..., \phi_4$) are invariant under transformations, thus a specific value may be chosen (symmetry breaking). Expanding
the field near this specific value gives a Lagrangian with a mass term for the gauge bosons. The photon remains massless and the masses of the other bosons can be given in terms of known variables [6].

1.2 Experimental high energy physics

1.2.1 Production of particles

Before discussing the detection of particles, it is necessary to explain the creation of particles for research purposes. For particles, other than electrons and protons, there are three main sources: cosmic rays, nuclear reactors and particle accelerators.

Cosmic rays

When particles, usually protons, from outer space hit atoms in the upper atmosphere they produce showers of secondary particles; the cosmic rays. The advantage of cosmic ray particles is that they are free and that their energy can be enormous. The problem is that they are uncontrollable and that the rate at which they strike a detector is very low.

Nuclear reactions

A disintegrating radioactive nucleus may emit a variety of particles: alpha particles, beta rays, neutrinos, gamma rays and neutrons. Since radioactive sources are available in small formats, they are often used in laboratorium experiments.

Particle accelerators

In particle accelerators stable charged particles are accelerated by electrical fields. Two kinds of accelerators can be distinguished. Linear accelerators (linacs) and cyclic accelerators. In a linac, the beam is accelerated and directed onto a fixed target. After hitting the target, new particles can be created. A disadvantage of fixed target machines is that the center of momentum$^2$ energy $\sqrt{s}$ rises only with $\sqrt{E}$, as part of the energy is needed

$^2$The center of momentum system (CMS) is defined as the reference frame in which the total momentum of all particles is zero. The energy in the CMS is the maximum mass
for the motion of the secondary particles for preservation of total energy and momentum. This is one of the main reasons for building circular colliders. In colliding beam machines, two beams of particles collide head on. Now the center of momentum energy $\sqrt{s}$ rises with $E$. In circular colliders, the beam is bent back, therefore the particles can be re-used and the accelerating elements are used more efficiently. The disadvantage is that bending introduces radiation losses, though these get less severe with mass, since the loss goes with $m^{-4}$. Electrons therefore suffer much more from radiation loss than protons. The use of an electron-positron storage ring in the range of 1 TeV is out of the question for this reason. The mass of the proton is $\sim 2000$ times the electron mass, thus the radiation loss is $\sim 16 \times 10^{12}$ times less.

### 1.2.2 Detection of particles

![Diagram of detection of particles](image)

**Figure 1.2:** Signature of some typical high energetic particles in a tracker, electro-magnetic calorimeter, hadronic calorimeter and muon tracker.

\[\text{that a newly created particle (or particles) can have.}\]
1.3. THE LARGE HADRON COLLIDER

Figure 1.2 shows the behavior of different particles in the different detector types. Three types are shown in this figure: inner tracker, calorimeter and the outer tracker. Only the muon will reach the outer tracker, the other particles will have lost all their energy in the calorimeter. The difference between a photon and an electron can be recognized in the inner tracker, the photon will not lose energy here. A charged hadron can be distinguished from the electron since the charged hadrons lose their energy in the second half of the calorimeter.

1.3 The Large Hadron Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam energy</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Bunch size</td>
<td>75mm × 16μm × 16μm</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>10^{11}</td>
</tr>
<tr>
<td>Nominal luminosity</td>
<td>10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>Field of bending magnets</td>
<td>8.65 T</td>
</tr>
</tbody>
</table>

Table 1.3: Machine parameters of the Large Hadron Collider.

The Large Hadron Collider (LHC) is an accelerator which will bring protons into head-on collision at higher energies (14 TeV) than ever achieved before to allow scientists to penetrate still further into the structure of matter [11]. To open up this high energy range the LHC will collide two proton beams of high intensity in the tunnel now used for the Large Electron Positron accelerator (LEP). The beams are accelerated by the most advanced super conducting magnets. Separate proton beams are used, which are only brought together at interaction points. In each of the collision points, of the order of 10^9 interactions per second will take place. The luminosity \( \mathcal{L} \) describes the potential interaction rate of colliding beams, it can be calculated by:

\[
\mathcal{L} = f \frac{N_1 N_2}{A}
\]  

(1.5)

where \( N_1 \) and \( N_2 \) are the number of particles in each bunch, \( f \) is the bunch...
crossing frequency and $A$ is the cross-sectional area of each particle bunch. The luminosity relates the cross section $\sigma$ of a certain process to its rate of occurrence $R$:

$$R = \sigma \mathcal{L} \tag{1.6}$$

The cross section of the relevant processes are in the order of picobarn ($10^{-36} cm^2$), thus for example at the LEP luminosity ($\sim 10^{31}$) such an event would occur only once every other day. The crucial point of the LHC is therefore to create such a high luminosity ($\sim 10^{34}$) that interesting events can be seen at an observable rate. Some of the parameters of the collider machine are given in table 1.3.

One of the main goals of the Large Hadron Collider is to study the Higgs mechanism. Experiments at the LHC will be able to search for the Higgs boson with masses up to 1 TeV. Different $m_H$ correspond to different decay channels. Typical decay channels of the neutral Standard Model Higgs are (given in order of increasing Higgs mass):

$$H \rightarrow b\bar{b}$$
$$H \rightarrow \gamma\gamma$$
$$H \rightarrow ZZ^* \rightarrow 4l^\pm$$
$$H \rightarrow ZZ \rightarrow 4l^\pm, 2l^\pm \nu$$
$$H \rightarrow WW, ZZ \rightarrow l^\pm \nu, 2l^\pm 2\text{jets}$$

Since the LHC opens up a new energy range, more physics can be studied than the search for the Higgs boson. For example the theory of super symmetry, an extension of the Standard Model which interrelates bosons and fermions, can be tested on its validity.

At the LHC heavy particles (composed of bottom and top quarks) will be produced abundantly. Therefore it is possible to study $B$ physics extensively. The main issue of $B$ physics is the observation of CP violation in $B$-systems. The aim is to find the three angles of the unitarity triangle corresponding to the Cabibo-Kobayashi-Maskawa matrix (CKM) [9].

The LHC also gives the possibility to observe the tau-neutrino ($\nu_\tau$). This particle only interacts weakly and is therefore hard to identify. Since there is a large flux of tau-neutrinos at the LHC, the particle may be recognized from the sudden appearance of a tau lepton.
At the collision points in the LHC ring, experiments to detect particles are placed. At this moment the ATLAS experiment, which is the acronym of A Toroidal LHC Apparatus and the CMS experiment (Compact Muon Solenoid) have been approved. Two other experiments, LHC-B and ALICE are still under study. The ATLAS experiment is designed as a general pur-
pose pp-detector, to exploit the full discovery potential of the LHC. The detector optimization is therefore guided by physics issues such as described above.

![Diagram of ATLAS detector](image)

**Figure 1.4:** The ATLAS pixel barrel. The pixel detector system is the innermost layer of the ATLAS detector.

The detector layout is shown in figure 1.3. The three main subsystems of the ATLAS detector [12] are the calorimeter, the inner detector and the muon spectrometer. Higgs physics demands good resolution for the muon spectrometer. The ability of the muon spectrometer safeguards against background and ensures a good discovery potential in the presence of unexpected event topologies.

The enormous size of ATLAS is mainly caused by the large magnet and the calorimeter. The outer chambers of the barrel are at a radius of about
The length of the barrel toroid coils is 26 m, and the third layer of the forward muon chambers, mounted on the cavern wall, is located at ±21 m from the interaction point. The overall weight of the ATLAS detector is about 7000 tons. The calorimeter is a high performance system, capable of reconstructing the energy of the electrons, photons and jets, as well as measuring the missing transverse energy. The inner detector is the part of the detector placed closest to the interaction point. Precise tracking in the inner detector is needed to study three fields of physics: B physics, SUSY and the decay vector bosons. The production of long living particles results in a displaced vertex, that can be measured in the inner detector.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius (mm)</th>
<th>Half length(cm)</th>
<th>Chips</th>
<th>Channels</th>
<th>Active area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-layer</td>
<td>47.5</td>
<td>35</td>
<td>4160</td>
<td>1.6 × 10⁷</td>
<td>0.26</td>
</tr>
<tr>
<td>first layer</td>
<td>105.5</td>
<td>37.8</td>
<td>9152</td>
<td>3.5 × 10⁷</td>
<td>0.57</td>
</tr>
<tr>
<td>second layer</td>
<td>137.5</td>
<td>37.8</td>
<td>25376</td>
<td>9.7 × 10⁷</td>
<td>0.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disk Z (mm)</th>
<th>Inner Radius (mm)</th>
<th>Outer Radius (mm)</th>
<th>Chips</th>
<th>Channels</th>
<th>Active area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>490</td>
<td>107.1</td>
<td>196.0</td>
<td>1680</td>
<td>6.05 × 10⁶</td>
<td>0.10</td>
</tr>
<tr>
<td>608</td>
<td>107.1</td>
<td>196.0</td>
<td>1680</td>
<td>6.05 × 10⁶</td>
<td>0.10</td>
</tr>
<tr>
<td>759</td>
<td>107.1</td>
<td>196.0</td>
<td>1680</td>
<td>6.05 × 10⁶</td>
<td>0.10</td>
</tr>
<tr>
<td>103.5</td>
<td>151.0</td>
<td>196.0</td>
<td>960</td>
<td>3.46 × 10⁶</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 1.4: Sizes of the pixel barrels and disks for the ATLAS pixel system.

The inner detector consist of (see figure 1.4) pixel detectors, strip detectors, GaAs detectors and straw tubes. The strip detectors are used for the larger area precision detection. The straw tubes are used where the track density is relatively low, the vertexing layer around the beam pipe enhances significantly the vertex-finding capability for B-physics. The main performance task of the pixel detectors in ATLAS is pattern recognition and vertex construction. Therefore, the ATLAS pixel system consists of 3 barrel layers and 2×4 disk layers in the forward region. The three barrel layers are: a first and a second layer with radii of 11 and 14 cm respectively and the so-call B-layer. This layer has a radius of 4 cm and will mainly be used for studying B-physics and other topics at lower luminosity, because the expected radiation damage at high luminosity will be of great concern. Each
layer in the barrel consist of ladders which have the same length as the barrel itself. Then each ladder is subdivided into several modules. These modules consist of 16 readout chips. The total number of readout channels in the pixel barrel will be 14 million on a total surface of about 2-3 $m^2$. The Omega pixel detector is now being used in the WA97 experiment at CERN. Here the area coverage is about 2 $dm^2$ with approximately 700,000 readout channels.
Chapter 2

Silicon as a detector material

Several materials are currently used for semiconductor detectors: Silicon, Germanium and recently also GaAs and Diamond. The most common in high energy physics is Silicon, due to the advantages of operation under normal circumstances, wide availability and easy production. Since the energy gap of Silicon is only 1.12 eV a large number of electron-hole pairs can be created. The energy gap is large enough to avoid large dark currents. Silicon is a semiconductor and therefore is non-conducting under normal circumstances. When a particle passes through the material it will deposit energy which enables a electron to cross the energy band, this is visible to the readout electronics as a small current. Besides all the advantages Silicon has, the main disadvantage which will play a important role in the Large Hadron Collider (LHC) is the limited radiation hardness, this is the motivation for studying diamond as a possible detection medium [14].

