Analysis of pixel systematics and space point reconstruction with DEPFET PXD5 matrices using high energy beam test data

Dissertation
zur
Erlangung des Doktorgrades (Dr. rer. nat.)
der
Mathematisch-Naturwissenschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt von
Lars Reuen
aus
Nettetal

Bonn 2011
Angefertigt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät
der Rheinischen Friedrich-Wilhelms-Universität Bonn

1. Gutachter: Prof. Dr. N. Wermes
2. Gutachter: Prof. Dr. K. Brinkmann

Tag der Promotion: 21.2.2011

Erscheinungsjahr: 2011

Diese Dissertation ist auf dem Hochschulschriftenserver der ULB Bonn unter
http://hss.ulb.uni-bonn.de/diss_online elektronisch publiziert.
# Contents

1 Particle detection with silicon sensors ........................................... 1
   1.1 Passage of particles through matter ........................................... 1
      1.1.1 Energy loss of heavy charged particles in matter ...................... 2
      1.1.2 Delta electrons ......................................................... 7
   1.2 Semiconductor Detectors ...................................................... 17
      1.2.1 The DEPFET sensor .................................................... 22

2 The ILC prototype system ........................................................... 27
   2.1 The vertex detector at the ILC ............................................... 27
      2.1.1 The DEPFET vertex detector concept for the ILC ..................... 30
   2.2 The DEPFET prototype system for the ILC ................................. 35

3 Test Beam Experiment and Analysis .............................................. 47
   3.1 The Experimental Setup ..................................................... 47
   3.2 Data Analysis ................................................................. 54
   3.3 Position reconstruction ....................................................... 66
      3.3.1 Tracking and residual corrections .................................... 77
   3.4 In-pixel studies ............................................................... 80

4 Position reconstruction studies .................................................. 91
   4.1 Multiple $\eta$ distributions ................................................ 93
   4.2 A charge cloud based algorithm .......................................... 97
      4.2.1 Sampling the charge cloud shape .................................... 98
      4.2.2 Analytical fit ......................................................... 100
      4.2.3 Position Reconstruction .............................................. 104
      4.2.4 Comparison of charge cloud based methods and $\eta$ methods ...... 107
   4.3 Multivariate analysis ......................................................... 112
      4.3.1 Information value of input variables ................................ 117
      4.3.2 Performance of the multivariate analysis ........................... 127
   4.4 Summary ................................................................. 131

5 Summary and Conclusion .......................................................... 133

Bibliography .................................................................................. 135
Introduction

Over the past century our understanding of the foundations of space, time, and the building blocks of energy and matter have been revolutionized by the discoveries made in modern physics. Among them are the advances in the field of particle physics which saw in the last three decades the emergence of what is now known as the standard model of particle physics (Fig. 1). This model describes three of the four known fundamental forces: the strong force that binds the atomic nuclei and their constituents, protons and neutrons, together, the electromagnetic force that governs the field of chemistry, and weak force which is responsible for the radioactive beta decay. These forces are mediated between certain particles, the fermions, via particles called bosons. However, not all particles interact with every force, leptons for example do not interact via the strong force. In the standard model the weak with the electromagnetic force are unified to the electroweak force which was experimentally confirmed by the discovery of the neutral current (1973) and the W and Z boson (1983).

Despite its large success the standard model there are some remaining questions. For example, how do particles acquire their mass? In the standard model the Higgs mechanism explains the generation of the masses. It also predicts the existence of the Higgs particle which has yet to be discovered. Another issue is the so-called hierarchy problem: Why is the weak force $10^{32}$ times stronger than gravity. On the other hand the $\Lambda$CDM model, which is in a certain sense the equivalent of the particle physics standard model in the field of modern cosmology, states that the universe consists to about 74% of so-called dark energy and to ~ 22% of dark mater and only to ~ 4% of baryonic matter. The nature of dark matter and dark energy is unknown and the standard model lacks an explanation. New theories that tackle these problems predict the existence of new physics like super symmetric particles or extra dimensions.

---

1Fermions have spin $\frac{1}{2}$ and bosons spin 1.
2Abdus Salam, Sheldon Glashow and Steven Weinberg received the nobel price in 1979 for their ground breaking theory, Carlo Rubbia and Simon van der Meer received the nobel price in 1983 for their experimental work that led to the discovery of the W and Z bosons
3Cold Dark Matter, $\Lambda$ is the cosmological constant
To address these questions a new generation of particle accelerators is on its way. The most noted is the Large Hadron Collider (LHC) at CERN\textsuperscript{4}, that is operational since 2009 and is expected to soon run at the targeted 14 TeV energy. To accomplish its goals the new generation of high energy collider experiments needs high precision particle detectors. In case of the LHC the two prominent, general purpose detectors\textsuperscript{5} are the ATLAS\textsuperscript{6} and the CMS\textsuperscript{7} detectors. The innermost central part of these detectors is called vertex detector, which in case of ATLAS and CMS is a silicon pixel detector. The precision with which it measures a particle’s position is a key quantity as the identification of a particles decay products depends on this figure of merit. The proper identifications of these decay products is vital for the validation of theories and for the discovery of new physics.

An accelerator experiment complementary to the LHC experiments would be the planned International Linear Collider (ILC), which is an electron positron collider envisioned to work with a center of mass energy of up to 1 TeV and which would provide high precision measurements accompanying the findings of the LHC. The vertex detector of the ILC must fulfill ambitious specifications, including a spatial resolution of better than 5µm while contributing with not more than 0.1% of a radiation length per layer to the material budget. These demands have driven the development of new detector technologies like the DEPFET pixel and are central to this thesis. The DEPFET (DEPleted Field Effect Transistor) is an active pixel semiconductor detector that integrates a first electronic amplification stage into the sensor material allowing for excellent signal to noise measurements. The first chapter explains the basic principles of a DEPFET semiconductor detector. It also comprises a short review of the underlying physical processes of particle detection with an emphasis on thin detectors.

Based on a DEPFET pixel matrix a vertex detector concept for the ILC has been put forward and a prototype system with a 64x128 pixel matrix has been developed. The DEPFET detector concept and the prototype system are the topic of chapter two. For a complete understanding and evaluation of a detector laboratory measurements of its performance alone are not sufficient. The detector has to be put in a more realistic test environment in the form of a beam test experiment where the detector’s response to high energetic particle is measured. The results of such a beam test with the DEPFET prototype system including in-pixel homogeneity measurements will be presented in chapter three.

The quest for higher precision does not only drive the hardware side but also the software side of modern high energy particle experiments. New tools like multivariate analyses are becoming common place in the analysis of particle physics data. However, the position reconstruction method for pixel detectors at large is still the $\eta$ algorithm, a technique that was originally developed for strip detectors. Therefore another focus of this thesis is the comparative study of new position reconstruction algorithms. These studies will be presented in chapter four. This thesis is completed with a summary of the results given in the last chapter.

\textsuperscript{4}European Organization for Nuclear Research, originally Conseil Européen pour la Recherche Nucléaire
\textsuperscript{5}The other two detector at the LHC, ALICE and LHCb, are more specialized
\textsuperscript{6}ATLAS = A Toroidal LHC ApparatuS
\textsuperscript{7}Compact Muon Solenoid
Particle detection with silicon sensors

For any particle physics experiment it is important to understand how the detector interacts with the particles, what kind of physical processes are involved, and what kind of signature to expect inside the detector as a result of such interactions. This chapter will address these issues with respect to the test beam experiment and the position reconstruction studies examined in later chapters of this thesis. The first part will describe the interaction of charged particles in matter: how much energy is deposited in a silicon detector with a given impinging particle and what is the nature of secondary particles, so called knock-on or δ-electrons. The second part covers the fundamentals of semiconductor particle sensors and the basic working principle of a DEPFET. Throughout this chapter references will be made to the actual experiment, e.g. the sizes of a sensor pixel or the energy of the pions in the test beam:

The beam test was undertaken at CERN with 120 GeV pions. The DEPFET sensor type used for the experiment is subdivided in pixels with different dimensions in X and Y. The X axis of a pixel is 32 µm wide and the Y axis is 24 µm wide. For illustrative purposes the dimensions of three pixels in each axis were added to some figures in this chapter.

1.1 Passage of particles through matter

There are several means by which a charged particle can lose energy in matter, though they can be broadly divided into the collision and the radiation regime. Collision processes are important because for moderately relativistic charged particles heavier than electrons these are the dominant processes responsible for energy loss (section 1.1.1). For electrons on the other hand radiation effects play a much bigger role even at moderate relativistic energies. However, the electrons encountered in the scope of this thesis have energies low enough that collision is the dominant process (section 1.1.2). Figure 1.1 shows the energy loss of muons in copper as a function of the particles energy over several orders of magnitude. As is indicated in the figure the collision loss regime described by the Bethe equation 1.3 is only valid between energies of $\beta\gamma \approx 0.05$ and $\beta\gamma \approx 500$ in case of $\mu^+$ passing through copper. At higher energies, radiative effects begin to be important, while
at lower energies the velocity of the particle approaches that of the shell electrons and therefore certain approximations are not valid anymore.

![Diagram](image)

**Figure 1.1:** The stopping power $-\frac{dE}{dx}$ for $\mu^+$ particles in copper as a function of $\beta\gamma$ over several decades of energy taken from [1]. The plot is divided in different regimes where the energy loss is dominated by different processes.

1.1.1 Energy loss of heavy charged particles in matter

For moderately relativistic charged particles heavier than electrons the main energy loss is due to collisions with atoms. The maximum amount of energy $T_{\text{max}}$ that can be transferred from an incident particle with rest mass $m_0$ and a momentum of

$$p = mv = \beta\gamma m_0$$

(1.1)

to an electron (rest mass $m_e = 0.511 \text{ MeV}$) in one collision is [1]

$$T_{\text{max}} = \frac{2m_e\beta^2\gamma^2}{1 + 2\gamma \frac{m_e}{m_0} + \left( \frac{m_e}{m_0} \right)^2}$$

(1.2)

with the speed of light set to one ($c = 1$) throughout this work. The test beam data used in this work was gathered using 120 GeV pions with a rest mass of $m_\pi^0 = 139.5 \text{ MeV}$ which yields a $\beta\gamma = 860$ and a maximum energy transfer of $T_{\text{max}} \simeq 103.5 \text{ GeV}$. It should be noted that the approximation $T_{\text{max}} = 2m_e\beta^2\gamma^2$ sometimes found in older literature is
only valid if $\gamma \ll (m_0/m_e)$ and therefore does not apply here. While $T_{\text{max}}$ is an upper limit for the energy transfer the lower limit arises from the interaction time between the particle with a speed of $\beta$ and the shell electron with a binding energy of $\hbar \omega$ and rotation period of $\tau = 1/\omega$. This is described by a material specific ionization constant $I$. A thorough quantum-mechanical calculation first performed by Bethe [2] states the mean energy loss (Bethe equation) as

$$-\frac{dE}{dx} = K z^2 Z A^{\nu} \beta^2 \left[ \frac{1}{2} \ln \left( \frac{2m_e\beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]$$

(1.3)

with constants and variables defined as in table 1.2. $\delta(\beta \gamma)$ is the so-called density correction.