2.1 Energy loss of charged particles

Charged particles passing through matter will lose energy due to several interaction processes. A distinction has to be made considering the behavior of charged particles into two groups: heavy charged particles (e.g. muons, pions, protons) and electrons and positrons. Inelastic collisions are dominantly responsible for the energy loss of heavy, charged particles. During the collision the traversing particle transfers energy to the atom causing an ionisation
of this atom. Like heavy, charged particles, electrons and positrons suffer a collisional energy loss when passing through matter. Since the electrons and positrons have small mass, the emission of electromagnetic radiation arising from scattering in the electric field of a nucleus (Bremsstrahlung) plays a more important role. At energies of a few 10's MeV or less, this process is still a relatively small factor. However, as the energy increases, the probability of Bremsstrahlung quickly shoots up (see figure 2.1(b)), so that at about a few 10's MeV, loss of energy by radiation is comparable to or greater than the collision-ionisation loss.

The average energy loss due to ionisation of a heavy charged particle traversing a thin layer is given by the Bethe-Bloch equation [15]:

\[
\frac{-1}{\rho} \frac{dE}{dx} = 4\pi N_A m_e r_e^2 \frac{Z^2}{A} \frac{1}{\beta^2} \left[ \ln \left( \frac{2m_e\beta^2}{I(1-\beta^2)} \right) - \beta^2 - \frac{\delta}{2} \right]
\]

(2.1)

where \( N_A \) is the Avogadro number, \( r_e \) is the classical radius of the electron, \( Z \) and \( A \) are the atomic number and mass (in g/mol), \( m_e \) is the electron rest mass (in MeV), \( I \) is the average ionisation potential (172 eV for Silicon), \( \rho \) is the density, \( \beta = \frac{v}{c} \) and \( \delta \) is the screening effect. The mean energy loss in a 300 \( \mu \)m Silicon layer is shown in figure 2.1(a), for protons, muons and electrons as a function of their momentum. From this plot it can be seen that the energy loss of a Minimum Ionizing Particle (MIP) is around 90 keV.

The Bremsstrahlung, where the electric field of a nuclei decelerates the particles results in the emission of a photon. The radiative energy loss becomes (see for example [18]):

\[
\frac{dE}{dx} = -\frac{E}{\lambda_0}
\]

(2.2)

Thus \( \lambda_0 \) is the radiation length, that is the distance over which the electron energy is reduced by a factor 1/e due to radiation loss only. This radiation length \( \lambda_0 \) is given by, [18]:

\[
\frac{1}{\lambda_0} \approx 4Z(Z+1)\left(\frac{\rho N_e}{A}\right)r_e^2\alpha[\ln(183Z^{-1/3}) - f(Z)]
\]

(2.3)

2.1.1 Thin absorbers

The statistical nature of the ionisation process during the passage of a fast charged particle through matter results in large fluctuations of the energy
2.1. ENERGY LOSS OF CHARGED PARTICLES

Figure 2.1: (a) Energy loss due to ionisation in 300 µm Silicon, for the proton, muon and electron. (b) The energy loss compared to the Bremsstrahlung. The critical energy, the particle energy where Bremsstrahlung is dominant to ionisation, is shown for two definitions.

loss¹ in absorbers which are thin compared with the particle range. This is very well described by the Landau-Vavilov distribution [17] (see figure 2.2). This Landau distribution can be approximated by [20]:

\[ \phi(\lambda) = \frac{1}{2\pi i} \int_{\gamma=i\infty}^{\gamma=-i\infty} \exp(\lambda s + s \ln s) ds \]  \hspace{1cm} (2.5)

It is essential to realize that the energy loss of the particle in passing through the detector does not correspond exactly to the energy deposited in the sample, as measured by the total number of electron-hole pairs created. This is due to the fact that a particle may suffer hard collisions with electrons

¹For heavy particles, \( W_{\text{max}} \) is kinematically limited by:

\[ W_{\text{max}} \simeq 2m_e c^2 \eta^2 \]  \hspace{1cm} (2.4)

with \( \eta = \beta \gamma \). Landau calculated the energy loss distribution for different values of the ratio \( \kappa = \frac{\text{mean energy loss}}{W_{\text{max}}} \), see for example [18].
in the detector giving rise to energetic electrons which may escape from the detector. This will especially influence the tail of the energy loss distribution. Another effect which will influence the tail of the energy loss distribution, is nuclear reactions. Nuclear reactions may result in the production of several particles which (if charged) lose energy in passing through the detector [16]. Because of the long high energy tail the mean energy loss corresponds no longer to the peak. In contrast, the position of the peak now defines the most probable energy loss.

2.2 Semiconductor physics

2.2.1 Energy gap

We can characterize solids by the energy gap $E_g$ between the top of the highest filled band(s) and the bottom of the lowest empty band. In a conductor both the valence band and the conduction band are half-full. The electrons can drift through the material freely, and can therefore carry current. Electrons in a completely filled band can not carry current. A solid with an energy gap will be non-conducting at $T = 0$. However, when the temperature is not zero there
is a non-vanishing probability that some electrons will be thermally excited across the energy gap into the lowest unoccupied bands, which are called, in this context, the conduction bands, leaving behind unoccupied levels in the highest occupied bands, called valence bands, see figure 2.3. Whether such thermal excitation leads to appreciable conductivity depends critically on the size of the energy gap. This is the basis for the distinction between insulators and conductors. Solids that are insulators at $T = 0$, but which energy gaps are of such size that thermal excitation can lead to observable conductivity at temperatures below the melting point, are known as semiconductors.

Evidently the distinction between a semiconductor and an insulator is not a sharp one, but roughly speaking the energy gap in most important semiconductors is less than 2 eV and frequently as low as a few tenths of an electron volt. Table 2.1 gives a summary of the energy gaps of some solids.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (at $T = 0$ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>1.12 eV</td>
</tr>
<tr>
<td>Germanium</td>
<td>0.67</td>
</tr>
<tr>
<td>Gallium-Arsenide</td>
<td>1.4</td>
</tr>
<tr>
<td>Diamond</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 2.1: Energy gaps of some semiconductors
2.2.2 Charge carriers

In semiconductors there are two kinds of charge carriers, electrons in the conduction band and holes in the valence band. In a pure semiconductor free electrons and electron holes are produced by thermal excitation. This production is found to be in equilibrium with the recombination of electron and holes. The product of densities of electrons and holes in thermal equilibrium is given by:

\[ pn = N_e N_v \exp \left( \frac{E_g}{2kT} \right) \]  \hspace{1cm} (2.6)

where \( n \) and \( p \) are the densities of electrons and holes, \( N_e \) and \( N_v \) are effective densities of states at the conduction and valence band edge respectively. \( T \) is the temperature and \( k \) is the Boltzmann constant. In intrinsic material (a pure and perfect crystal) \( n = p \) and is called the intrinsic carrier density \( (n_i) \). In pure Silicon the intrinsic carrier density is \( n_i = 1.45 \times 10^{10} \text{ cm}^{-3} \) at room temperature. The volume of one pixel is for example \( 7.5 \times 10^{-6} \text{ cm}^3 \), thus at room temperature one pixel will contain \( \sim 100,000 \) free intrinsic carriers.

2.2.3 Doping

![Diagram of a silicon lattice with a donor ion implanted](image)

Figure 2.4: Schematic lattice with donor ions implanted.

The number of carriers can be changed drastically by doping, replacing some of the atoms by atoms from different chemical groups. Impurities that contribute to the carrier density of a semiconductor are called donors if they supply additional electrons to the conduction band, and acceptors if they...
supply additional holes to the valence band. When for example Silicon is doped with one of the group V elements, like phosphorus, then each phosphorus is found to occupy an atomic site normally occupied by a Silicon atom. Since the host Silicon atoms are tetravalent only four of the five valence electrons of the impurity are used in forming covalent bonds, leaving one electron weakly bound to its parent atom, a schematic of a Silicon lattice with a phosphorus donor can be seen in figure 2.4.

Since the energy level of the impurity is within the energy gap, less energy is needed to free an electron (figure 2.5).

![Diagram showing the energy levels of acceptors and donors. The energy required to create an electron-hole pair is far less than the energy gap.](image)

Donor impurities are atoms that have a higher chemical valence than the atoms making up the pure material, while acceptors have a lower chemical valence. If the material has a preponderance of donor impurities it is called n-type since the conduction is predominantly due to negative charges. While material having a preponderance of acceptor impurities is called p-type since positive charges are the majority charge carriers here. The concentration of majority charge carriers is typically of the order of $10^{11} \text{cm}^{-3}$.

### 2.2.4 P-N junction

Consider two semiconductor crystals of p- and n-types with impurity concentrations $N_a$ and $N_d$ brought together forming the abrupt junction (figure 2.6).

At the junction a gradient appears of electrons and holes densities which
results in a diffusive migration of majority carriers across the junction. From
the p-type region there is a flow of holes to the n-type region, in the opposite
direction there is a flow of electrons. The electrons that leave the n-type
layer will immediately recombine with a hole on the p-side. In the p-type
region there are now immobile donor impurities left which have absorbed
electrons and therefore have a negative charge. As a result charge is being
built up, reducing the free flow of holes and electrons. The resulting potential
difference is called the built-in potential, $V_{bi}$.

An external voltage can be applied with the same polarity as the built-
in potential, this is called reverse bias (figure 2.7). As a result the size of
the n-type region saturated with holes from the p-layer, the depletion layer,
increases. If the bias voltage is increased until the thickness of the depletion
2.3. **PRINCIPLE OF DETECTION**

![Diagram of pn junction with bias voltage](image)

Figure 2.7: *Three different ways to apply the bias voltage.*

Layer equals the thickness of the Silicon layer the sensors are fully depleted. Below the limit of full depletion the thickness $W$ of the depletion layer is approximately given by [19]:

$$W \approx \sqrt{2\varepsilon \rho \mu V_B}$$  \hspace{1cm} (2.7)

where $\rho$ is the material resistivity, $\mu$ is the majority carrier mobility, $\varepsilon$ the dielectric constant and $V_B$ is the reverse bias voltage. Since the electrons left the n-type region and the holes the p-type region the electrical neutrality is disturbed. This creates an electric field, see figure 2.6. If a particle passes through the pn-junction, depositing energy that might create electrons and holes. The holes and electrons will be driven away by the electric field, the electric field works as a slide bank. By applying an external field in the direction of the built-in voltage, this effect is enforced. The time between the creation of the charge carriers and their collection on the electrodes, the charge collection time, is therefore shorter.

### 2.3 Principle of detection

A semiconductor detector is built as a pn-junction. When a charged particle crosses the Silicon, it will deposit energy as explained in the first section.
CHAPTER 2. SILICON AS A DETECTOR MATERIAL

This energy allows the electrons in the valence band to jump to the conduction band, creating a free charge carrier, see figure 2.8. The energy required to create an electron-hole pair depends on the material, for Silicon for example it is 3.6 eV (see table 2.2).

Figure 2.8: Schematic of a Silicon particle detector. The created electrons and holes will drift towards the electrodes.

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy (at $T = 0$ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>3.62 eV</td>
</tr>
<tr>
<td>Germanium</td>
<td>2.8</td>
</tr>
<tr>
<td>Gallium-Arsenide</td>
<td>4.2</td>
</tr>
<tr>
<td>Diamond</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 2.2: Energy required to create an electron-hole pair for some semiconductor materials.

The created electron and holes will drift freely through the material and will be directed towards the electrodes by the electric field. On the electrodes electrons and holes can be collected, they will appear as an electric pulse.
2.4 Noise in Silicon detectors

The noise in Silicon detectors has three main contributors, the sensor creates thermal noise and leakage current. The noise of the read out electronics can be summarized in one term. The leakage current itself has three contributors: surface current, generation current and diffusion current [29]. The leakage current depends on the fabrication process, fabrication quality, detector size and operation temperature. The electronics noise is mainly due to the noise of the preamplifier. Since the signal of a semiconductor detector appears as electric charge, electronics noise is usually quantified by giving its equivalent noise charge (ENC). The following equations give the ENC for the three different noise sources:

\[
ENC_A^2 \approx \frac{8kT}{3} \frac{C_t^2}{g_m \tau_s} \tag{2.8}
\]
\[
ENC_G^2 \approx 2qI_0 \tau_s \tag{2.9}
\]
\[
ENC_J^2 \approx C_t^2 \tag{2.10}
\]

where \(C_t\) is the total detector input capacitance, \(\tau_s\) is the shaping time and the rest of the symbols have their usual meaning.

It is clear that the noise is dominated by the detector capacitance, noise reduction can thus be established by decreasing this capacity. This can be achieved by segmenting the sensitive area into smaller elements connected to individual readout circuits. The noise due to the leakage current can be reduced by using shorter shaping times, this increases the thermal noise since the thermal noise \(\sim 1/\tau_s\), thus an intermediate shaping time has to be found. The noise can be calculated by making reference to the energy of the particle or radiation which produced the signal charge in the detector in terms of full width at half maximum\(^2\) (FWHM) of the spectral peak obtained.

\(^2\)C_t is the sum of the detector capacitance and the parasitic capacitance at the input.

\(^3\)The Gaussian distribution is given by:

\[
P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2.11}
\]
\[ ENC = \frac{\Delta E(\text{FWHM})}{2.35w} \]  
(2.13)

where \( w \) is the average energy required to create an electron-hole pair.

### 2.5 Types of Silicon particle detectors

To get track information from Silicon detectors, several choices concerning the design of the detector have to be made as there is for example the readout (digital, analogue). To make a Silicon detector position sensitive one should divide the p-side into smaller elements. One possibility is to make an array of pads, called pixels (from picture elements). This was not used until recently because of the problems with the coupling of the readout channels to the electronics and the enormous amount of data. This will be discussed in the next chapter. Another geometry, used more frequently, is an array of narrow strips. The spatial resolution with analog readout is limited to the minimum of 5 \( \mu \text{m} \) because of the size of the cloud of the electrons and holes created. Using binary readout the spatial resolution is given by the \( \frac{1}{\sqrt{12}} \) times the width of the detector segment. The factor \( \frac{1}{\sqrt{12}} \) comes from the standard deviation \( \sigma \) of the square distribution.\(^4\)

The FWHM can be used though the half width of the peak at about 60 \% corresponds to the \( \sigma \). The FWHM is somewhat larger than \( \sigma \) and from the distribution it can be shown that the FWHM is given by:

\[ \text{FWHM} = 2\sigma \sqrt{(2\ln 2)} = 2.35\sigma \]  
(2.12)

\(^4\)This can easily be calculated as follows:

\[ \sigma = \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \]  
(2.14)

with

\[ \langle x \rangle = \int f(x)dx \]  
(2.15)

where \( f(x) \) is given by

\[ f(x) = 0 \quad x < 0 \text{ and } X > L \]  
(2.16)

\[ f(x) = \frac{1}{L} \quad 0 \leq x \leq L \]  
(2.17)
2.5. TYPES OF SILICON PARTICLE DETECTORS

2.5.1 Micro strip detectors

Silicon micro strip detectors were developed in the early 80’s. They are widely used in collider and fixed target experiments and consist of Silicon areas of up to several 10 cm$^2$. Most currently running colliding beams experiments have a vertex detector made of several layers of Silicon micro strip detectors. An example of a Silicon micro strip detector can be seen in figure 2.9. The segments are strips with a width of typically 20 to 50 μm, resulting in a spatial resolution of 5.8 to 14.4 μm. The experience with gaseous detectors and wire chambers would inspire [19] to make a very dense readout in order to measure the signal on several strips and reconstruct the shape of the charge distribution to find the center. The pitch should be of the order of a few micrometers. High resistivity n-type Silicon (2000 Ω cm) is used as the base material onto which p$^+$ diode strips with aluminum contacts are implanted. An n$^+$ electrode is similarly implanted on the opposite face. The thickness of the detector is in the order of 300 μm which implies an operation voltage in the order of 100 Volts to obtain full depletion. A MIP will create about 25 000 electron-hole pairs.

To get a 2-dimensional track point it is possible to place one detector rotated over a certain angle with respect to the other. The disadvantage is that there might be some ambiguity on the correspondence of a track in the two detector planes and more material is used. Because of their small size and full depletion, micro-strip detectors offer a fast response time. Charge collection can be performed in less than 10 ns [18]. Another advantage (compared to the traditional detectors: gaseous detectors, wire chambers) is the good geometrical precision. Using appropriate data analysis and the charge distribution, precisions as good as 2.6 μm can be reached [19]. The main problem in future collider experiments is the limited radiation hardness of Silicon. Radiation damages the Silicon lattice and the electrical field in

\[
< x > = \int_0^L \frac{1}{L} x dx = \frac{1}{2} L \quad \text{(2.18)}
\]

\[
< x^2 > = \int_0^L \frac{1}{L} x^2 dx = \frac{1}{3} L^2 \quad \text{(2.19)}
\]

therefore

\[
\sigma(x) = \sqrt{\frac{1}{3} L^2 - \frac{1}{4} L^2} = \frac{L}{\sqrt{12}} \quad \text{(2.20)}
\]
the detector is disturbed. This results in a deterioration of the resolution, since the charge spreads over more strips, and an increase in the leakage current. Some compensation can be obtained by increasing the bias voltage, to restore the electrical field and to keep the S/N ratio constant.

2.5.2 CCD detectors

The first successful two dimensional detector is the Charged Coupled Device. The Charge Coupled Device (CCD) was first devised in 1970 by Bell Laboratories. The CCD is a monolithic\(^5\) array of closely spaced MOS capacitors which transfers an analogue signal charge from one capacitor to the next. CCDs are used for three purposes: optical imaging, digital memory and analogue signal processing. A CCD can store and transfer analogue-charge signals that may be introduced optically or electrically. The readout is performed serially (a CCD is a kind of shift register) and therefore is very slow, in the order of 10 ms \cite{23}. The CCD can not be used for high rate

\(^5\)Monolithic here means the integration of the detector and the electronics in the same substrate layer. This will be discussed more thoroughly in the next chapter.
readout since during the readout the sensor elements stay sensitive which
would result in a mixture of several events in one readout cycle. CCDs are
thus not being used much in high energy experiments\textsuperscript{6}.

2.5.3 Pixel detectors

Pixel detectors consist, like CCD detectors, of rows and columns. The advan-
tage of pixel detectors is that each detector element has its own (fast) readout
electronics (with readout frequencies in the order of MHz). In this way it is,
even at high luminosity, possible to get precise position determination. Pixel
detectors can be used for high rate tracking since the dead time and timing
precision are mostly limited by the readout electronics. The readout can be
done both analogue or binary. Analogue readout has not yet been used in
experiments, since it will increase the amount of data enormously, but will
on the other hand give a far better resolution. The most important thing
about micro pattern pixel detectors is the microscopic segmentation of the
sensor material, which results in a capacitance\textsuperscript{7} of only \( \sim 100 \) pF. Such small
capacitance allows a relatively simple readout amplifier, since the noise is in
the order of 100 \( \epsilon^{-} \) r.m.s.. This low capacitance should not be spoiled by
oversized connections and therefore a monolithic structure or a bump-bonded
signal processor in close proximity must be chosen. Pixel detectors will be
discussed more thoroughly in the next chapter. A very important advantage
of pixel detectors compared to strips is that they can stand more radiation.
Since the pixel capacitance is far less than the strip capacitance the signal to
noise ratio will be better. Pixels will have far less leakage current since the
leakage current is proportional with the length of the strips.

\textsuperscript{6}The CCD is currently used in the SLD experiment at SLAC.

\textsuperscript{7}This capacitance is the result of two neighboring charged plates, the capacitance is
given by: \( C = \frac{\epsilon A}{d} \). Where \( A \) is the surface, \( \epsilon \) is the dielectric of the material and \( D \) is the
distance between the layers. Thus the capacitance decreases with smaller areas.
Chapter 3

Silicon pixel detectors

The previous chapter shows that pixel detectors may have a lot of advantages, as there are the high resolution, small noise, fast read out, two dimensional read out and high rate tracking. Still some answers had to be found to problems such as: the enormous amount of data, the advanced read out, the integration of detector and electronics, the corresponding yield of electronics readout chips and expensive bump bonding, the choice of digital/analogue readout and radiation hard fabrication process. In the first half of this chapter some general features of pixel detectors will be discussed, the second part will give a description of the Omega3/LHC1 detector, this is the detector developed by the CERN RD19 group. The Omega3/LHC1 is the first pixel detector to come close to meeting the LHC requirements.

3.1 Integration of the detector and the electronics

One of the problems which has to be faced is the integration of the detector with the readout electronics. To avoid extreme data flows, active readout electronics should be connected close to the sensor. Silicon micro strip detectors can have their electronics placed at one or two strip ends, with a pixel detector the only ends are on the back and the front. So new ways of integrating the sensor and the electronics are required, in this section only
the most frequently used will be discussed. These are shown in figure 3.1.

**Figure 3.1:** Possibilities for the integration of electronics and detector: (a) monolithic integration, (b) Silicon on insulator, (c) hybrid integration.

### 3.1.1 Monolithic integration

With monolithic integration the electronics will be implanted in the detector substrate. In this way very thin detectors (≳ 300 μm) can be created, which because of their very small contact capacitance produce very little noise. Since the electronics are integrated in the detector, not the entire detector surface is active, since there will be dead (not active) material between two
neighboring pixels. An other disadvantage of this method is that the processing technique is still very immature. Monolithic integration is used in CCDs, for pixels the risk of ruining the advanced electronics is larger.

3.1.2 Silicon on insulator technique

The Silicon On Insulator (SOI-technique) is an improvement of the monolithic method. The substrate material (= detector material) is in this case high resistivity Silicon. The substrate represents the detector. On top there is a layer of oxide, followed by a second layer of Silicon. This layer contains the readout electronics. The seed is the electrical connection between the detector and the front end of the electronics, the seeds are openings between the insulating oxide. This makes the entire detector surface active. This method is not yet standard for the industry. In the framework of RD19, research on SOI is carried out [30].

3.1.3 Hybrid integration

The solder bump bonding process has been developed around 1970 by IBM as a more reliable alternative to wire bonding. The electronics and the detector are fabricated in different semiconductor substrates. Both substrates are connected by small solder bump bonds (~25 μm). The advantages are that detector and electronics can be optimized separately, e.g. by using different materials). As can be seen in figure 3.1 the entire surface is active and the fabrication methods are standard. The disadvantages in comparison to the other solutions are that the detector is now thicker than the two other options, and the difficulties and the cost of the bump bonding technique. It is not the fabrication costs which are higher, it is the low yield per wafer that makes this method expensive.

3.2 Fabrication of the detector

Figure 3.2 gives an overview of the layers that are used for the detector. For the fabrication of the detector high resistivity Silicon wafers, see figure 3.3, are used.

In the first process step the oxide 1 is produced (this is a passivation layer). It marks the border where later no p-implantation is desired. On the
remaining surface the ion implantation is not screened and the next process step produces a strongly doped p-layer, called $p^+$. On the backside a $n^+$ layer is placed. Then aluminum is evaporated on both sides of the detector. For reasons of field shaping and to be sure that all the $p^+$ area is covered the aluminum layer overlaps the $p^+$ by some $\mu m$. The metal layers will distribute the detector bias voltage over the entire detector. The next process step is the covering with oxide 2, which serves as a protection layer. This layer has holes where the contact electrodes can be placed for the connection between the detector and the readout electronics. The strongly doped $p^+$- and $n^+$-layers avoid a Schottky\textsuperscript{1} diode structure between semiconductor and metal. The maximum size of such a detector chip is limited by the wafer size and by the fabrication costs, because of the low yield.