**Density correction**

At high energies the particles field extents and as a result of the distant collisions the mean energy loss rises with $\ln(\beta \gamma)$. However, the sensor material also becomes polarized and thus the field extension is limited effectively truncating the logarithmic rise [1]. There are several ways these corrections can be parameterized. For figure 1.2 this parametrization was used [3]:

$$\delta(X) = \begin{cases} 
0 & X < X_0 \\
4.6025X + C + a(X_1 - X)^m & X_0 < X < X_1 \\
4.6025X + C & X > X_1 
\end{cases}$$

(1.4)

where $X = \log_{10}(\beta \gamma)$. The constants in these equations are listed in table 1.1. For 120 GeV pions the high energy limit applies, $X(\beta \gamma = 860) = 2.93 < X_1 = 2.87$. At these energies the density correction becomes

$$\delta/2 \rightarrow \ln(\hbar \omega_p) + \ln(\beta \gamma) - 1/2$$

(1.5)

and the stopping power growth as $\ln(\beta \gamma)$ instead of $\ln(\beta^2 \gamma^2)$. $\hbar \omega_p$ is the plasma energy, which scales as the square root of the electron density [1], hence the name density correction. The remaining relativistic rise is due to the growth of $T_{\text{max}}$ which is caused by very rare, large energy transfers to a few electrons (see equation 1.8).

<table>
<thead>
<tr>
<th>$X_0$</th>
<th>$X_1$</th>
<th>$m$</th>
<th>$a$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2014</td>
<td>2.87</td>
<td>3.25</td>
<td>0.1492</td>
<td>4.44</td>
</tr>
</tbody>
</table>

**Table 1.1**: Density correction constants for silicon taken from [3]. Note that $C$ can be calculated with $C = \ln(I/\hbar \omega_p)$. These constants are used in equation 1.4 and for figure 1.2.

For a sufficiently thin detector the effect of the energy loss on the energy of the particle is negligible and the particle’s energy can be considered constant. The mean energy loss is then simply $E_{\text{mean}} = dE/dx \cdot x$ or

$$E_{\text{mean}} = \frac{\xi}{\beta^2} \left[ \ln \left( \frac{2m_e\beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - 2\beta^2 - \delta(\beta \gamma) \right]$$

(1.6)
1. PARTICLE DETECTION WITH SILICON SENSORS

where $\xi$ is a sensor specific constant that will be used frequently in this chapter:

$$\xi = \frac{K}{2} \rho \frac{Z}{A} x$$  \hspace{1cm} (1.7)

with $x$ the absorber thickness. Figure 1.2 shows the evolution of the energy loss as a function of pion momentum in 450 $\mu$m silicon with and without density corrections. For low kinetic energies ($\beta \gamma \lesssim 1$) equation 1.3 scales with $dE/dx \approx \beta^{-2}$ until a minimum is reached at $\beta \gamma \approx 3.5$ while for high energies $\beta \gamma > 4$ the logarithmic rise dominates. The position of the minimum of $dE/dx$ is at $\beta \gamma \approx 3$ in good accuracy independent of the particle as can be seen in figure 1.3. The energy loss at this minimum is roughly the same for all materials in this minimum $dE/dx \approx 2$ MeV cm$^2$/g ($dE/dx(Si) = 1.66$ MeV cm$^2$/g). Relativistic particles with an energy loss corresponding to this minimum are called "minimum-ionizing particles" (MIPs) and their $dE/dx$ is often used as an approximation for particles with higher energies since there is only a (density correction dampened) logarithmic rise in $dE/dx$.

Restricted energy loss

So far no distinction has been made between the energy loss of the particle and the actual energy deposition inside the sensor. As we shall see later this distinction is important in presents of so called $\delta$-electrons. Although up to $T_{\text{max}}$ energy can be transferred form the pion to an electron, but this electron might leave the sensor before depositing all of $T_{\text{max}}$. Therefore one can restrict the maximum energy transfer for deposition to $T_{\text{cut}}$ and gets [1, 4]

$$E_{\text{mean}} = \frac{\xi}{\beta^2} \left[ \ln \left( \frac{2m_e \beta^2 \gamma^2 T_{\text{cut}}}{I^2} \right) - 2 \beta^2 \left( 1 + \frac{T_{\text{cut}}}{T_{\text{max}}} \right) - \delta(\beta \gamma) \right]$$  \hspace{1cm} (1.8)

For $T_{\text{cut}} \rightarrow T_{\text{max}}$ this approaches the Bethe equation 1.6. For high energies the energy loss approaches the constant "Fermi plateau", since the $\ln(\beta^2 \gamma^2)$ rise in $T_{\text{max}}$ is replaced by a constant and the remaining $\ln(\beta^2 \gamma^2) = 2 \ln(\beta \gamma)$ is canceled out by the density correction. The energy loss in a 450 $\mu$m thick silicon sensor, restricted to $T_{\text{cut}} = 2$ MeV, is shown in figure 1.2. Its shape in relation to the full Bethe loss is in agreement with curves shown in [4, p.46].

Energy loss fluctuations in thin absorbers

So far only the mean energy loss has been covered. However, the energy loss process in a sensor is of statistical nature. This results in large fluctuations of the energy loss which becomes more crucial in thinner sensors. One important number to characterize how much a sensor is affected by these fluctuations with regard to its thickness is the ratio of the mean energy loss $E_{\text{mean}}$ to the maximum energy transfer $T_{\text{max}}$:

$$\kappa = \frac{E_{\text{mean}}}{T_{\text{max}}}$$  \hspace{1cm} (1.9)

The smaller the $\kappa$ the stronger the fluctuations are, with $\kappa \gtrsim 1$ already approaching an energy distribution that is Gaussian, whereas $\kappa < 0.01$ means that the Landau theory
1.1. PASSAGE OF PARTICLES THROUGH MATTER

Figure 1.2: The energy loss or, respectively, energy deposition in 450 µm silicon (left axis in keV) and the equivalent number of electron/hole pairs in 1000 as a function of $\beta\gamma$ (and pion momentum). From top to bottom: The first two curves are the Bethe collision loss with and without density effect corrections (equations 1.6 and 1.4). Below is the restricted energy loss for a upper cut on the deposited energy of $T_{\text{cut}} = 2$ MeV (equation 1.8) and finally the lowest two are the most probably $dE/dx$ value (equation 1.12) as a function of the pion energy and in the ultra relativistic limit (flat line, equation 1.13). The vertical line at $\beta\gamma = 860$ indicates the energy of the 120 GeV pion used in the DEPFET test beam. The numbers next to the arrows indicate the number of electron/hole pairs in 1000 equivalent to the energy loss for the various curves at $\beta\gamma = 860$. The two other arrows at $\gamma\beta = 4$ show the computed values of the most probable value at this $\gamma\beta$ and in the high energy limit. The difference is $\approx 5\%$.

applies to the energy loss [5, 6, 3]. The latter is also true for 120 GeV pions with $\kappa \ll 10^{-5}$. In this case the energy spectrum can be parameterized by the highly asymmetric Landau distribution which can be approximated with [7]

$$L(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} (\lambda + e^{-\lambda})}$$  \hspace{1cm} (1.10)

with $\lambda$ the deviation from the most probable energy loss:

$$\lambda = \frac{E - E_{\text{MPV}}}{\xi}$$  \hspace{1cm} (1.11)
Figure 1.3: The mean energy loss rate in the Bethe regime for various materials and (heavy) particles. Radiation effects are not considered. (They become significant at $\beta \gamma \gtrsim 1000$.) The minimum of the energy loss rate is virtually independent of the material (when normalized by the materials density) and the particle and roughly at $\beta \gamma = p/mc \approx 3$. \[1\].

and $E$ the actual energy loss, $\xi$ defined as in equation 1.7 and $E_{MPV}$ the most probable value of the energy loss $[1]$:

$$E_{MPV} = \xi \left[ \ln \left( \frac{2m_e \beta^2 \gamma^2}{I} - \xi \right) + 0.2 - \beta^2 - \delta(\gamma \beta) \right]$$

(1.12)

Since the Landau distribution depicted in figure 1.4 is highly asymmetric with a long tail towards higher energies the mean value, calculated with the Bethe equation (1.3 or 1.8 for restricted energy loss), is not an easy quantity to measure but the peak of the Landau distribution is. This is the most probable energy loss, shortly $E_{MPV}$ for most probable value. The most probable value follows closely the restricted energy loss in its dependence on the impinging particles energy as can be seen in figure 1.2. At high energies the density effect correction $\delta(\gamma \beta)$ (equation 1.6) influences the equation such that

$$E_{MPV} = \xi \left[ \ln \left( \frac{2m_e \xi}{(\hbar \omega_p)^2} \right) + 0.2 \right]$$

(1.13)
and the most probable value approaches a plateau. For the DEPFET test beam with
\( x = 450 \mu m \) \( \xi \) and \( E_{MPV} \) are:

\[
\begin{align*}
\xi &= 178 \text{ keV} \cdot x \simeq 8 \text{ keV} \\
E_{MPV} &= 8 \text{ keV} \cdot 15.95 \approx 129 \text{ keV}
\end{align*}
\]

(Figure 1.4: The Landau distribution for three different silicon sensor thicknesses. The distributions were calculated using the ROOT software package from CERN[8]. The values for \( E_{MPV} \) and \( \xi \) were calculated using the high relativistic limit (equations 1.13 and 1.6 with \( \beta = 1 \)). The bottom axis shows the energy in keV, the upper axis the corresponding number electron hole pairs in 1000.