\textsuperscript{1}A Schottky barrier is a junction formed between a semiconductor and a certain metal, for example $p$-type Silicon with aluminum. Because of the different Fermi levels in these materials, a contact emf arises when the two are put together. This causes a lowering of the band levels in the semiconductor.
3.3 THE LHC1/OMEGA3 DETECTOR

Figure 3.3: Picture of a wafer at a 1:1 scale. The 'a'-type detector are the darker chips.

3.3 The LHC1/Omega3 detector

3.3.1 Requirements

The development of pixel detectors has been strongly stimulated by the plans to build the Large Hadron Collider. The CERN RD 19 group has been developing pixel detector prototypes, aiming to fulfill the LHC requirements. These requirements are dictated predominantly by the physics goals of the LHC (see also chapter 1) and are shown in table 3.1. One of the basic tasks of the pixel system is a good tracking performance. This results in demands on the pixel system concerning impact parameter resolution, momentum resolution and pattern recognition. These demands can be translated into requirements on the basic pixel performance.
Table 3.1: Principal requirements for the pixel detector and its readout electronics

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution ($R\phi$)</td>
<td>&lt; 14 $\mu$m</td>
</tr>
<tr>
<td>Input threshold</td>
<td>$\sim$ 1000 e$^-$</td>
</tr>
<tr>
<td>Input threshold uniformity</td>
<td>$\pm$30%</td>
</tr>
<tr>
<td>Overall track efficiency</td>
<td>95 %</td>
</tr>
<tr>
<td>Noise (after irradiation)</td>
<td>&lt; 250 e$^-$</td>
</tr>
<tr>
<td>S/N - before(after) irradiation</td>
<td>$\sim$ 50(20)</td>
</tr>
<tr>
<td>$&lt;$readout time$&gt;$ per pixel</td>
<td>&lt; 200 ns</td>
</tr>
<tr>
<td>Pixel dead time (inc. readout)</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>Mask each pixel</td>
<td>yes</td>
</tr>
<tr>
<td>Calibrate each pixel</td>
<td>yes</td>
</tr>
<tr>
<td>$&lt;$power$&gt;$ per pixel</td>
<td>&lt; 40 $\mu$W</td>
</tr>
<tr>
<td>Max. fluence (1 MeV n equiv.)</td>
<td>$\sim$ 10$^{15}$cm$^{-2}$</td>
</tr>
<tr>
<td>Max. ionizing dose</td>
<td>$\sim$ 200 kGy</td>
</tr>
</tbody>
</table>

Good tracking performance is critically depending on the spatial resolution. The geometry of the pixel cell is as narrow as can be to obtain good resolution. The limiting factor is multiple scattering due to material in the tracking system. A spatial resolution of less than 10 $\mu$m does not lead to a improved impact parameter.

The expected signal at the beginning is expected to be 12 ke$^{-2}$, thus a threshold of 3 ke$^{-}$ would be acceptable. Since the noise is estimated 200e and the threshold variation is about 200e, a threshold of 2 ke$^{-}$ is allowed. The noise and the threshold variation should be less than the missing signal due to the threshold. Operation at such low thresholds implies that the cross-talk caused by single large pulse-heights is to be limited. A cross-talk ratio of 5-10 % is appreciable.

The overall track efficiency has to be 95 %, since at least 4 or 5 points are needed to construct a reliable track. Loss in efficiency is due to dead time, poor time walk performance, inefficiencies in the regions between pixel chips or masked pixels.

Exclusive for the Omega readout electronics, in comparison to other ATLAS

\footnote{This is calculated with a detector thickness of 150 $\mu$m, for a thickness of 300 $\mu$m the signal would be about 23 ke$^{-}$.}
Table 3.2: Radiation doses in the inner detector for distances to the interaction point

<table>
<thead>
<tr>
<th>$R$ (cm)</th>
<th>Ionizing dose (Mrads)</th>
<th>Fluence ($MeV\text{ n/cm}^2\text{10}^{-14}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>117</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>55</td>
<td>18.8</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>7.4</td>
</tr>
<tr>
<td>11.5</td>
<td>17</td>
<td>5.8</td>
</tr>
<tr>
<td>14.5</td>
<td>11.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

pixel detector candidates, is that the Omega chip does not use a shift register but uses a delay line. This means that the chip does not have an internal clock with 40 MHz frequency. Such a clock could be a cross-talk enhancer. The private readout electronics of each pixels, allows the masking and calibration of every pixel.

ATLAS studies [33] concerning the cooling have concluded that the power budget for the pixel area is 0.6 W/cm$^2$, thus per pixel the available power is 30 $\mu$W. In the LHC the time between two successive bunch crossings will be 25 ns. The length of the bunches is about 75 cm. Each bunch crossing takes about 2.5 ns and produces an average of about 18 proton-proton collisions. This imposes an overall timing resolution better than 25 ns. Since the occupancy is only $10^{-4}$ the pixel readout time can be 200 ns. The dead time is the finite time required by the detector to process an event which is usually related to the duration of the pulse signal. A dead time of 2 % is good enough to reach the track efficiency of 95 %.

Individual masking of noisy pixels will reduce the amount of data. Individual calibration is necessary because of the threshold non-uniformity. Since each readout chain behaves differently, it is necessary for precise measurements to know this individual behaviour. This non-uniformity should be limited, ATLAS demands 30 %, since the threshold voltage has the same values for all pixels. The enormous rate of proton-proton collisions makes radiation damage of detector or detector parts a major concern. The ATLAS environment imposes an expected maximum radiation dose in the inner detector of 34 kGy/yr and $5.9 \times 10^{13}$ neutrons per cm$^2$ per year for the pixel detector layers. The amount of radiation is a function of the distance from the in-
teraction point. Table 3.2 shows the radiation at several distances from the interaction point. The inner layers of the detector may have to be replaced after a certain time, since no detector system has survived such radiation dose at that rate so far.

### 3.3.2 Read-out electronics

Every readout sensor cell has its corresponding readout cell. The size of the readout electronics cell is the same as the size of a sensor cell. A readout cell contains about 400 transistors. Because of the high component density a very refined fabrication process is used \(^3\). One readout cell is shown in figure 3.4. Each cell can be addressed individually for electrical tests. Figure 3.5

![Figure 3.4: Photograph of a single readout cell. The bump pad is the octagonal on the left.](image)

shows the corresponding block diagram.

Each pixel readout chain contains from left to right the successive functions with in brackets their geometrical size \([31]\): switch for connection of analogue test signal (length 25 \(\mu m\)), bump bonding pad (octagonal in metal 1 and 2 with 22 \(\mu m\) diameter), preamplifier with leakage current compensation, asynchronous comparator with externally adjustable threshold and fast-OR output (preamplifier and comparator 250 \(\mu m\)), the masking flip-flop (25 \(\mu m\)), a globally adjustable delay (100 \(\mu m\)) with local 3-bit fine-tuning (100 \(\mu m\)), coincidence logic, memory cell (25 \(\mu m\)) and bus lines.

The charge preamplifier is a fast charge sensitive amplifier, designed to consume 19 \(\mu W\). The feedback capacitance is of the order of 3.5 \(nF\). The feedback resistance is non-linear to limit the swing for high input signals. The amplifier is based on a folded cascode circuit. The signal rise time is designed to be \(\sim 80\) ns. An additional reset has been provided to force a fast

---

\(^3\)The chip is manufactured in the 1 \(\mu m\) SACMOS (self aligned contacts MOS) process from FASELECO, a non-radiation hard process (up to 50 kGy) \([32]\). This process is equivalent to a 0.6 \(\mu m\) standard CMOS process.
Figure 3.5: Block diagram of the readout electronics.

return to zero to decrease the dead time of the cell after a large signal, since the rise time of the amplifier is the bottleneck in the signal processing time. The amplified signal will then enter the comparator, where it will be compared with the threshold set by an external current. The comparator contains a bistable non-linear load, see figure 3.6 and is ac coupled to minimize offset effects. The current in the bistable non-linear load determines the threshold and can be varied externally by a common bias adjustment. In the state after reset this current runs in one of the two branches of the non-linear load.

The comparator can be reset by the reset-signal. The reset can be external or from the feedback from the delay chain. The comparator provides a fast-OR and can be masked, i.e. inhibited to operate if the preamplifier or the comparator prove to be too noisy or defective.

The delay chains enable, together with the feedback after 4 stages (out of a total of 36 stages), allows several hit pulses to propagate consecutively in the delay line and should decrease dead-time to below ~250 ns. As a distinctive feature a 3-bit digitally controlled delay tuning has been added. The improvement by using a delay line instead of a more commonly used shift register is that the internal clock of the shift register might increase the cross talk. The coincidence logic will write a one into the data flip-flop if
during the externally provided strobe a rising edge at the end of the delay line is detected.

### 3.3.3 Sensor

The detector consists of two parts, the sensor chip and the electronics chip. The mechanical and electronic connection is made by bump bonds. The sensor has a total area of 0.8 cm$^2$, with a sensitive area of 8 mm $\times$ 6.35 mm, just over 0.5 cm$^2$. A schematic of this configuration can be seen in figure 3.9. A photograph of a detector readout chip can be seen in figure 3.10(a).

The 300 $\mu$m thick sensor chip consists of small pixel cells, in a matrix of 16 $\times$ 127 sensor cells, surrounded by a guard ring. An additional row of dummy cells at the bottom is connected to a leakage current sensing circuit for each column. The guard ring is connected to ground through the readout chip. As described above, the capacitance is of crucial importance on the noise behaviour. Therefore two different type basic cells are used, the conventional type (c-type) and the advanced type (a-type), a photograph of these types.
can be seen in respectively figure 3.7 and figure 3.8. The capacitance of the c-type is about 90 fF and the capacitance for the a-type is 55 fF [22].

3.3.4 Bump bonding for the LHC1/Omega3 detector

Since the small capacitance is an important feature of the pixel detector, this should not be spoiled by using large connections. For the Omega3/LHC1 hybrid integration has been used. In figure 3.10(b) a readout chip with 8 bumps is shown. For the Omega3/LHC1 a fine-pitch solder bump technology
Figure 3.8: Picture of the lower part of a type 'a' (alternative) detector. The 2 lower-most cells are connected to the guard ring. The opening in the passivation layer for the bump bonding connection is visible in the rightmost island of a cell.

developed by GEC-Marconi Ltd has been chosen [23]. A mask is used to place the bumps exactly on the openings in the passivation layer where a bond is foreseen. The bumps are made of a lead/tin composition in the ratio 95/5. The size of the bump is chosen so that the contact between the chips is optimized [23] (in the order of 28 μm). The detector chip and the electronics chip are placed exactly on top of each other and then heated until the connection areas are fully covered (reflowed). The distance between the two chips is of the order of 10 μm. The bonding can withstand a force of 10 mN (1 gram) before breaking.
Figure 3.9: Schematic view of the readout cells, detector cells and bump bonds.
Figure 3.10: (a) Photo of a type 'a' detector chip. The guard ring surrounding the active matrix and the column structure is clearly visible. (b) Photograph taken with a scanning electron microscope of a column of solder bumps on the readout cell after reflow.
Chapter 4

Measurements using the NIKHEF set up

For the use of pixel detectors in the ATLAS experiment it is necessary to know their behaviour under specified circumstances. Tests can be performed with the electronics and sensor, using the sensor input (see fig 3.5) or with the read out electronics alone using the test input. A test set up, similar to the CERN test set up, has been built to do both kind of tests. For a comparison between the efficiency using the test input and the efficiency using the sensor input a calibration has to be carried out. Measurements with radioactive sources or test beam can be compared with the electronics measurements. The signal coming from either the sensor input or the test input is read out binary, the signal is shaped by the read out electronics and compared with a reference voltage. We describe the temperature dependence of the electronics in this chapter. Though the behaviour of the readout electronics from cell to cell may be different, some uniformity is required. The uniformity has been measured and is presented in section 4.2.4. The noise in a pixel originates from 3 sources: thermal generation of current, leakage current in the sensor and noise from the read out electronics. The latter noise is measured and presented in this chapter. The height of the reference voltage of the comparator for operation in ATLAS has to be estimated. The ATLAS specifications impose a threshold voltage of about 2000 electrons, in section 4.2.6 the results of a measurement are presented to see whether this number
can be matched.