1.1.2 Delta electrons

Until now the treatment of energy loss of a particle when passing through matter has been focused on particles heavier than electrons (\( m \gg m_e \)). There are two reasons why electrons need to be treated differently:

- The emission probability for bremsstrahlung is proportional to the inverse square of the particles mass. Therefore radiative effects have a much earlier onset in terms of the particles energy for an electron than for heavy particles like pions.

- In the treatment of the collision loss it was assumed that the mass of the particle is large compared to the shell electron mass. The particles are now identical (ignoring the case of positrons).
Table 1.2: Constants and variables used in this chapter. If not mentioned otherwise material properties reference to silicon and particle properties to a 120 GeV pion. (Sources: \[1\], \[3\]).

The collision energy loss is of statistical nature and the momentum transfer to shell electrons can sometimes be large enough to give them enough momentum to be treated like an independent particle. These electrons are called \(\delta\)- or knock-on electrons. This section will give a brief overview over both topics: the energy loss of electrons in matter and the characteristics of \(\delta\) electrons.

**The critical energy \(E_c\):**

There are two competing energy loss mechanisms, radiative and collision. Their importance for energy loss varies with energy. Radiative losses dominating the high energy regime and collision losses at lower energies. The critical energy \(E_c\) describes at which energy radiative losses become equal to ionization losses:

\[
-\frac{dE}{dx}(E_c)_{\text{ionization}} = -\frac{dE}{dx}(E_c)_{\text{bremsstrahlung}}
\]

There are several parameterizations for \(E_c\), among them \[9\]

\[
E_C = \frac{800}{Z + 1.2} \text{[MeV]}
\]  \hspace{1cm} (1.17)

and more accurate \[4\]

\[
E_C = 2.66 \left( \frac{ZX_0^0}{A} \right)^{1.11} \text{[MeV]}
\]  \hspace{1cm} (1.18)

where \(X_0^0\) is the radiation length normalized by material density. For silicon equation (1.18) yields \(E_C = 37.6\) MeV, other values found in the literature are \(E_C = 39\) MeV \[3\] or \(E_C = 40.19\) MeV \[1\]. The critical energy can also be defined for other particles but
is much larger since the radiative losses are proportional to $m^{-2}$. A rough estimate for muons in silicon would be

$$E_c^\mu(Si) \approx E_c^e(Si) \left(\frac{m_\mu}{m_e}\right)^2 \approx 1.7 \text{ TeV},$$

(1.19)

however, the critical energy for muons given in [1] is $E_C^\mu = 582 \text{ GeV}$. As this number is still considerably larger than the 120 GeV of the pions used in the test beam experiment and the pion mass itself is larger than the muon mass by factor of $(m_\pi/m_\mu)^2 \approx 1.6$ any radiative losses for the primary particle can be neglected.

Collision energy loss of electrons

![Figure 1.5: Energy loss of electrons in 450\(\mu\)m silicon in keV as a function of the electrons kinetic energy from 1 keV to $E_c \approx 40 \text{ MeV}$ in a double logarithmic plot. Three of the curves were generated by the NIST online service and show the losses due to radiative and the collision process separated as well as the total energy loss. Furthermore equation 1.20 (Bethe/collision loss for electrons) and equation 1.22 (low energy approximation) are plotted as well. Below 10 MeV the radiative loss becomes negligible small.](image)

As will be shown later the majority of $\delta$ electrons are well below the critical energy and therefore the electron energy loss can be limited to Coulomb interaction. The result is
1. PARTICLE DETECTION WITH SILICON SENSORS

similar to the Bethe equation \[4\]

\[- \frac{dE}{dx} = K Z \frac{1}{A \beta^2} \left[ \ln \left( \frac{m \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 + f(\gamma) - \delta(\beta \gamma) \right] \] (1.20)

with

\[f(\gamma) = \left( \frac{2 \gamma - 1}{\gamma^2} \right) \ln 2 - \frac{1}{8} \left( \frac{\gamma - 1}{\gamma} \right)^2 \] (1.21)

Equation 1.20 is plotted in figure 1.5 together with data for collision, radiative, and total energy loss generated by the online service of the National Institute of Standards and Technology (NIST). For non-relativistic energies \(I \ll E \ll m_0\) the drop of the stopping power can be approximated with \[10\]

\[- \frac{dE}{dx} = 7.8 \cdot 10^{10} Z \frac{1}{A E} \ln \left( \frac{1.166 E}{I} \right) \] (1.22)

with \(E\) and \(I\) in eV and \(dE/dx\) in eV g\(^{-1}\)/cm\(^2\). Indeed for kinetic energies below 100 keV equation 1.22 is a sufficient approximation as can be seen in figure 1.5. The general shape of the energy loss shows a minimum just like the energy loss for heavy particles, however for higher energies the energy loss is dominated by radiative process (red line in fig. 1.5) and not by the logarithmic rise of equation 1.20.

The \(\delta\) electrons energy spectrum and angular distribution

When a charged, heavy particle like a pion passes through matter it transfers energy in a large number of collisions. The differential probability for a certain energy to be transferred from a traversing particle with a speed of \(\beta\), i.e. to create a free electron with energy \(T\) is described by \[1\]

\[\frac{d^2N}{dxdT} = \frac{1}{2} K Z^2 \frac{1}{A \beta^2} \frac{F(T)}{T^2} \] (1.23)

where \(F\) describes a spin dependent factor \[4\]:

\[F(T_\delta) = \begin{cases} \frac{1}{2} - \frac{\beta^2 T_\delta}{T_{\text{max}}} & \text{for spin-0 particles,} \\ 1 - \frac{\beta^2 T_\delta}{T_{\text{max}}} + \frac{T_\delta^2}{2E_\gamma^2} & \text{for spin-} \frac{1}{2} \text{ particles} \end{cases} \] (1.24)

For all energies much smaller than the maximum energy transfer possible \(T_{\delta e} \ll T_{\text{max}}\) the spin factor \(F\) can be neglected and since the \(\delta\)-electron energies are \(T_{\delta e} \ll 100\) GeV equation 1.23 becomes \(\frac{d^2N}{dT} \propto T^{-2}\). Furthermore the differential collision probability given by equation 1.23 is only valid if the energy transfer is much larger than the ionization constant \(I\) of the material, \(T_{\delta e} \gg I = 173\) eV. Assuming a thin detector limit, that is that the energy of the primary particle is considered constant (analog to the Landau distribution equation 1.14), one can integrate over the number of electrons per path length \(x\). With \(\xi\) given by equation 1.6 one obtains for the average number \(\delta\) electrons per energy (with \(T_{\delta e} \ll T_{\text{max}}\) and \(\beta = 1\) for 120 GeV pions):

\[\frac{dN}{dT} = \frac{\xi}{T^2}.\] (1.25)
1.1. PASSAGE OF PARTICLES THROUGH MATTER

Figure 1.6: Left plot: The differential collision probability for a pion in 450 µm silicon as a function of the transferred energy $E$ from $E = 3$ keV to $E = 100$ MeV in a double logarithmic scale. Furthermore in red the total number of $\delta$ electron in a range from 3 keV to $E$, which is basically the amount of kicked out electrons up to this energy. For a silicon sensor with 450 µm most of the $\delta$ electrons are below 100 keV. The blue line shows the number of missing electrons, i.e. the number of $\delta$ electron in a range from $E$ to 1 GeV. Right plot: The emission angle $\theta_\delta$ of a $\delta$ electron with respect to the primary particle track.

Finally the average number of $\delta$ electrons within a given energy range $T_{\text{low}}$ to $T_{\text{high}}$ is (again assuming $T_{\text{low}} \gg I$ and $T_{\text{high}} \ll T_{\text{max}}$):

$$\frac{dN}{dT} = \xi \left[ \frac{1}{T_{\text{low}}} - \frac{1}{T_{\text{high}}} \right].$$

(1.26)

From equations 1.25 and 1.26 it becomes evident that high energetic $\delta$ electrons are rare and that the majority of the collision processes are small scale energy transfers. With $\xi \approx 8$ keV the probability of a $\delta$ electron with an energy higher than 100 keV is $\xi/E = 8\%$ or in other words 92% of all $\delta$ electrons are below 100 keV and 50% are below 16 keV. This is illustrated in figure 1.6.

Due to the kinematics involved there is a fixed relationship between energy and emission angle of a $\delta$ electron with kinetic energy $T_e$ [1]

$$\cos \Theta = \frac{T_e \ p_{\text{max}}}{p_e \ T_{\text{max}}} \simeq \frac{T_e}{p_e}$$

(1.27)

and with $p = \sqrt{T_{\text{kin}}(T_{\text{kin}} + 2m)}$

$$\theta = \arccos \sqrt{\frac{T_\delta}{T_\delta + 2m_e}}$$

(1.28)

This means that most $\delta$ electrons, since they have a low energy, are emitted in a direction perpendicular to the primary particle track at $\theta$ close to 90°.
Range and energy dissipation of electrons

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The energy range relationship for electrons in silicon plotted for three different approximations for an energy range that sheds light on the energy deposition of $\delta$ electrons inside the detector as a whole. The plotted curves are: \textbf{NIST} is continuous slowing down approximation taken from the online service of the national institute of standard and technology (NIST), \textbf{Kanyaka} is the Kanaya-Okayama range using equation 1.30, \textbf{Leroy} is the practical range given by equation 1.29, $\delta$-\textbf{e$_{\text{orthogonal}}$} is the projection of a $\delta$ electron range onto the plane orthogonal to the primary particle track when using the practical range (equation 1.29) and taking the effects of the angular distribution of $\delta$ electrons (equation 1.28) into account. $\delta$-\textbf{e$_{\text{parallel}}$} is parallel complement to $\delta$-\textbf{e$_{\text{orthogonal}}$}, $\phi_\delta$ is the emission angle of the $\delta$ electron according to equation 1.28. From $\delta$-\textbf{e$_{\text{orthogonal}}$} it becomes clear that electrons with more energy than $E \approx 550$ keV start leaving the sensor and that therefore the deposited energy inside the detector will be different from the total energy lost by collisions (the restricted energy loss, equation 1.8).}
\end{figure}

For the primary particles impact point reconstruction it is not only of importance how many $\delta$ electrons are created with a certain energy but how far they can travel. There are several definitions for the range of an electron (e.g. [10, p.98]), among them are

- **The CSDA range**: a very close approximation to the average path length traveled by a charged particle as it slows down to rest, calculated in the continuous-slowing-down approximation (CSDA). In this approximation, the rate of energy loss at every
1.1. PASSAGE OF PARTICLES THROUGH MATTER

Figure 1.8: The energy range relationship for electrons in silicon plotted for three different approximations. The plot is a zoom in of plot 1.7 for a smaller energy range. Also the plotting of $\phi_\delta$ has been omitted. The electron ranges are now in the order of the dimensions of the pixels and clusters used in the DEPFET test beam experiment. For illustrative purposes the extent of three DEPFET pixels in X and Y direction are plotted to the left of the curves. "hit" refers to the pixel hit by a particle; "1st" and "2nd" are the according neighbor pixels.

point along the track is assumed to be equal to the total stopping power. Energy-loss fluctuations are neglected. The CSDA range is obtained by integrating the reciprocal of the total stopping power with respect to energy. In the range energy relationship plot in figures 1.7 and 1.8 the CSDA approximation of the NIST estar online service was used.

• The practical range: The transmission curves for mono energetic electrons (fig. 1.9) have a long, linear part. The extrapolation of this linear part to zero transmission is the so-called practical electron range $R_p$. In the range energy relationship plot in figures 1.7 and 1.8 the following approximation valid for $0.01 < E < 3$ MeV is used [4] 

$$R_p = 0.412E^{1.265 - 0.0945 \ln E}$$

(1.29)

with in E in MeV and $R_p$ in g/cm$^2$.

• Kanaya-Okayama range: This range takes elastic and inelastic scattering effects
into account [11]

\[
\rho R = 2.76 \cdot 10^{-11} A E_0^{5/3} \frac{(1 + 0.978 \cdot 10^{-6} E_0)^{5/3}}{(1 + 1.957 \cdot 10^{-6} E_0)^{4/3}}
\]

(1.30)

with \(E_0\) in eV and \(\rho\) in g/cm\(^3\)

In figure 1.7 these three ranges are plotted together with the emission angle of a \(\delta\) electron (equation 1.28) and the according horizontal and vertical component of the practical range (equation 1.29). From this plot it becomes clear that \(\delta\)-electrons with an energy above \(E(\delta e^-) \gtrsim 550\,\text{keV}\) will leave the sensor and therefore the deposited energy inside the detector will be different from the total energy lost by collisions. Here the restricted energy loss, equation 1.8, comes into play with - judging from fig. 1.7 - an upper limit between 1 and 2 MeV. A similar plot is shown in figure 1.8 where the electron ranges are compared to the pixel sizes and the read out area of a cluster. A cluster is the read out area of the sensor where the pion has passed through and is \(5 \times 5\) pixel large and centered at the impact point of the particle. One can see that \(\delta\) electrons with an energy above \(E > 150\,\text{keV}\) will leave the cluster. One way to estimate how much electrons with a given energy will leave the detector or a given read out area are *transmission curves*.

Transmission curves

![Transmission curves](image)

**Figure 1.9:** Transmission curves for electrons in silicon according to the Kanaya-Okayama approximation (equation 1.32). On the abscissa is the sensor thickness in \(\mu\)m. The left plot (a) shows electrons at energies where they start leaving the sensor (450 \(\mu\)m). The right plot (b) shows distances and energies in the regime of the pixel dimensions.

These curves show the fraction of electrons which will leave material of a given thickness. Among others there are these two approximations:
1.1. Passage of Particles Through Matter

- Plotting $T$ versus $x/x_0$ with $x_0$ being the mass-thickness corresponding to a transmission of 50\% [10]:

$$ T(x/x_0) = \exp \left( \frac{x}{x_0} \right)^p $$

(1.31)

- A transmission curved based on the Kanaya-Okayama range $R_{ko}$ [11],

$$ T(y) = \exp \left( -\frac{\gamma y}{1-y} \right), $$

(1.32)

where $y = x/R_{ko}$ is a reduced depth with $R_{ko}$ from equation 1.30 and $\gamma = 0.187 \cdot Z^{2/3}$ is a factor that takes into account diffusion loss due to multiple collisions for returning electrons and energy retardation due to electronic collisions. For silicon $\gamma_{Si} = 1.086$.

Figure 1.9 shows the latter approximation for the transmission curve (a) for distances comparable to 450 $\mu$m thick sensor in the left plot and (b) for distances comparable to the typical DEPFET pixel cluster size in the right plot. This plot supports the above estimate which gives a limit to the energy deposition by $\delta$ electrons of roughly $(1-2)$ MeV.

Energy deposition vs penetration depth

Figure 1.10: The energy deposition in 450 $\mu$m silicon as a function of penetration depth in silicon according to equation 1.33. The Kanaya-Okayama range $R_{ko}$ from equation 1.30 was used for the reduced depth $y = x/R$. The graph on the left (a) shows distances comparable to the thickness of a DEPFET sensor (450 $\mu$m). The graph on the right (b) shows distances comparable to a typical pixel cluster. For illustrative purposes the extent of three DEPFET pixels in X and Y direction is added to the plot on the left. "hit" refers to the pixel hit by a particle; "1st" and "2nd" are the according neighbor pixels.
Besides the emission probability, angle, and range of a $\delta$ electron with a certain energy it is also important to know how the energy deposition looks like as a function of distance traveled or penetration depth. The following approximation comes from low energy electron beam studies [12]:

$$\phi(y)_{Norm} = 0.60 + 6.21y - 12.4y^2 + 5.69y^3$$

(1.33)

where $\phi_{Norm}(y)$ is a normalized approximation for the depth distribution of dissipated energy with $y = x/R$ being the reduced depth. Alternatively a shifted Gaussian can be used as an approximation [10]. Figure 1.10 shows the electron energy deposition $\phi(y)$ in 450 $\mu$m silicon as a function of reduced depth using the Kanaya-Okayama range $R_{ko}^1$ as denominator. From the left plot (a) in this figure it is clear that higher energetic electrons with $E > 500$ keV leave only a fraction of their energy in the sensor thus again arguing for a energy loss restricted to $E \approx 1 - 2$ MeV. The righthand plot (b) shows that - similar to the transmission curves - $\delta$ electrons below $E \lesssim 50$ keV are absorbed within the seed pixel.

**Multiple Coulomb Scattering**

As presented before there are several definitions for the range of an electron in matter. This is mainly because there is a profound difference between the total path length a particle travels in matter and the actual path length in one direction (e.g. the depth of the silicon sensor). The difference is caused by scattering processes deflecting the electrons trajectory. So far the interaction between a particle and the nuclei of the traversed medium has been ignored because the cross sections for nuclear interactions is negligibly small in the cases dealt with in this thesis. However, coulomb interaction with nuclei plays a role since this causes the particle trajectory to be deflected. For small angles the distribution of scattering angles can be approximated by a Gaussian distribution with a width of [1]:

$$\theta_0 = \frac{13.6 \text{ MeV}}{p\beta} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \left(\frac{x}{x_0}\right)\right],$$

(1.34)

where $p$, $\beta$, and $z$ are the momentum, velocity, and charge of the incident particle, and $x/X_0$ is the thickness of the scattering medium in units of $X_0$. It should be noted that outside the small angle range the distribution of scattering angles becomes non Gaussian. Multiple scattering plays a crucial role for particle detectors, especially silicon vertex detectors. As will be further explained in the section 2.1 vertex detectors consist of several layers each providing a space point for particle track reconstruction. Multiple scattering alters the tracks and impairs the detector’s tracking abilities. Hence multiple scattering should be minimized. The same is true for a test beam experiment where the beam telescope provides the space point for tracking. As can be deduced from equation 1.34 there are two ways to keep the multiple scattering angle small:

- Increase the particles momentum. This option is only viable in a test beam experiment and was the main reason why the DEPFET test beam activates were moved

\(^1\)The Kanaya-Okayama range $R_{ko}$ is plotted in figure 1.7 and figure 1.7.
from the 6 GeV electron beam at DESY, Hamburg to the 120 GeV pion beam at the SPS at CERN, Geneva. As will be explained in the next chapter, a vertex detector should have little effect on the particle trajectory even if it has a small momentum.

- Decrease the material length \( x/X_0 \). This basically means thinner sensors and small \( Z \) and is important for vertex and tracking detector subsystem in particle experiments. Large parts of the DEPFET vertex detector concept for the ILC, which will be presented in the next chapter, are built reducing the amount of scattering material.

## 1.2 Semiconductor Detectors

Semiconductors are materials that have an electrical conductivity between that of a conductor and an insulator (fig. 1.11). Crystalline semiconductors like silicon have two important energy bands similar to metallic conductors: the valence and the conduction band. Unlike a metallic conductor, however, these bands do not overlap but are separated by an energy gap which is characteristically for each material. The band gap in silicon is \( E_{\text{gap}}^{\text{Si}} = 1.12 \text{eV} \), which is beneficially low for an utilization as a particle detector material. Due to thermal excitation some electrons will leave the valence band and leave a hole.

![Conductivity of several materials](https://via.placeholder.com/150)

**Figure 1.11:** The conductivity of several materials. Semiconductors have a large range of conductivity due to different doping concentrations.

After some time they will then recombine. The product of electrons \( n \) and holes \( p \) is
constant for a given temperature

\[ np = n_{int}^2 \]  

(1.35)

\( n_{int} \) is the intrinsic carrier concentration and for silicon at \( T = 300 \) K, \( n_{int} \approx 1.45 \cdot 10^{10} \) cm\(^{-3} \) [4]. The intrinsic carrier concentration has a temperature dependence of

\[ n_{int} \approx T^{3/2} \exp \left( \frac{E_{gap}}{2k_bT} \right) \]  

(1.36)

where \( k_b = 8.617 \cdot 10^{-5} \) eV/K is the Boltzmann constant. The mobility for electrons \( \mu_e \) and holes \( \mu_h \) is different and therefore they have a different velocities \( v = \mu E \) in a given field \( E \). Both mobilities are temperature and field depended.

By introducing impurities in the lattice structure of silicon one can modify the amount of free charge carriers of one type, a process called doping. The two types are called \( n \) or donors type if there is an electron excess and conversely \( p \) or acceptor if an excess of holes is created. Doping allows to change the properties of silicon, for instance the conductivity

\[ \rho = \frac{1}{q_e N \mu} \]  

(1.37)

where \( N \) is the dopant concentration and \( \mu \) the majority carrier mobility.