4.1 Set up

4.1.1 Hardware

Figure 4.1 shows the lay out of the test set up. The set up consists of 5 parts: the pixel detector, the control electronics, the supply voltages, the timing circuits and the data analysis. The laboratory set up uses two fully equipped detectors, i.e. sensor and readout electronics, which are placed on a test board. The detectors on the test board are connected to the mother board. The function of the mother board is twofold. On the one hand the mother board transfers the supply voltages and the signals (see table 4.1) to the test board. The other function of the mother board is to control the pixel detector. The software running under the OS9 operation system controls the VME readout module. The readout module in turn controls the mother board. The voltages are provided by 2 Delta Dual Power E 018-0.6D power supply and 1 Delta power supply SM 3540. The VME readout module generates a trigger signal, which can be used to time the strobe signal and test signal. Figure 4.2 shows the the synchronization between test and strobe signals. The timing of the signals is obtained via NIM modules. The strobe signal is a NIM signal, the test signal is shaped, both in duration and amplitude, by a pulse generator\(^1\) PM 5786 (1Hz-125MHz). The local disk is placed in a VME crate together with the readout module and the FIC 8234 (Fast Intelligent Controller). The FIC 8234, an MC68030 full 32-bit enhanced microprocessor from Motorola based on a VME single board unit, connects the OS9 system to the VME crate. The data on the local disk can be transported to the HP workstation through the TCP/IP protocol. The data is analyzed using the PAW (Physics Analysis Workstation) software on the HP workstation.

\(^1\)The voltage is lowered by a factor 23 by an attenuator on the test board.
4.1. SET UP

Figure 4.1: Schematic overview of the laboratory set up. Not to scale.

4.1.2 Software

The VME readout module is controlled by a data acquisition program, running under OS9. The program provides the following options:
TABLE 4.1: OVERVIEW OF THE DIFFERENT VOLTAGES AND SIGNALS USED IN THE LABORATORY SET UP.

- SERVICE ROUTINES
- SET BIAS VOLTAGES
- DATA ACQUISITION
- MAKE MASK
- LOOP ON RATE

The service routines provide the tools to check the set up, e.g. error flags, timing, data buffers. The bias voltages for the readout electronics: threshold voltage, compensation voltage and the two delay voltages can be set in the program using the option set bias voltages.
4.2. **ELECTRICAL MEASUREMENTS**

![Diagram of test and strobe signals vs time]

Figure 4.2: Required timing for the signals test and strobe. The strobe is a NIM signal of approximately 2 μs, the test pulse has a length of 10 μs and a height of ~ 3V.

The options **data acquisition**, **make mask** and **loop on rate** are based on the same principle. The structure of this principle is shown in figure 4.3. It is divided in three steps, initialization, data acquisition and write to file. The initialization prepares the VME control (in the VME readout module), the LCA region (signal processing and transfer unit) on the motherboard, clears the data buffer and writes the mask and test array (both in the readout electronics). During the data-acquisition the same steps are repeated a number of times (i.e. the number of measurements). Reset defines the physical area in the LCA region, corresponding with the option, on the motherboard. The trigger out signal, used to generate the test and strobe pulse, is generated here. Now the real measurement can start, that is if the error flag is not raised. The data are read and decoded before they are written to file in the last step.

### 4.2 Electrical measurements

In section 3.3.1 the ATLAS requirements for the pixel system were listed. The test set up, described above, allows us to verify most of these specifications. The requirements to be able to individually mask and calibrate each pixel are already fulfilled in the electronics design. The power consumption is designed to be 100 μW per pixel cell. The overall track efficiency and the spatial resolution can only be tested using a test beam, this will be discussed in the next chapter. The temperature dependence of the electronics, the signal to noise ratio, the threshold value, the threshold uniformity and the detector offset are experimentally tested and presented in this chapter. But first of all the detector is calibrated, which allows us to compare the input of the sensor with the test signal input.
4.2.1 Detector response

The readout in the Omega3/LHC1 chip is binary, the height of the signal is compared with a reference voltage. If the signal is larger than the reference height, a 1 will be registered. In this case only one bit is needed, analogue readout converted to a digital number needs at least 8 bits. The threshold voltage of the comparator can be set externally. The height of the signal is fluctuating due to noise in the electronics chain from the input to the comparator. The sum of the signal and the fluctuation might sometimes result in a responding pixel, even if the height of the signal is less than the reference height, or exactly the other way around (non-responding pixel if the height of the signal is larger than the reference voltage). The uncertainty obtained by these fluctuations can be reduced by performing the same measurement $N$ times. The error is then given by $\sigma_N = \sqrt{N}$.

The electronic behaves differently from cell to cell. Figure 4.4(a) shows the variation in the comparator answer for $N=5000$, in (b) the variation over the chip is shown to be Gaussian distributed. The variation over the pixel cells is $\sigma_Y^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2$ where $\bar{x}$ is the mean value and $x_i$ is the value
4.2. ELECTRICAL MEASUREMENTS

Figure 4.4: (a) Three dimensional plot showing the variation in the comparator response over the pixel chip at -10 °C, at a certain threshold. On the vertical axis one can see the number of times the pixel responds, \( N = 5000 \). (b) The variation in the efficiency is Gaussian distributed. The sigma is very small, only \( \sim 20 \) compared to a mean of \( \sim 2800 \) mV.

for one pixel cell. The total error \( \sigma_T \) is then given by:

\[
\sigma_T^2 = \sigma_V^2 + \sigma_N^2
\]  

(4.1)

This equation gives an indication of a the preferred number of measurements. We choose the number of measurements such that the relative error in the variation over the chip \( \left( \frac{\sigma_V}{\bar{V}} \right) \) is of approximately the same order as the relative error in the statistical fluctuation \( \frac{1}{\sqrt{N}} \). Naturally N is kept constant during a measurement, therefore \( \frac{\sigma_V}{\bar{V}} \) is smaller than \( \frac{1}{\sqrt{N}} \) for lower threshold voltages. On the average the relative error due to variations over the pixel chip is about 3 %, thus N is chosen to be 1000.

4.2.2 Calibration

A calibration is carried out to get a one to one correspondence between the threshold voltage and the number of electrons injected at the sensor input.
Figure 4.5: Efficiency curve for a test signal corresponding with the energy loss of a Minimum Ionizing Particle (90 keV) at room temperature and at -10 °C (ATLAS operating temperature).

Thus, a certain threshold voltage only allows pulse heights (i.e. number of created electrons) above this reference voltage. The test signal is kept constant while the threshold voltage is increased stepwise. The threshold voltage will go beyond the characteristic input voltage and the count rate (efficiency) will drop to zero. Considering the behaviour of one detector, the efficiency is defined as the number of times a pixel cell responds divided by the number of input signals on this pixel, at a certain threshold. The efficiency has been measured for each cell and is afterwards averaged over the pixel chip. The error bars are calculated from the sum (according to equation 4.1) of $\sigma_N = \sqrt{N}$ and:

$$\sigma_{\text{thres}}^2 = \frac{1}{N} \sum_{\text{all pixels}} (V_{\text{thres}i} - \overline{V_{\text{thres}}})^2$$  \hspace{1cm} (4.2)

in this case N is the total number of pixels (1024 for one chip). The number of electrons corresponding to the test pulse can be calculated since the
4.2. ELECTRICAL MEASUREMENTS

The capacitance\(^2\) \(C_{\text{test}}\) at the test input is known. The number of electrons is:

\[
\#e\text{lectrons} = \frac{Q_{\text{test}}}{e^-} = \frac{V_{\text{test}} \times C_{\text{test}}}{e^-}
\]  

(4.3)

The variation in the number of electrons can be calculated as follows:

\[
\Delta(\#e\text{lectrons}) = \Delta C \frac{V}{e^-} + \Delta V \frac{C}{e^-}
\]  

(4.4)

Two examples of this threshold voltage scan are shown in figure 4.5. The curves in figure 4.5 are measured at a pulse height corresponding to the energy loss of a Minimum Ionizing Particle\(^3\) (MIP). From this curve it is obvious that the readout electronics behaves differently at the two temperatures. The temperature dependence is more thoroughly investigated in the next section. The threshold scan is repeated for a range of test pulses. From each curve the 50 % efficiency level is selected. The results for two temperatures can be seen in figure 4.6. The data are fitted with the following parameterization:

\[
\#e\text{lectrons} = c_1 + c_2 \times V_{\text{thres}} + e^{c_3 + c_4 \times V_{\text{thres}}}
\]  

(4.5)

The fit has an excellent \(\chi^2\) for both calibrations and matches the data within the error bars. The purpose of the calibration is to relate the number of electrons with the threshold voltage, the fit provides us a mathematical function. We use the fit to calculate the number of electrons, see table 4.2 for a summary of the results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Room temperature</th>
<th>-10 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_1)</td>
<td>-19130</td>
<td>-12168</td>
</tr>
<tr>
<td>(c_2)</td>
<td>11.1</td>
<td>9.9</td>
</tr>
<tr>
<td>(c_3)</td>
<td>-0.2749</td>
<td>-14.5</td>
</tr>
<tr>
<td>(c_4)</td>
<td>0.0027</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 4.2: Values of the fit parameters, using the data of the calibration measurements. The fit function is given in equation (4.5).

\(^2\)The capacitance, 25 \(\text{fF} \pm 5\%\), at the input of the preamplifier(see figure 3.5).

\(^3\)A MIP corresponds to 90 keV, which is equivalent to a production of 25000 electrons for a detector of 300 \(\mu\text{m}\) thickness.
Figure 4.6: (a) Threshold calibration at room temperature, (b) shows the threshold calibration at -10 °C (ATLAS operating temperature).

4.2.3 Temperature dependence of the readout electronics

The calibration is performed at different temperatures. Obviously the behaviour of the read out electronics is temperature dependent. During operation (in ATLAS) the pixel temperature will not be uniform. Due to variations in the occupancy and different temperature gradients in the support structure. The temperature dependence of the sensor material is \( \sim \exp\left(\frac{-1}{kT}\right) \). Thus higher temperatures will result in higher signals. The behaviour of the readout chain at different temperatures is tested by determining the 50% efficiency level of the threshold scan (compare figure 4.5). The test board is placed on a heating plateau, which has a temperature variance of 0.5 °C. Since the electronics are not exactly on this plateau, the temperature may not be the same in the electronics, we did not probe the temperature in the electronics. The total uncertainty is estimated to be 2 °C. Figure 4.7 shows that the threshold is linearly dependent on the temperature. The temperature dependence of the readout electronics is opposite to that of the sensor material. An increase of 10 °C means a decrease of 70 mV, corresponding to 700 e⁻. For precise measurements it is therefore necessary to test the
4.2. ELECTRICAL MEASUREMENTS

Figure 4.7: Threshold versus temperature for which the efficiency is 50%.

temperature effect of the electronics and the sensor separately.

4.2.4 Threshold variation and uniformity

As shown in section 4.2.1, the efficiency is non-uniform for the 1028 readout chains. For appropriate functioning in the LHC it is necessary that this variation is limited over the detector. The specifications 3.3.1 demand a threshold uniformity of about 30%. We have measured this uniformity for 4 different temperatures (20 °C, 40 °C, 60 °C, 80 °C). This measurement only considers the readout electronics. Non-uniformity in the bump bonding or in the sensor are not taken into account. The uniformity (or rather the spread) can be investigated by looking at the cell-to-cell spread at the 50% efficiency level over a pixel chip. Figure 4.8 shows that this variation is Gaussian distributed. The $\sigma$ of this distribution is the non-uniformity, the threshold uniformity (in percentages) is the ratio of the sigma of this distribution and the mean of this distribution. The mean value is threshold dependent.

In this case the threshold is set at 10000 electrons. An overview of the results from figure 4.8 are given in table 4.3, the threshold uniformity is
Table 4.3: Threshold uniformity at different temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>sigma (electrons)</th>
<th>mean (electrons)</th>
<th>threshold uniformity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>778.7</td>
<td>11610</td>
<td>6.7</td>
</tr>
<tr>
<td>40</td>
<td>739.9</td>
<td>10130</td>
<td>7.3</td>
</tr>
<tr>
<td>60</td>
<td>630.5</td>
<td>10580</td>
<td>5.9</td>
</tr>
<tr>
<td>80</td>
<td>886.4</td>
<td>12030</td>
<td>7.3</td>
</tr>
</tbody>
</table>

better than 8 % at all temperatures, and thus far better than the 30 % required in the specifications.

4.2.5 Noise

In section 2.4 three noise sources are mentioned, the leakage current, thermal generated current and the leakage current in the electronics. This current in the electronics is mainly caused by fluctuations in the signal from the input to the comparator. In the limit where there is no noise, the efficiency curve (constant threshold, increasing input signal) would approach a step function. The derivative would then be a Dirac $\delta$ function. The electronics noise can be estimated by measuring the efficiency as a function of the input, see figure 4.9. The derivative of this function is the sum of the threshold non-uniformity and the noise, since the plot shows the average over all pixels. The noise can be derived from 4.9 by taking the derivative of the efficiency curve of each pixel separately and fitting the result with a Gaussian. The width of the fitted curve ($\sigma$) is the noise (ENC) per pixel. The $\sigma$ for all pixels is plotted in 4.10. Table 4.4 summarizes the results, averaged over all pixels. The

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>noise (electrons)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>295 $\pm$ 32</td>
<td>85 $\pm$ 17</td>
</tr>
<tr>
<td>40</td>
<td>281 $\pm$ 31</td>
<td>89 $\pm$ 15</td>
</tr>
<tr>
<td>60</td>
<td>276 $\pm$ 32</td>
<td>91 $\pm$ 15</td>
</tr>
<tr>
<td>80</td>
<td>330 $\pm$ 25</td>
<td>76 $\pm$ 15</td>
</tr>
</tbody>
</table>

Table 4.4: Electronics noise measured at different temperatures.
variation in the noise is better than about 10\%. The measured noise is on average 50 e\textsuperscript{-} larger than the specified noise. The measured signal to noise ratio (S/N) is far better than the demanded S/N. Note that this signal to noise ratio has been calculated using the signal of a MIP passing through a 300 µm, undamaged and fully depleted Silicon detector. Investigations of the S/N after radiation is recommendable. This noise is not only caused by the fluctuation in the readout electronics. Another contributor is the fluctuation in the test signal, this signal is generated by a pulse generator and transported over long cables. The fluctuation in the signal of the pulse generator [36] is less than 50 electrons for a test signal of 25000 electrons, thus is relatively small. Figure 4.10(a) shows two peaks, one around 300 electrons noise and one around 500 electrons noise. Figure 4.11 shows the pixels with a noise larger than 400 electrons. More noisy pixels are in general to be found on the left side (low column number) of the detector. An increase of number of noisy pixels can be seen on the right as well, the pixels in the middle appear to be less noisy. This might be caused by more solid bump bonds in the middle than on the left or right. The process technique might play an important role as well, this has not been studied yet. Another effect causing a variation in the noise over the pixel may be the overload. The pixel detector is not designed to handle all channels at the same time, for this test all pixel cells were addressed. This might result in more noisy pixel cells on the left side of the detector. Individual tests will avoid this overload effect and allow the verification of this assumption.

4.2.6 Detector offset

One of the specifications for operation in the ATLAS detector is that the threshold voltage should be \(~ 2000\) electrons. Figure 4.12(a) shows a measurement without test pulse input or sensor input at -10 °C. The test input is connected to the pulse generator (50 Ω impedance). The sensor is shielded from light. This situation is comparable with operation in ATLAS at the time that there is no collision, the test input is not used and no particles are passing the detector. The efficiency falls to zero at about 1800 mV, this corresponds to about 5000 electrons. Figure 4.12(b) shows the theoretical energy loss distribution in a thin layer for a MIP compared with the detector offset as measured in 4.12(a). A threshold of 2000 electrons will thus be a bit too low, since all pixels will be responding as the height of the offset signal (both sensor and test) is larger than the threshold. An input threshold of
about 5000 electrons will not decrease the efficiency for detecting Minimum Ionizing Particles. The Landau distribution in figure 4.12 shows that the minimum energy loss is about 16000 electrons in 300 \( \mu m \) Silicon at full depletion. Radiation damage in the detector will increase the noise and decrease the signal.
Figure 4.8: The spread over the pixel of the 50% level. (a) at 20°C, (b) at 40°C, (c) at 60°C, (d) at 80°C.
Figure 4.9: The comparator efficiency at different temperatures. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C.
Figure 4.10: The noise calculated at different temperatures. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C.
Figure 4.11: The areas in the detector where the noise is larger than 400 electrons. The plot shows the column number on the x-axis and the number of noisy pixels in this row on the y-axis. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C.
Figure 4.12: (a) The efficiency versus the threshold for a offset measurement at -10 °C. Neither a test pulse nor charge was injected at the test input or the sensor input. (b) The Landau distribution of the energy loss of a pion in a 300 μm Silicon detector compared with the offset in the detector.
Chapter 5

Test beam measurements

During several test beam periods at CERN in the SPS H6 beam the Omega3/LHC1 detectors have been tested extensively. The beam consists of charged pions ($\pi^\pm$) with an energy of 120 GeV. The test beam allows to calibrate the pixel detector and to verify the Landau distribution of the energy loss in the detector. The thickness of the depletion layer is proportional to the bias voltage. The efficiency is linear to the thickness, as can be seen in this chapter. With the measurements from the test beam telescope the spatial resolution and the average cluster-size as function of the threshold can be calculated.

5.1 Set up

Figure 5.1 shows the schematic of the test beam set up. The data acquisition is similar to that of the laboratory set up. The pixel detectors are placed on a test board. This board is connected to a mother board. The mother board transfers the supply voltages, timing signals and the data. The VME read out module controls the motherboard and thereby the pixel detector. The VME read out module is controlled by software running under an OS9. The pre-trigger is provided by two scintillators readout by photomultipliers. The scintillators have a surface of ca. 5 cm$^2$ (elements 1 and the 2). A more restricted area is defined by 4 scintillating fingers (3,4,5 and 6) of approximately 6 cm length and 1.5 mm diameter, read out as well by photomultipliers. The coincidence of the signals from the four scintillating fingers,
the two scintillators and the veto generate a trigger profile of approximately 1.5 $mm^2$ (see figure 5.2). After a trigger, a busy signal is set until the data acquisition is ready to process the next event. During a burst of 2 s it is possible to take up to 2000 events. The data are kept in memory and written to disk in the 14 s gap between two consecutive bursts. Three closely spaced

![Diagram showing the test beam setup and trigger logic.](image)

Figure 5.1: Schematic of both the test beam set up and the trigger logic. The data acquisition is carried out by software running under the OS9, the data are transferred to the HP workstation every 14 s. 1 and 2 are the pre-triggers; 3, 4, 5 and 6 are scintillating fingers defining a restricted area. The trigger is provided by a coincidence of the pre-triggers, the scintillating fingers and the veto. Not to scale.

300 $\mu m$ thick pixel detectors are placed in a row and form a pixel telescope. The complete telescope is mounted on a computer driven movable table in order to scan different regions of the detector area.
5.2 Results

5.2.1 Calibration with pion beam

As described in section 2.3, the energy loss in thin layers is Landau distributed. The most probable energy loss of 120 GeV pions in a 300 $\mu$m Si-detector is expected to be 83 keV [35] corresponding to the generation of 23,000 electrons. The variation in this energy loss can be derived from the width of the Landau distribution and is about 4000 electrons. This gives an opportunity to compare the response of test input and the sensor input. The measurement method is in principle the same as for the threshold calibration. In this case the detector input is used. The threshold voltage is increased stepwise, until the count rate falls to zero. The 50 % efficiency level can be taken from figure 5.3(a).

The level where the efficiency is 50 % is found to be 3290 mV ± 30 mV, the 30 mV error comes from the cell to cell variation. The threshold calibration has already been measured (figure 4.6(a)). The result from the measure-
Figure 5.3: (a) The efficiency as a function of the comparator threshold. The level where the efficiency is 50% is at 3290 mV. (b) The asterisk marks the 50% efficiency level for the pion beam energy on the curve 4.6(a).

ment with the pion beam is marked with an asterisk in figure 5.3(b). The electron-threshold correspondence from the pion beam matches the threshold calibration rather well. The result would be more precise if the pulse height (energy loss) had been measured for example with a true ADC (analogue to digital converter).

5.2.2 Landau distribution

All measurements and calculations have been performed assuming that the energy loss of a pion in a thin layer is landau distributed (see section 2.1.1). This can be verified as follows. The integral of the landau distribution is normalized to 100%. Figure 5.4(a) shows that the signal on the left of the threshold is not measured. This part can be calculated by taking the integral over this area. The efficiency of a pixel is now given by 100% - (integrated area). Figure 5.4(b) shows the efficiency versus the threshold for two detector types, 'a' and 'c' type, compared with the theoretical Landau distribution. However, the theoretical distribution is calculated for the energy loss in one pixel, while to the curves for the 'a' and 'c' type detectors are obtained after
averaging over pixels. Thus if the efficiency of some pixels fall to zero rather soon, the average will decrease faster as well. This causes the discrepancy between the theoretical curve and the curve for the 'c' type. The 'c' type curve follows the distribution better than the 'a' type (see section 3.3.3). The anode surface (where the charge is collected) of the 'a' type detector is smaller than the 'c' type, this enhances charge sharing between pixels. The collected charge per pixel in the 'a' type will thus be less than the collected charge in the 'c' type. The anode surface of the 'a' type detector cell is about 2500 $\mu m^2$ compared to a anode surface area of 25000 $\mu m^2$ for the conventional cell. (see also figures 3.8 and 3.7. Preliminary results indicate that the electric field is not homogeneous over the detector. At a bias voltage of 60 V (far above the depletion voltage) the efficiency is at most 80 %. This needs further study. The shape of the Landau distribution looks more like the shape of the curve for the 'a' type detector.

\begin{figure}[h]
\centering
\subfigure[]{
\includegraphics[width=0.4\textwidth]{landau_distribution.png}
\caption{(a) Landau distribution with the effect of applying a threshold. The non-measured area is hatched.}
\label{fig:landau_distribution}
}
\subfigure[]{
\includegraphics[width=0.4\textwidth]{efficiency.png}
\caption{(b) Efficiency measurements summed over all pixels compared to the theoretical landau distribution (dotted line) for a single pixel. Bias voltage is 40 V. The efficiency of the 'a' type detector falls to zero at a lower threshold than that of the conventional detector.}
\label{fig:efficiency}
\end{figure}
5.2.3 Effect of the bias voltage on the efficiency

Figure 5.5: (a) The efficiency as function of the threshold voltage, at different bias voltages. (b) The efficiency versus the bias voltage, measured at 3300 mV threshold voltage.