P-N junction

The standard silicon detector consists of a \( p \) and a \( n \) doped region and it is therefore a diode. \( p \) and \( n \) type charge carriers diffuse along the concentration gradient. While the two carriers types diffuse they recombine with each other and create a border zone void of free charge carriers. However, in this initially neutral zone the depletion of charge carriers will leave (now) electrically charged atoms behind and two space charge regions, a positive and a negative one, are created. This generates a field that, in a state of equilibrium, cancels the migration pressure caused by the concentration gradient (fig. 1.12). The size of the space charge region \( x_n \) and \( x_p \) is dependent on the donor concentrations \( N_d \) and \( N_a \):

\[ N_d x_n = N_a x_p \]  

(1.38)

Assuming an abrupt junction one can approximate the space charge densities \( \rho(x) \) with

\[ \rho(x) = \begin{cases} q_e N_d & \text{for } 0 \leq x \leq x_n \\ q_e N_a & \text{for } 0 \leq x \leq x_p \end{cases} \]  

(1.39)

and calculate the contact or build-in voltage \( V_{bi} \) and the size of the depletion zone by solving the Poisson equation

\[ \frac{\partial^2 \phi(x)}{\partial x^2} = -\frac{\rho(z)}{\epsilon} \]  

(1.40)

with [4]

\[ \epsilon = \epsilon_0 \epsilon_{eSi} = 1.054 \text{ pF/cm} \]  

(1.41)
1.2. SEMICONDUCTOR DETECTORS

The build-in voltage is then [13]

\[ V_{bi} = \frac{kT}{q_e} \ln \left( \frac{N_a N_d}{n_{int}^2} \right) \] (1.42)

where \( q_e \) is the elementary charge and the width of the depletion zone is

\[ d = \sqrt{\frac{2\epsilon}{q_e} \left( \frac{1}{N_a} + \frac{1}{N_d} \right)} (V_{bi}) \] (1.43)

For the detection of particles it is desirable to enlarge the depletion zone. This is done by applying a voltage in the same direction as the built-in voltage. This process is called reverse biasing and equation 1.43 becomes

\[ d = \sqrt{\frac{2\epsilon}{q_e} \left( \frac{1}{N_a} + \frac{1}{N_d} \right)} (V_{bi} + V_{ext}) \] (1.44)

Usage as a particle detector

With a sufficiently large reverse bias the diode becomes fully depleted. If an ionizing particle traverses the silicon detector the energy it deposits will create electron hole pairs. However, the energy needed on average to create an electron hole pair in silicon is not \( E_{Si_{gap}} = 1.21 \text{ eV} \) but

\[ E_{e/h} \simeq 3.6 \text{ eV} \] (1.45)

This is because a part of the energy is used for phonon excitations in the silicon lattice. In the absence of a particle there is still a “signal” generated by the dark or leakage current which is caused by the thermal fluctuation of charge carriers. This leakage current has a temperature dependence of

\[ I_l \propto T^2 \exp \left( -\frac{E_{gap}}{2k_B T} \right) \] (1.46)

For most silicon sensors the junction is realized by a shallow and highly doped (\( N_a > 10^{18} \text{ cm}^{-3} \)) \( p^+ \)-implant in a low doped (\( N_d \approx 10^{12} \text{ cm}^{-3} \)) bulk material [13]. Furthermore the build-in voltage is much smaller than the usual reverse bias voltage \( V_{bi} \sim 0.5 \text{ V} \ll V_{dep} \gtrsim 50 \text{ V} \). These conditions simplify equation 1.44 to

\[ d = \sqrt{\frac{2\epsilon}{q_e N_d} V} \simeq 0.53\sqrt{\rho_R V} \mu\text{m} \] (1.47)

where \( \rho_R \) is the resistivity in \( \Omega \text{cm} \) given as [4]

\[ \rho_R = \frac{1}{\mu q_e N_D} \] (1.48)

and \( V \) in volts. The bias voltage at full depletion of a silicon sensor of thickness \( D \) can be expressed by [4, 14]

\[ V_{dep} \simeq \frac{D^2}{2\mu \epsilon \rho_R} \approx \frac{q_e N_d D^2}{2\epsilon} \] (1.49)
The Charge Cloud

The charge generated by an ionizing particle will drift towards the anode with

$$v_{\text{drift}}(z) = \frac{dz}{dt} = \pm \mu E(z)$$  \hfill (1.50)
1.2. SEMICONDUCTOR DETECTORS

However, during this drift time the initially small charge cloud will become broader due to diffusion effect. The diffusion process is governed by the diffusion constant $D_n$ and $D_p$ for electrons and holes and the gradients $\nabla n$ and $\nabla p$ of the electron and hole concentration and the resulting diffusion current density is

$$J_{n,\text{diff}} = -D_n \nabla n = -\frac{kT}{q_e} \mu_n n$$ (1.51)

where the Einstein equation

$$\frac{D_n}{\mu_n} = \frac{kT}{q_e}$$ (1.52)

was used. $\frac{kT}{q_e}$ is sometimes called the thermal voltage and is $\frac{kT}{q_e} = 0.0259 \text{ V}$ for $T = 300 \text{ K}$. The width of the charge cloud is in first approximation a function of the drift time and the drift time in turn depends on the electric field:

$$E(z) = - \left[ \frac{V + V_{\text{dep}}}{d} - \frac{2zV_{\text{dep}}}{d^2} \right]$$ (1.53)

Integration of 1.50 together with 1.53 yields an expression for the drift time [14]

$$t_{\text{drift}} = \frac{d^2}{2\mu_e V_{\text{dep}}} \ln \left[ \frac{V + V_{\text{dep}}}{V - V_{\text{dep}}} \left( 1 - \frac{z}{d} \frac{2V_{\text{dep}}}{V + V_{\text{dep}}} \right) \right]$$ (1.54)

If one assumes for the initial charge distribution a Dirac $\delta$ distribution, the charge cloud shape can be approximated by the fundamental solution to the diffusion equation

$$\phi(x, t_{\text{drift}}) = \frac{1}{\sqrt{4\pi D_e t_{\text{drift}}}} \exp \left( -\frac{x - x_0}{4kT} \right)$$ (1.55)

which is a normal distribution with a width of

$$\sigma_{\text{cloud}} = \sqrt{2D_p t_{\text{drift}}} = \sqrt{\frac{2kT}{q} \mu_e t_{\text{drift}}}$$ (1.56)

Figure 1.13 shows the drift time and the charge cloud width as a function of the sensor depth for different bias and depletion voltages. The actual charge cloud is the superposition of the charge clouds generated along the track of an ionizing particle. This cloud will have a non-Gaussian shape, in this work, however, it will be approximated to first order with a Gaussian with a width which is equal to the average of all Gaussian widths along the path. These are the red lines in the figure 1.13. For a 450 $\mu$m thick sensor the width is $\sigma_{\text{cloud}} \approx (6 - 7) \mu$m. This is a lower limit as other effects have been neglected:

- The initial charge distribution was approximated with a Dirac $\delta$ function. However, a real charge distribution will have a certain extension. According to equation 1.26 on average every track will have a $\delta$ electron with an energy of $E_{\delta} \approx 8 \text{ keV}$ and accordingly more at lower energies, although the condition $E_{\delta} \gg I = 0.173 \text{ keV}$ starts to be violated. The range of a $E_{\delta} = 8 \text{ keV}$ electron is roughly $R \approx 1 \mu$m, which could be used as a first approximation.
According to [15] the broadening of the initial distribution due to electrostatic re-
pulsion is not negligible. However, their work focuses on electrons in silicon drift
detectors and they assume a complete electron hole separation as initial condition.

It is therefore difficult to give a precise width of the charge cloud, however, for a 450 µm
thick silicon sensor a width of $\sigma_{\text{cloud}} \approx 6 - 8 \mu$m can be expected.

**Figure 1.13:** These four plots shows the dependence of the drift time $t_{\text{drift}}$ (upper two plots, A and B) and the charge cloud size $D_{\text{cloud}}$ (lower two plots, C and D) as a function of the sensor depth for a 450 µm thick silicon sensor. In the plots on the left side the voltage at full depletion $V_{\text{dep}}$ is varied and the bias voltage is kept fixed at $V_{\text{bias}} = 180$ V. In the plots on the right the voltage at full depletion was kept fixed at $V_{\text{dep}} = 120$ V and the bias voltage $V_{\text{bias}}$ was changed. The drift time and the cloud size were calculated using equations 1.54 and 1.56. The red lines in the two lower plots mark the average of the widths for each voltage settings.

### 1.2.1 The DEPFET sensor

The abbreviation DEPFET - Depleted Field Effect Transistor - contains already the basic principle of this detector type: A FET transistor inside a fully depleted sensor bulk, which is steered by electrons in a potential minimum below its channel. This potential minimum is created by means of sidewards depletion.
1.2. SEMICONDUCTOR DETECTORS

Sidewards depletion

The idea of sidewards depletion was first introduced as a way to realize silicon drift detectors [16]. Instead of a simple p-n junction the detector has a p implantation on each side of the n doped bulk material. With an additional n+ implantation on the top side as illustrated in figure 1.14 the bulk is set to a constant potential \( V_{\text{bulk}} \), e.g. ground. With increasing reverse bias voltages \( V_u \) and \( V_d \) on both p contacts the depletion zone of both p-n junctions grows until the sensor is fully depleted. By solving the Poisson equation (1.40) the one dimensional potential distribution perpendicular to the sensor surface is now

\[
\phi(z) = \frac{\rho}{2\epsilon} z(d - z) + \frac{z}{d}(V_d - V_u) + V_u
\]

with a minimum \( (d\phi(z)/dz = 0) \) at

\[
z_{\text{min}} = \frac{d}{2} + \frac{\epsilon}{p\rho d}(V_d - V_u)
\]

For equal bias voltages \( V_u = V_d \) the voltage necessary for complete depletion of the sensor is four times lower with sidewards depletion than without as \( V_{\text{dep}} \propto D^2 \) (equation 1.49). As can be seen from equation 1.58 it is possible to move the potential minimum close to one surface by applying correspondingly asymmetric bias voltages, which is essential for the DEPFET sensor. When an ionizing particle creates charge the electrons will drift to this potential minimum. In case of drift sensor a second field moves the electrons towards a read out anode. The DEPFET however works differently.