The thickness of the depletion layer is dependent on the applied bias voltage, as described in section 2.2.4. A non-depleted detector will have a lower efficiency\(^1\) than a fully depleted detector. Radiation damage in the detector may cause a decrease in efficiency that can be compensated partially by applying a larger bias voltage. The efficiency versus the threshold voltage is measured as a function of the bias voltages (figure 5.5(a)). Figure 5.5(b) shows the efficiency versus the bias voltage at a threshold of 3300 mV. Since the thickness of the depletion layer is proportional with \(\sqrt{V_{\text{bias}}\)}), the curve 5.5(b) will follow a square root until the detector is fully depleted. At bias voltages above the depletion voltage the efficiency will not further increase. The depletion voltage of a 300 \(\mu\)m Silicon detector is about 40 V. The overall

\[^1\text{The track efficiency is be defined as follows:}\]

\[
\epsilon(\text{plane}2) = \frac{\text{number of hits in plane 2, that belong to tracks in plane 1 and 3}}{\text{number of tracks in plane 1 and 3}}
\]  

(5.1)

The three detector planes are shown in figure 5.1.
track efficiency is about 98 % at 40 V bias voltage and 2200 mV threshold voltage. At the proposed threshold input of 2000 $e^-$ an efficiency of 96 % is reached for a bias voltage of 15 V.

5.2.4 Cluster size

Due to charge sharing between two or more pixels more than one pixel may be fired. In this case the center of gravity of the cluster determines the hit coordinates. The spatial resolution is critically depending on the cluster size and therefore it is important to study the cluster geometry as a function of for example the threshold. The amount of charge collected in the pixels is proportional to the position of the track in between pixels. If the threshold increases the pixel with more charge will longer be activated. Thus an increasing threshold voltage will decrease the number of double hits. Figure 5.6 shows the correlation between the threshold voltage and the cluster size. The effect of charge sharing indeed decreases for increasing thresholds.

![Cluster geometry as function of the threshold voltage. The number of clusters with two pixels decreases with the threshold voltage.](image-url)
5.2.5 Spatial resolution

A prime property of a pixel detector used as vertex detector, is the good two dimensional space resolution. The theoretical spatial resolution for a binary system is the pitch divided by \( \sqrt{12} \). The resolution has been measured using a Silicon strip telescope made of three planes with 20 \( \mu m \) pitch and three planes with 40 \( \mu m \) pitch. The set up is the same as in figure 5.1 except that in this case two pixel detectors are replaced by strip detectors. The residuals in the track fit give the distance between the measured point in the detector and the impact point of the track. These residuals are the convolution of the pixel detector resolution and the resolution of the reference telescope. The spatial resolution is obtained by calculating the residuals of the track in the pixel detector. The distribution of the residuals has to be shaped as a rectangle in the ideal case. The measured distribution however can be described as an overlay of a rectangle and a Gaussian (figure 5.7). The latter is caused by the overlap region at the edge of each pixel cell. If a particle passes the intermediate region between two pixels, the induced charge will be shared by the two pixels. The spatial resolution is determined by the size of the rectangle plus the sigma of the Gaussian. In the column direction the

![Image](image-url)

Figure 5.7: Residuals for one pixel cluster in z (column) (a), for two pixel cluster in z (b), and for one pixel cluster in the y direction (row) (c).

resolution is about 16.5 \( \mu m \) and in the row direction the resolution is about
235 $\mu m$ (figure 5.7). These results can be compared with the theoretical spatial resolution, 14.4 $\mu m$ ($50/\sqrt{12}$) in the column direction and 144 $\mu m$ ($500/\sqrt{12}$) in the row direction. Spatial resolution better than 14 $\mu m$ requires smaller sensor cells. The resolution in case of two pixel clusters is better, about 8.9 $\mu m$. 
Chapter 6

Discussion and conclusions

6.1 Conclusion

Having succeeded in building a working laboratory set up, measurements could be performed with the test input of the readout electronics. We did not succeed in making measurements with sensor input using radioactive sources. The Omega3/LHC1 detector is not yet suited for operation in the ATLAS detector. Table 6.1 summarizes the result of both the measurements using the test set up as the test beam compared to the ATLAS specifications. The distribution of the detector response is Gaussian, which allows us to

<table>
<thead>
<tr>
<th>Requirement</th>
<th>LHC value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input threshold</td>
<td>$\sim 1000 , \text{e}^-$</td>
<td>4000 $, \text{e}^-$</td>
</tr>
<tr>
<td>Input threshold uniformity</td>
<td>$\pm 30%$</td>
<td>$\sim 8 %$</td>
</tr>
<tr>
<td>Noise</td>
<td>$&lt; 250 , \text{e}^-$</td>
<td>295 $, \text{e}^-$</td>
</tr>
<tr>
<td>S/N</td>
<td>$\sim 50(20)$</td>
<td>$\sim 75 \pm 15$</td>
</tr>
<tr>
<td>Overall track efficiency</td>
<td>95 $%$</td>
<td>$\sim 98 %$</td>
</tr>
<tr>
<td>Spatial resolution($R_\phi$)</td>
<td>$&lt; 14 , \mu\text{m}$</td>
<td>16.5 $\mu\text{m}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requirement</th>
<th>LHC value</th>
<th>Current value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;$power$&gt;$ per pixel</td>
<td>$&lt; 40 , \mu\text{W}$</td>
<td>100 $\mu\text{W}$</td>
</tr>
<tr>
<td>Mask each pixel</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Calibrate each pixel</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.1: Measured values compared to the LHC requirements.
use the average and the r.m.s. over the pixel chip. A calibration which interrelates the threshold voltages with the number of electrons is performed at two temperatures. In order to compare the response using the test input and the sensor input the calibration curves are parameterized. The behavior appeared to be quite different, the read-out electronics behavior has been measured at different temperatures. The response of the comparator appears to depend linearly on the temperature. Increasing the temperature will result in a lower threshold voltage at the 50 % efficiency level. An increase of 10 °C results in a decrease of 70 mV. This corresponds to 700 e⁻, which is more than the measured noise in the electronics.

The 50 % efficiency level differs from cell to cell. The uniformity required by ATLAS is about 30 %, our measurements result in a threshold uniformity of better than 8 % at all temperatures. Note that only the electronics are taken into account, the effect of bump bonding or the non-uniformity over the sensor are not measured.

One of the important features of pixel detectors is their low noise. ATLAS requires a noise of less than 250 e⁻ and a signal to noise ratio (S/N) of 50. The noise in the electronics A measurement has been carried out to calculate the readout electronics noise (see table 6.2). The noise is larger (about 300 e⁻) than the required noise. This might be due to the noise of the test signal, which injects a noise of about 50 electrons. This effect however is relatively small. The noise has been measured at 20 °C, 40 °C, 60 °C and 80 °C. The noise will probably be smaller at the ATLAS operation temperature - 10 °C, though this cannot be concluded from the results in table 6.2. The uniformity in the noise is better than 10 %. The signal to noise ratio is better than 70, calculated for a signal from the energy loss of a MIP in a 300 μm thick, undamaged and fully depleted detector. Radiation damage will lower will increase the noise and decrease the signal at fixed depletion voltage.

The ATLAS specification of the input threshold is not met. The detector offset is measured to be about 4000 e⁻. A threshold input of 5000 e⁻ would be more advisable. A higher threshold voltage will not decrease the efficiency of the detector as long as the detector is undamaged and fully depleted. Higher threshold voltages would also decrease the number of events where two clusters are hit.

The CERN RD19 group has been performing tests in the SPS H6 test beam. Since the energy deposition of the pion beam is Landau distributed, a threshold scan can be used to calibrate the detector. The data fit the
6.1. CONCLUSION

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Uniformity (%)</th>
<th>Noise (electrons)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.7</td>
<td>295 ± 32</td>
<td>85 ± 17</td>
</tr>
<tr>
<td>40</td>
<td>7.3</td>
<td>281 ± 31</td>
<td>89 ± 15</td>
</tr>
<tr>
<td>60</td>
<td>5.9</td>
<td>276 ± 32</td>
<td>91 ± 15</td>
</tr>
<tr>
<td>80</td>
<td>7.3</td>
<td>330 ± 25</td>
<td>76 ± 15</td>
</tr>
</tbody>
</table>

Table 6.2: Result for 4 temperatures of the noise and the threshold uniformity.

electrical calibration curve quite well. The calibration using the sensor input should improve if the energy loss is known more precisely (e.g. by using an analogue measurement of the detector response). The calibration is more reliable if more measurement points are used, i.e. using sources with different energies.

The threshold scan can be compared with the theoretically expected distribution, deduced from the landau distribution. The threshold scan shows discrepancies with the theoretical curve. The theoretical curve is calculated for one pixel instead of the measured curve, which is the average over the pixel chip. The efficiency plot for an 'a' and a 'c' type detector show that the efficiency of an 'a' type detector drops to zero at a lower threshold voltage. The 'a' type detector has a smaller anode area, which enhances charge sharing between pixels. The collected charge per pixel will thus be less.

The track efficiency is indeed proportional to the bias voltage until the detector is fully depleted. A track efficiency of more than 98 % can be achieved at a bias voltage of about 40 V. At a threshold voltage of 2000 mV the track efficiency is still about 95 % for a undamaged detector.

One of the first requirements for a good vertexing detector is high spatial resolution. The spatial resolution in $R\phi$ has to be better than 14 $\mu$m according to the ATLAS specifications. Measurements in the test beam give us a resolution of at least 16.5 $\mu$m for cluster size one. For a cluster size of two pixels the resolution improves (8.9 $\mu$m). The spatial resolution will be better if analogue read out is used, as the distribution of the charge can be used. To obtain a satisfactory resolution using binary readout requires a pixel size of less than 50 $\mu$m in the $R\phi$ direction.
6.2 Suggestions for the future developments

Having succeeded in getting the test set up working, a number of other measurements could now be performed. First of all measurements using the sensor input, e.g. with radioactive sources, can be performed. These measurement can be used to obtain a more precise calibration. Or to consider the sensor non-uniformity in the threshold variation. We might succeed in performing measurements using the sensor input if we would expose the detector to the radiation for a longer period. We now used a exposure time of about one week. Furthermore it is interesting to investigate the behaviour of the leakage current, one of the main noise sources, as a function of for example the bias voltage. This measurement can be performed using a precise amperes meter (nA) and a stable power supply. The measurements give no indication for the temperature dependence of the noise. It is, since the pixel system will operate at -10 °C, good to investigate the noise at that temperature. The measurements described in this report have been carried out with detectors which have not been irradiated. Characterization of the detector after various amounts of radiation may give an indication of the time the detector will operate properly.

An improvement to the current set up will be the use of a CAMAC attenuator, to perform the calibrations automatically.

We studied the conventional detector cell layout, since the noise in the alternative layout should be less, it is interesting to compare the two designs. The electric field in the sensor needs further study for the alternative detector layout. It would also be favorable to reduce the thickness of the sensor material. This reduces the multiple scattering and would improve the spatial resolution of inclined tracks. To get a better insight in the effect of changes in the design of the detector of the layout of the pixel system simulations are a very useful tool. Further study on simulations will probably bring up new ideas on the detector layout.

The radiation damage has been mentioned repeatedly. The innermost detector layer will have to be removed after one year due to radiation damage. The electronics will probably last longer since the size of the elements are smaller than the pixel size. Currently, NIKHEF is investigation Diamond as a possible detection medium, since Diamond is more radiation hard than Silicon. The production and use of Silicon is easier than Diamond. Investigations concerning the reduction of the effects due to radiation damage are recommended. One of the effect is an increased leakage current due to gen-
6.2. SUGGESTIONS FOR THE FUTURE DEVELOPMENTS

eration of carriers from defect levels. Studies indicate that warming up the
detector in a cyclic manner might clear the detector lattice from defects [37].
Acknowledgements

First and foremost I thank Cees Daum for having introduced me to the world of High Energy Physics, for being a member of my graduation committee and for reading my drafts over and over. Bob van Eijk made it possible to do my graduation work at NIKHEF: thanks for arranging such an enjoyable project after my sick-leave. Thanks for the good advice concerning both my actual graduation work as my graduation thesis. I would like to thank Harold Zandvliet and Herman ten Kate for joining my graduation committee and for rearranging their agendas over and over.

Special thanks to Ernst-Jan, his company made my graduation a real pleasure, at the off set of the experiment or while ordering pizza or beers. You always knew how to revive my enthusiasm. Thanks to Rutger, Jaap, Bob, Armin, Reinier and Fred for their company and good advice.

This graduation marks the end of my study, a period during which I not only learned physics. I would like to thank the people who have been supporting me during my study. Cora Eggink, for her love and encouragement. For teaching me what is not taught in college. Tanja de Baare for supporting me, especially when my motivation for my study was at a nadir. I wanted to give up my studies after a long period of illness. Thanks for learning me how to relax and enjoy life.

Emmy Tessel for her loyalty from day one. I will never forget our regular appointments to go shopping on Saturday afternoon, half an hour before closing time. My time in Enschede wouldn’t have been as joyful had it not been for Christa Hooijer, thanks for all the tea at your place. I always enjoyed working together.

Special thanks to Willem for his final corrections, which, although not changing my initial conclusions, did alter the final contents of my research (remember the cat in the box).
List of Figures

1.1 The Higgs potential. The circle of minimum values is shown. If one point on this circle is chosen, the symmetry is broken. 8
1.2 Signature of some typical high energetic particles in a tracker, electro-magnetic calorimeter, hadronic calorimeter and muon tracker. 10
1.3 Three dimensional view of the ATLAS detector. Three persons on the right may give an idea of the size of the 7000 tons weighing experiment. 13
1.4 The ATLAS pixel barrel. The pixel detector system is the innermost layer of the ATLAS detector. 14
2.1 (a) Energy loss due to ionisation in 300 μm Silicon, for the proton, muon and electron. (b) The energy loss compared to the Bremsstrahlung. The critical energy, the particle energy where Bremsstrahlung is dominant to ionisation, is shown for two definitions. 19
2.2 Landau distribution of the energy loss. 20
2.3 Diagram showing the energy band diagram of a conductor and an insulator (the hatched area represents occupied states in a band). 21
2.4 Schematic lattice with donor ions implanted. 22
2.5 Diagram showing the energy levels of acceptors and donors. The energy required to create an electron-hole pair is far less than the energy gap. 23
2.6 A sketch of an abrupt pn-junction, showing the charge built up and the resulting field and potential across the junction. 24
2.7 Three different ways to apply the bias voltage. 25
2.8 Schematic of a Silicon particle detector. The created electrons and holes will drift towards the electrodes. 26
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>Silicon micro strips as used in the L3 luminosity detector. The left detector is the ( \phi )-sensor and the right the ( \tau )-sensor.</td>
</tr>
<tr>
<td>3.1</td>
<td>Possibilities for the integration of electronics and detector: (a) monolithic integration, (b) Silicon on insulator, (c) hybrid integration.</td>
</tr>
<tr>
<td>3.2</td>
<td>Schematic drawing of the layers used for the pixel detector.</td>
</tr>
<tr>
<td>3.3</td>
<td>Picture of a wafer at a 1:1 scale. The 'a'-type detector are the darker chips.</td>
</tr>
<tr>
<td>3.4</td>
<td>Photograph of a single readout cell. The bump pad is the octagonal on the left.</td>
</tr>
<tr>
<td>3.5</td>
<td>Block diagram of the readout electronics.</td>
</tr>
<tr>
<td>3.6</td>
<td>The comparator containing a bistable non-linear load.</td>
</tr>
<tr>
<td>3.7</td>
<td>Picture of the lower part of a type 'c' (conventional) detector. The 2 lower-most cells are connected to the guard ring. The opening in the passivation layer for the bump bonding connection is visible on the right side of the cell.</td>
</tr>
<tr>
<td>3.8</td>
<td>Picture of the lower part of a type 'a' (alternative) detector. The 2 lower-most cells are connected to the guard ring. The opening in the passivation layer for the bump bonding connection is visible in the rightmost island of a cell.</td>
</tr>
<tr>
<td>3.9</td>
<td>Schematic view of the readout cells, detector cells and bump bonds.</td>
</tr>
<tr>
<td>3.10</td>
<td>(a) Photo of a type 'a' detector chip. The guard ring surrounding the active matrix and the column structure is clearly visible. (b) Photograph taken with a scanning electron microscope of a column of solder bumps on the readout cell after reflow.</td>
</tr>
<tr>
<td>4.1</td>
<td>Schematic overview of the laboratory set up. Not to scale.</td>
</tr>
<tr>
<td>4.2</td>
<td>Required timing for the signals test and strobe. The strobe is a NIM signal of approximately 2 ( \mu )s, the test pulse has a length of 10 ( \mu )s and a height of ( \sim 3V ).</td>
</tr>
<tr>
<td>4.3</td>
<td>Flow chart of the data acquisition.</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

4.4 (a) Three dimensional plot showing the variation in the comparator response over the pixel chip at -10 °C, at a certain threshold. On the vertical axis one can see the number of times the pixel responds, \( N = 5000 \). (b) The variation in the efficiency is Gaussian distributed. The sigma is very small, only \( \sim 20 \) compared to a mean of \( \sim 2800 \) mV. ............................. 53

4.5 Efficiency curve for a test signal corresponding with the energy loss of a Minimum Ionizing Particle (90 keV) at room temperature and at -10 °C (ATLAS operating temperature)............................................................. 54

4.6 (a) Threshold calibration at room temperature, (b) shows the threshold calibration at -10 °C (ATLAS operating temperature) ............................................................. 56

4.7 Threshold versus temperature for which the efficiency is 50 %. ............................. 57

4.8 The spread over the pixel of the 50 % level. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C. ....................................................... 61

4.9 The comparator efficiency at different temperatures. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C. ..................................................... 62

4.10 The noise calculated at different temperatures. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C. ..................................................... 63

4.11 The areas in the detector where the noise is larger than 400 electrons. The plot shows the column number on the x-axis and the number of noisy pixels in this row on the y-axis. (a) at 20 °C, (b) at 40 °C, (c) at 60 °C, (d) at 80 °C. ..................................................... 64

4.12 (a) The efficiency versus the threshold for a offset measurement at -10 °C. Neither a test pulse nor charge was injected at the test input or the sensor input. (b) The Landau distribution of the energy loss of a pion in a 300 μm Silicon detector compared with the offset in the detector. ..................................................... 65

5.1 Schematic of both the test beam set up and the trigger logic. The data acquisition is carried out by software running under the OS9, the data are transferred to the HP workstation every 14 s. 1 and 2 are the pre-triggers; 3, 4, 5 and 6 are scintillating fingers defining a restricted area. The trigger is provided by a coincidence of the pre-triggers, the scintillating fingers and the veto. Not to scale. ..................................................... 68

5.2 Beam profile of approximately 1.5 mm². ..................................................... 69
5.3 (a) The efficiency as a function of the comparator threshold. The level where the efficiency is 50% is at 3290 mV. (b) The asterisk marks the 50% efficiency level for the pion beam energy on the curve 4.6(a). ........................................ 70

5.4 (a) Landau distribution with the effect of applying a threshold. The non-measured area is hatched. (b) Efficiency measurements summed over all pixels compared to the theoretical landau distribution (dotted line) for a single pixel. Bias voltage is 40 V. The efficiency of the 'a' type detector falls to zero at a lower threshold than that of the conventional detector. .... 71

5.5 (a) The efficiency as a function of the threshold voltage, at different bias voltages. (b) The efficiency versus the bias voltage, measured at 3300 mV threshold voltage. .......................... 72

5.6 .................................................................................. 73

5.7 Residuals for one pixel cluster in z (column)(a), for two pixel cluster in z (b), and for one pixel cluster in the y direction (row)(c). ......................................................... 74
## List of Tables

1.1 Overview of known leptons and quarks: The masses of the light quarks (u,d,c,s) are not defined unambiguously. Besides these particles, anti-particles exist with the same mass but opposite charge. .............................................. 6

1.2 Summary of the bosons (except the graviton) with their mass and the force for which they are the mediator. The mass of weak gauge bosons can be explained by the Higgs mechanism. ... 7

1.3 Machine parameters of the Large Hadron Collider ............... 11

1.4 Sizes of the pixel barrels and disks for the ATLAS pixel system. 15

2.1 Energy gaps of some semiconductors .......................... 21

2.2 Energy required to create an electron-hole pair for some semi- conductor materials ................................................. 26

3.1 Principal requirements for the pixel detector and its readout electronics ................................................................. 38

3.2 Radiation doses in the inner detector for distances to the inter- action point ................................................................. 39

4.1 Overview of the different voltages and signals used in the lab- oratory set up .............................................................. 50

4.2 Values of the fit parameters, using the data of the calibration measurements. The fit function is given in equation (4.5). ... 55

4.3 Threshold uniformity at different temperatures ..................... 58

4.4 Electronics noise measured at different temperatures .......... 58

6.1 Measured values compared to the LHC requirements .......... 77

6.2 Result for 4 temperatures of the noise and the threshold uni- formity ................................................................. 79
Bibliography


[6] B. van Eijk, Higgs production in $e^+e^-$ interactions, University of Amsterdam, January 1983


[17] S. Hancock et al., Energy loss and energy straggling of protons and pions in the momentum range 0.7 to 115 GeV/c, Physical Review A-28(2), 1983


[25] G.D. Halewell, Development of active pixel vertex detectors for high luminosity particle physics applications, Centre de Physique des Particules de Marseille, February 1994


[29] E.N. Koffeman, A luminosity measurement at LEP using the L3 detector, Katholieke Universiteit Nijmegen, 25 juni 1996


[31] E.H.M. Heijne et al., LHC1: A semiconductor pixel detector readout chip with internal, tunable delay providing a binary pattern of selected events, CERN ECP/96, 7 january 1996


[34] P. Middelkamp, L. Scharfetter, The LHC1/Omega3 set up (draft version), RD19 internal note, February 1996


[36] 125 MHz Pulse Generator, PM 5786, Operator’s manual, Philips, The Netherlands 1986

[37] G. Lutz et al., A simplistic model for reverse annealing in irradiated silicon, MPI-PhE/94-10, March 1994