The DEPFET pixel

The sidewards depletion enables the shaping of a vertical potential minimum, however for the DEPFET also lateral potential minima are needed. This is realized by implanting a small deep-n doped region located under the external gates and therefore the channel of a transistor (fig. 1.15). Electrons created by a radiation will move to this confined area and their presence will alter the potential below the transistor just like a voltage change on the external gate therefore acting like an internal gate. The device amplification is the amount of current modulation \( \partial I_D \) due to the collected charge \( \partial Q \)

\[
g_q = \left. \frac{\partial I_d}{\partial Q} \right|_{V_{GS},V_{DS}}
\]

Current values of \( g_q \) are in the order of \( g_q \approx 300 \text{ pA/e}^- \). This concept has several benefits over other sensor types:

- Charge collection is ongoing even if the DEPFET transistor is switched off which plays an essential role for the energy dissipation budget in the ILC vertex detector concept.

- The charge is collected in a fully depleted bulk. This allows for a fast and complete charge collection unlike diffusion based concepts like MAPS.
The input capacitance is very low, in the order of 10 fF. This allows very low noise measurements. Using an ILC type DEPFET with a 10 µm shaping time at room temperature $^{55}$Fe measurements with an R.M.S. noise of only $ENC = 1.6 e^-$ were achieved [17].

The combination of the last two points yields an excellent signal over noise ratio.
**The clear process** Unlike a silicon drift chamber the charge is not removed by the read out. Therefore an additional *clear contact* is introduced next to the FET gate (see Figure 1.15) to facilitate the removal of the electrons by applying a *clear* pulse. A further contact, the *clear gate*, allows to further control the clear process. This is necessary since clearing of electrons out of the internal gate and collection of electrons inside the internal gate are competing processes. Their interplay is a complicated process and a fined tuned set of bias voltages is needed to achieve the highest signal to noise. Studies can be found in [18, 19, 20, 21]. Originally, the *clear gate* signal was pulsed but the innovations of new DEPFET generations allowed for the introduction of a so called *Common Clear Gate* or *CoCG* device type where only one static *clear gate* voltage is applied. A detailed description of the clear process can be found in [18, 22].
Figure 1.15: Cross section of a linear DEPFET: The deep n-doping area labeled 'internal gate' is a potential minimum created by means of sideways depletion and proper doping profiles. Electrons generated by an ionizing particle will move to the internal gate and modulate the transistor current, thus creating a signal. To remove the electrons from the internal gate after readout a clear pulse is applied to the n⁺-clear contact. The additional clear gate contact allows to steer the competing charge clearing and collecting processes to achieve an optimal signal to noise ratio.
2

The ILC prototype system

2.1 The vertex detector at the ILC

The physics goals of the international linear collider (ILC) and other modern high energy particle accelerator experiments are manifold. Among them are:

- Precision measurements of the Higgs boson.
- Is there physics beyond the standard model of particle physics like super symmetry?
- How many dimensions does the universe have?

In all these areas, access to the high quality physical measurements relies on heavy flavor identification with high efficiency and purity [23, 24]. The ability to separate $b$, $c$, and $udsg$ jets helps for example in suppressing background events.

Flavor tagging

The ability to distinguish between different heavy quark flavors of jets relies on their different properties in terms of mass and decay time. In the interaction point of the experiment short lived particles like the $\gamma(4s)$ decay virtually instantly and the fragments are splitting up in the primary vertex (PV). The lifetime of the $B$ mesons, however, is in the order of 1.6 picoseconds (Table 2.1) and therefore long enough to displace a secondary vertex, created by the $B$ meson decay, from the primary vertex. This is illustrated in figure 2.1. Since the $B$ meson decay is likely to contain a $c$ quark fragment, even tertiary vertices can be found. There are several variables used to tag a yet as a $b$ or $c$ quark type [25]:

- The impact parameter (IP), which is the distance between the reconstructed track of a particle and the primary vertex, i.e. the collision point. This is illustrated in figure 2.1.
- Measurement of secondary (and tertiary) vertices and their distance to the primary vertex.
2. THE ILC PROTOTYPE SYSTEM

Figure 2.1: Illustration of heavy flavor tagging by lifetime/vertex displacement: A primary particle decays into several fragments of which one is a heavy quark (i.e. with b or c quark content) which travels a certain distance. The heavy quark then decays in several particles leaving displaced (with respect to the primary vertex) tracks inside the detector. The distance between the reconstructed track of a particle and the primary vertex $d_0$ is called the impact parameter and is used as a tagging variable. Furthermore all tracks associated with the secondary vertex can be used for further tagging variables (see figure 2.2).

- The invariant mass of all tracks associated with a secondary vertex. The mass in $c$-jets is limited by the $D$-meson mass.

- The fraction of the charged jet energy included in the secondary vertex. This reflects the different fragmentation properties of different flavors.

- The transverse momentum at a secondary vertex with respect to the $b$-hadron flight direction. This takes missing particles, e.g. neutrinos from semi-leptonic decays, into account.

- The track rapidity $\varphi = \arctanh \beta$ which differs for $b$- and $c$ jets due to the higher mass of $b$ mesons.

The first two variables are sometimes referred to as *lifetime tags*, whereas the last four are sometimes called *secondary vertex tags*. Figure 2.2 shows simulated distributions of secondary vertex tag variables for $b$ and $c$ quarks at the DELPHI experiment. Another
2.1. THE VERTEX DETECTOR AT THE ILC

![Simulated distribution of four secondary vertex tagging variables for Z hadronic events in the DELPHI experiment taken from [25].](image)

- **a)** is the invariant particle mass,
- **b)** The fraction of the charged jet energy included in the secondary vertex,
- **c)** the transverse momentum at the secondary vertex, and
- **d)** is the rapidity for each SV track.

Common to all tagging variables is that they need an excellent tracking performance as close as possible to the interaction point. The figure of merit is the impact parameter resolution

\[
\sigma_{IP} = \sigma_{IP}^{res} \oplus \sigma_{IP}^{ms}
\]

where \(\oplus\) is the quadratic addition of two resolution affecting parameters:

- the position resolution of the vertex detector \(\sigma_{IP}^{res}\), and
- the multiple scattering \(\sigma_{IP}^{ms}\) of the particle due to the material of the beam pipe and the vertex detector.

For efficient \(b\) and \(c\) tagging it is important to keep \(\sigma_{IP}\) as low as possible and there are basically three ways to achieve that:

1. The first sensor must be as close as possible to the interaction point, i.e. the radius \(R_1\) of the inner detector layer must be as small as possible,
2. THE ILC PROTOTYPE SYSTEM

2. the radiation length $x/X_0$ of the material of both, beam pipe and sensors, must be kept to a minimum possible, and

3. the intrinsic position resolution of the vertex silicon detector must be as good as possible.

These are, however, conflicting requirements and a realistic set of parameters for a vertex detector constituting a compromise of the technologically feasible and the desire for best physics performance.

<table>
<thead>
<tr>
<th>particle</th>
<th>quarks</th>
<th>spin</th>
<th>mass [GeV]</th>
<th>life time $\tau$ [s]</th>
<th>$c\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>$ud$</td>
<td>0</td>
<td>0.140</td>
<td>$2.603 \cdot 10^{-8}$</td>
<td>7.8 m</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>$u\bar{u}, d\bar{d}$</td>
<td>0</td>
<td>0.135</td>
<td>$8 \cdot 10^{-17}$</td>
<td>25 nm</td>
</tr>
<tr>
<td>$K^{+/-}$</td>
<td>$u\bar{u}$</td>
<td>0</td>
<td>0.494</td>
<td>$1.238 \cdot 10^{-8}$</td>
<td>3.7 m</td>
</tr>
<tr>
<td>$K^0_L$</td>
<td>$d\bar{s}$</td>
<td>0</td>
<td>0.497</td>
<td>$5.116 \cdot 10^{-8}$</td>
<td>15.8 m</td>
</tr>
<tr>
<td>$K^0_S$</td>
<td>$d\bar{s}$</td>
<td>0</td>
<td>0.497</td>
<td>$0.89 \cdot 10^{-10}$</td>
<td>2.7 cm</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$cd$</td>
<td>0</td>
<td>1.869</td>
<td>$1.04 \cdot 10^{-12}$</td>
<td>311.8 $\mu$m</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$c\bar{u}$</td>
<td>0</td>
<td>1.865</td>
<td>$0.41 \cdot 10^{-12}$</td>
<td>122.9 $\mu$m</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$ub$</td>
<td>0</td>
<td>5.279</td>
<td>$1.638 \cdot 10^{-12}$</td>
<td>491.1 $\mu$m</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$d\bar{b}$</td>
<td>0</td>
<td>5.279</td>
<td>$1.530 \cdot 10^{-12}$</td>
<td>458.7 $\mu$m</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$c\bar{c}$</td>
<td>1</td>
<td>3.097</td>
<td>$\lesssim 10^{-20}$</td>
<td>-</td>
</tr>
<tr>
<td>$\nu(4s)$</td>
<td>$b\bar{b}$</td>
<td>1</td>
<td>10.57</td>
<td>$\lesssim 10^{-20}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.1: Some properties of important mesons [1].

2.1.1 The DEPFET vertex detector concept for the ILC

The constrains and requirements for the ILC vertex detector are well established [26]. The main parameter is the impact parameter resolution with

$$\sigma_b(r,\Phi, z) \leq 5 \mu m \oplus \frac{10 \mu m \text{GeV}/c}{p \sin^{3/2} \theta}$$

To achieve the resolution, the first inner layer is placed very close to the beam pipe at $r = 15$ mm. To achieve this goal several technological challenges for the vertex detector must be met:

- **Pixel sizes**: To achieve the required spatial resolution an accordingly small pixel size in the order of $\approx 25 \times 25 \mu m^2$ is required.

- **Material budget**: The effects of multiple scattering especially for low momentum tracks are only within bearable limits if the material does not amount to more than $x/X_0 \approx 0.1\%$ per layer, which is $1/30$ of the radiation length per layer for the ATLAS pixel sensor with $x/X_0 \approx 3\%$ per layer [27]. This can only be achieved with thinned down sensors. However, this means the signal will be scaled down as well. To still achieve the above mentioned spatial resolution an excellent signal to noise performance is required.
2.1. THE VERTEX DETECTOR AT THE ILC

- **Power budget:** The above mentioned \( x/X_0 \approx 0.1\% \) per layer can only be achieved if no cooling system, which would add additional material, is needed. This means the power dissipation of the ILC vertex detector can only be a fraction of the power dissipation of conventional vertex detectors like e.g. the ATLAS pixel detector with its 18.7 kW [28].

- **Read out speed:** At the radius \( r = 15 \text{ mm} \) of the inner most layer the level of the \( e^+e^- \) pair production background becomes very high. A hit multiplicity of \( \approx 0.05 \) hits per \( mm^2 \) and bunch crossing at \( \sqrt{s} = 500 \text{ GeV} \) must be tolerated with a hit occupancy of around 1%.

- **Radiation tolerance:** The requirements on radiation hardness are much less stringent than for the LHC [27]: Electron fluxes of about \( 1.7 \times 10^{12} \text{ per cm}^2 \text{ and year} \) corresponding to a total ionizing dose of about 4 kGy for 10 years of operation and a supplementary neutron equivalent flux of \( 8.5 \times 10^{10} \text{ per cm}^2 \text{ and year} \). The innermost layer of the ATLAS pixel detector has to endure a dose of 500 krad after only 5 years of operation and a fluence of \( 10^{15} \text{n}_{eq}/\text{cm}^2 \) at the same time [29, 27].

All of these requirements are demanding, however a proposal for a DEPFET vertex detector for the ILC was put forward that could meet all the requirements [17]. The envisaged DEPFET vertex detector consists of several barrel shaped layers and each layer is made up of overlapping ladders. Table 2.2 shows the geometrical parameters of this concept and figure 2.3 shows a sketch of an ILC DEPFET module. In the following some features of the DEPFET ILC vertex detector will be addressed with regard to the technological challenges stated above. The radiation tolerance, however, will be skipped. As has been shown in studies the DEPFET sensor itself as well as the (newest generation of) ASICs are capable of working in the radiation environment of the ILC according to their specifications [17].

<table>
<thead>
<tr>
<th>Layer</th>
<th>Number of ladders</th>
<th>Radius (mm)</th>
<th>Ladder length (mm)</th>
<th>width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>15.0</td>
<td>100</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>26.0</td>
<td>2\times125</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>37.0</td>
<td>2\times125</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>48.0</td>
<td>2\times125</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>60.0</td>
<td>2\times125</td>
<td>22</td>
</tr>
</tbody>
</table>

*Table 2.2: Default geometrical parameters of the DEPFET based ILC micro-vertex detector [30, 17]*.

**Position resolution**

To achieve the impact parameter resolution of \( \sigma_{\mu} = 5 \mu m \) a spatial resolution of \( \lesssim 4 \mu m \) per layer is necessary. The binary position resolution of a 24 \( \mu m \) pitched pixels is \( 24/\sqrt{12} \approx 7 \mu m \). With analog interpolation and an assumed signal to noise ratio of \( \sim 30 - 40 \) this
value can be improved well below the required $4 \, \mu m$ [17]. As will be shown later the active part of the DEPFET sensor needs to be thinned down to $\approx 50 \, \mu m$. An ionizing particle will create a signal (most probable value, eqn. 1.13) of $\approx 3500$ electron/hole pairs or roughly 10% of a $450 \, \mu m$ thick sensor. The noise of the detector is dominated by the readout electronics and not the DEPFET itself [31, 22]. The readout noise is targeted to be on the order of $\approx 100 \, e^-$ which would give the above mentioned signal to noise value of $\gtrsim 35$. There are two ways to achieve this goal:

1. Increase the internal gain of the DEPFET $g_q$. Since the readout electronics is the
dominant noise contributor this translates directly into an improved signal to noise. Current values for ILC pixel types are \( g_q \approx 300 \text{ pA/e}^- \), but with changes to the pixel geometry values of \( g_q \approx 500 \text{ pA/e}^- \) have been measured

2. Decrease the noise of the readout electronics. This is the topic of ongoing studies including the design and production of a new readout chip (DCD) [32] replacing the CURO readout chip [31]. However, readout speed and power consumption put limits to these efforts. The data used for this thesis was exclusively collected using the CURO readout chip (more below).

**Read out scheme and matrix operation**

As mentioned above the constrain on the readout for the first layer are severe due to the \( e^+e^- \) radiation background. Figure 2.4 shows the time structure of the TESLA ILC accelerator proposal. As the accelerator technology for the ILC will be superconducting the time structure will be close to the TESLA proposal. A readout in between the bunch trains is impossible because the occupancy per pixel in the first layer would be \( \approx 8\% \) just with single pixel hits and thus far above the allowed \( \approx 1\% \). A frame readout time of 50 µs would reduce the occupancy by a factor of 20 to \( \lesssim 0.5\% \). To achieve this speed the pixels are not read out sequentially but row wise (Fig. 2.5): The (external) gates of all DEPFET pixels in one row are connected to a steering ASIC\(^1\) (**SWITCHER**) and the drains of all DEPFET pixels in one column are connected to one input channel of the readout chip (**CURO**). The readout chip will then only sample the signals from that row that is switched on by the steering chip. The clear process is similar, all clear contacts of one row are connected to a clear SWITCHER. The volume of raw data generated inside the vertex detector would be too much to be transferred out of the vertex detector. Therefore two things will be implemented in the readout electronics:

1. **Zero suppression**: Signals below a tunable threshold will be discarded. Since hundreds of millions of pixels have to be read out several thousand times a second data reduction immediately after the sampling process is necessary

\(^1\)Application-Specific Integrated Circuit
2. **In-chip hit storage**: The detected hits will be stored on the readout chip and read out in between the bunch trains. The 0.2 seconds are ample time for data transfer. The readout is foreseen to be continuous without a trigger. Furthermore, to ease the speed constrains on the readout electronics, two rows are connected to the same switcher channel and are read out at once. This double row concept and the implementation of the matrix operations in the ILC DEPFET prototype system will be discussed below.

**Power consumption**

As stated above a material limit of $x/X_0 \approx 0.1\%$ means no (active) cooling system can be used inside the vertex detector. However, the power consumption of a DEPFET vertex detector will be very low. The DEPFET sensor itself is the first stage (i.e. the amplifier) of the readout electronics and an active pixel consumes $\approx 500 \mu W$ [17]. A ladder of the inner layer has 2048 active pixels at a time and a resulting power consumption of $\approx 1 W$. The switcher ASICs contribute with only 0.85 W since only 2 out of 32 switchers are active and those two have only one row active at a given time [17]. The main power consumer is the readout ASIC. The DCDI$^2$ needs 5 mW/channel and therefore 10.2 W are needed for all 2048 channels of layer one [17]. The outer layers are slightly wider and longer and produce 21 W per ladder. Table 2.3 gives a summary of these values. Two things are worth noting:

- Power dissipation is largely caused by the readout ASICs. These sit outside the active area and if unforeseen developments will drastically increase their power budget, some form of active cooling might still be feasible in the very far forward and backward region of the vertex detector.

- The total power consumption of the entire ILC DEPFET vertex detector as stated in table 2.3 is $\approx 1.3 kW$. However, it is foreseen that the detector is operated in a pulsed mode with the majority of the electronics virtually shut down during the 0.2 second long breaks in between the bunch trains (Fig. 2.4). This means that the power dissipation of the entire vertex detector will not exceed a few ten Watts.

<table>
<thead>
<tr>
<th>layer</th>
<th>ladders</th>
<th>active rows</th>
<th>columns</th>
<th>power/ladder</th>
<th>power/layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>2</td>
<td>1024</td>
<td>12W</td>
<td>96W</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>2</td>
<td>1535</td>
<td>21W</td>
<td>168W</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>2</td>
<td>1536</td>
<td>21W</td>
<td>252W</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>2</td>
<td>1536</td>
<td>21W</td>
<td>336W</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>2</td>
<td>1536</td>
<td>21W</td>
<td>420W</td>
</tr>
<tr>
<td>all</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1272W</td>
</tr>
</tbody>
</table>

*Table 2.3: Power dissipation per layer. The total power is 1272W, however, with the ILC duty cycle of 1/200 this is reduced to 6.4W [17].*

$^2$DEPFET Current Digitizer
Material budget

With a DEPFET vertex detector operated in a pulsed mode the power dissipation and therefore heat production is low enough to rely on air flow cooling only. However, even without cooling pipes the targeted goal of \( x/X_0 \approx 0.1\% \) is very demanding and can only be fulfilled by using thinned down sensors. In the DEPFET concept (the cross section is shown in fig. 2.3) the silicon of the active area is thinned down to \( \approx 50 \mu m \) with the area under the steering and readout chips left at \( 450 \mu m \) silicon. Furthermore a few parts of the wafer will also be left out of the thinning process, thus building a frame giving mechanical stability to the module. The principle feasibility of the thinning process has already been shown with diodes [33]. The switcher ASICs which are also inside the area sensitive to multiple scattering need to be thinned down to \( \approx 50 \mu m \) as well. An additional contribution comes from the gold bumps used for the flip chip bump bonding of the ASICs onto the silicon frame. Table 2.4 shows a summary of the contributors to the material budget. With a thinned down sensor the \( x/X_0 \approx 0.1\% \) is well in reach.

<table>
<thead>
<tr>
<th>component</th>
<th>material</th>
<th>( X_0 ) cm</th>
<th>area mm(^2)</th>
<th>thickness ( \mu m )</th>
<th>equivalent thickness ( \mu m )</th>
<th>( %X_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensor</td>
<td>Si</td>
<td>9.36</td>
<td>13 \times 100</td>
<td>50</td>
<td>50</td>
<td>0.05</td>
</tr>
<tr>
<td>frame</td>
<td>Si</td>
<td>9.36</td>
<td>2 \times 100</td>
<td>450</td>
<td>45</td>
<td>0.05</td>
</tr>
<tr>
<td>Switcher</td>
<td>Si</td>
<td>9.36</td>
<td>3 \times 100</td>
<td>50</td>
<td>11.5</td>
<td>0.01</td>
</tr>
<tr>
<td>gold bumps</td>
<td>Au</td>
<td>0.33</td>
<td></td>
<td></td>
<td>0.46</td>
<td>0.01</td>
</tr>
<tr>
<td>all</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
</tr>
</tbody>
</table>

*Table 2.4: Material breakdown of the proposed ILC module (innermost layer module). "Equivalent thickness" is the material normalized to the sensitive area of \( 13 \times 100 \text{ mm}^2 \). The gold bumps (gate and clear per line, service bumps for switcher) have a diameter of 48\( \mu m \) [17].*

2.2 The DEPFET prototype system for the ILC

With the ILC specification in mind the first iteration of a prototype system with a 64 by 128 pixel DEPFET matrix was built in 2005 [34, 35, 36, 37, 38]. Since then the system has been continually improved and tested in both lab and test beams [39, 40, 41]. Furthermore, it has successfully been used in cooperation with the EUDET project [42, 43, 44]. Figure 2.6 shows a picture of the system which consists of two main parts:

- A **hybrid PCB**: This board contains the actual DEPFET sensor matrix, two steering ASICs (SWITCHER), and the readout ASIC (CURO). Furthermore two transimpedance amplifiers convert the currents form the CURO (explained below) to voltages for the ADCs\(^4\) on the DAQ board. The name *hybrid* was chosen since the DEPFET is not a true monolithic active sensor, but needs ASICs to be operated.

---

\(^3\)Printed Circuit Board  
\(^4\)Analog-to-Digital Converter
• **A DAQ**\(^5\) **PCB**: The DAQ board holds two ADCs, a FPGA\(^6\), a RAM, and a USB to PC communication interface. As already specified by its name, this board is responsible for the data acquisition, i.e. steering the ASICs and (pre)processing incoming data.

In the following the most important components and their interplay with the DEPFET matrix operation will be elucidated.

![Diagram of DEPFET matrix](image)

**Figure 2.5**: The operation of a DEPFET matrix: The pixels are read out row wise. The gates of all pixels in one row are connected to a channel of a steering ASIC (**GATE SWITCHER**). Similar the clear contacts of this row are connected to another ASIC (**CLEAR SWITCHER**). The drains of each column are connected to a channel of the readout ASIC (**CURO**). The rows are read out sequentially in the following fashion: The according row is switched on by the GATE switcher and the current is sampled by the CURO. Then the CLEAR switcher removes the signal (and leakage current) electrons in this row and the CURO samples the pedestal current of the row.

**DEPFET matrix**

The DEPFET matrices used for this thesis are all part of the PXD5 sensor batch. Figure 2.7 shows the wafer layout of this production batch. This is the second of

\(^5\)Data ACquisition \(^6\)Field-Programmable Gate Array
ILC oriented DEPFET pixel design runs. The first run PXD4 has already been operated very successfully both in the laboratory as well as in test beam experiments [34, 35, 36, 37, 38, 39, 40, 41]. Among other things the new PXD5 run contains DEPFET matrices with 64 x 128, 128 x 128, 512 x 512, and 2048 x 128 pixels (length of an ILC
2. THE ILC PROTOTYPE SYSTEM

Figure 2.7: The layout of the PXD5 wafer: This run contains matrices with 64 x 128, 128 x 128, 128 x 2048, and 512 x 512 pixel as indicated in the figure. Other structures are for specific tests, single pixel setups, etc. The data in this thesis is solely gathered with 64 by 128 pixel matrices. However, the newest generation (as of 2010) of DEPFET DAQ and Hybrid boards can handle 128 x 128 pixel matrices.

module/half ladder). The data in this thesis is solely gathered with 64 by 128 pixel matrices with an older DAQ system. However, the newest generation (as of 2010) of DEPFET DAQ and Hybrid boards can handle 128 x 128 pixel matrices. While there are a few matrices on the PDX5 board which have still the old PXD4 layout ("REC small") for comparison measurements, the majority of the pixels have complete new and improved layouts. Some of these layouts will be explained in more detail in the next chapter together with the test beam setup.

Medium and high E implantations: A novelty in the PXD5 production is the so-called medium E implantation. In the last generation of DEPFET pixels, the PXD4 production, a global high energy implantation was applied at the beginning of the manufacturing process. The additional $n^+$ layer at $z \approx 1.2 \mu m$ depth moves the internal gate deeper to $\approx 1 \mu m$ instead of $\approx 0.6 \mu m$ [18, 45]. This makes the clear process much easier but has the disadvantage of reducing the internal amplification $g_q$ by $\approx 30\%$. For the PXD5 run this high energy implantation was replaced by a medium energy implantation with the idea of finding a compromise between clear efficiency and first stage amplification.
With medium E the \( n^+ \) implantation is at a depth of \( z \approx 0.6 \mu m \).

Bias voltages and the sampling sequence

Figure 2.8: The general sampling sequence for a DEPFET pixel as foreseen for the ILC: The GATE switcher turns all DEPFET transistors in a row on. Then the readout chip samples the signal and the pedestal current \( I_{\text{sig}} + I_{\text{ped}} \). After a clear pulse is applied and the electrons are removed the remaining pedestal current is sampled. Note that in this sampling sequence the leakage current \( I_{\text{leakage}} \) is part of the signal current \( I_{\text{sig}} \). Furthermore the actual sampling sequence for the CURO is somewhat different as will be explained in the CURO description.

The drain current of DEPFET \( I_{\text{total}} \) consists not only of a signal \( I_{\text{sig}} \) but also of a pedestal current \( I_{\text{ped}} \). \( I_{\text{ped}} \) is the current of a DEPFET transistor with a given gate voltage \( V_{\text{ON\_gate}} \) and an empty internal gate. In addition there will be a current \( I_{\text{leakage}} \) caused by electrons from the leakage current integrated since the last clear process. In the ILC concept the current of a row will be sampled twice with a clear pulse in between (Figure 2.8). The first current sampled will thus contain \( I_{\text{sig}} + I_{\text{ped}} + I_{\text{leakage}} \) where as the second sample contains only the pedestal \( I_{\text{ped}} \). The two dynamic voltages GATE and CLEAR are switched by the corresponding ASIC between the voltages \( \text{Gate\_ON} \) and \( \text{Gate\_OFF} \) and \( \text{Clear\_HIGH} \) and \( \text{Clear\_LOW} \), respectively. The double sampling and the subtraction of pedestal current will be done on-chip inside CURO.

The double pixel and double row structure

The DEPFET pixels have a double pixel layout as sketched in figure 2.9. This serves two goals:

- **Double row read out:** To ease the speed constraint on the readout electronics two rows are read out at once, i.e. each SWITCHER channel is connected to two rows. Hence, the drains of one matrix column are alternately connected to two CURO input channels.
2. THE ILC PROTOTYPE SYSTEM

Figure 2.9: Schematic of a ILC DEPFET double pixel. To increase the readout speed and to reduce the pixel size every SWITCHER channel is connected to two pixels. These pixels share a common source but have two different drains, each connected to a different CURO input channel. This means a Gate\textsubscript{ON} signal from the switcher is applied to a double row, and accordingly the CURO will sample two rows with each sample signal. Hence the readout speed is doubled.

- Common source: The pixel pairs connected to different curo channels share a common source. Thus two pixels are combined to one double pixel cell allowing for a smaller pixel size.

SWITCHER

The Switcher2 ASIC has been designed in 2002 in 0.8 $\mu$m high voltage technology and is able to drive voltage swings of up to 25 V. Each Switcher2 has 2x 64 output channels to drive 64 gate/128 rows. It has a simple on-chip sequencer and can be operated in a daisy chain mode. The chip also allows to bypass the internal sequencer and to steer the channels externally. The ILC prototype system makes exclusive use of the latter option. The range of the voltage swing of the switcher2 is limited by its lower and upper analog supply voltages $AVSS$ and $AVDD$. The digital ground level and the polarity of the switching voltages are adjustable. There are however some caveats when powering up the chip: At no time must any steering voltage (i.e. gate and clear) be outside the boundaries given by $AVSS$ and $AVDD$. To prevent this and other unintended misapplied voltages destroying the chip a protection board was added to the prototype system after a few month of operational experience. The Switcher2 was successfully used in all test
2.2. THE DEPFET PROTOTYPE SYSTEM FOR THE ILC

beam and lab experiments until 2009 when it was replace by the Switcher3. Among other reasons the replacement was necessary, because - unlike Switcher2 - the new Switcher3 is made in a more radiation tolerant technology using thinner gate oxides [32]. A detailed description of the Switcher2 can be found in [46].

CURO

The readout chip CURO 2 (CUrrent ROut) was designed in 2003 [31] and manufactured in a - intrinsically radiation hard - 0.25 \( \mu \text{m} \) process. It is specifically targeted at the ILC concept. Figure 2.10 shows an overview. The chip is operated with two signals:

- **Write signal WRT**: The write signal controls the analog current sampling, i.e. when a current is written into current memory cells. The WRT is level sensitive: The current \( I_{\text{sig}} + I_{\text{ped}} \) is sampled on logic high into an auxiliary storage cell, whereas \( I_{\text{ped}} \) is sampled on logic low. During the low phase the \( I_{\text{ped}} \) is subtracted from \( I_{\text{sig}} + I_{\text{ped}} \) and the remaining signal is stored in one of two alternating buffer cells. With the next WRT the content of the current buffer is written to an analog FIFO. The following WRT will then override the corresponding current buffer cell, but only in the low phase. During the high phase of the third write clock cycle and while \( I_{\text{sig}} + I_{\text{ped}} \) are stored in the auxiliary buffer, the current of the alternating buffer is compared to a channel specific threshold and the result is written to the digital counterpart of the analog FIFO (on-chip zero suppression). Unfortunately this write clock operation scheme has the disadvantage of neglecting the time needed to remove the signals from the DEPFET cell, i.e. it ignores the duration of the clear pulse. This leads to the problem that the pixel is cleared during the \( I_{\text{ped}} \) sampling (WRT is low) and therefore the sampling procedure and correspondingly the readout speed must be much slower than anticipated (see [22] for details).

- **Scan signal SCN**: The scan signal controls the hit scanner, a fast binary back propagating tree search that writes up to two hits per SCN including their addresses into a designated on-chip hit ram. If there are more than two hits in one FIFO row correspondingly more SCN cycles are needed to process the hits. Therefore for the ILC the SCN is targeted to work at a higher speed (40 MHz) than the WRT (20 MHz) and in addition a derandomizing FIFO with a depth of up to eight rows is foreseen. Simulations have shown that this combination is sufficient to handle the expected inner layer occupancy of a DEPFET ILC vertex detector without any dead time [31]. However, in the CURO 2 chip the analog FIFO was only implemented as a proof of principle with a depth of only one row. Further the CURO 2 possesses two current outputs. If with a scan clock one or two hits are found the currents stored in the according analog FIFO cells are multiplexed out. Although it has been shown that the zero suppression works in principle [22], the CURO is usually only operated in a fully analog, non zero-suppressed mode, because having access to the full analog information is necessary to study the various DEPFET types in detail. This is achieved by writing a “all hits” test pattern to the hit scanner and ignoring the results of the comparators. With 64 SCN cycles the currents of one row are then multiplexed out. Naturally the fully analog readout mode is much slower than...
Figure 2.10: Schematic overview of the CURO building blocks. The analog part of the chip works entirely with current signals. For clarity only one out of 128 input channels is shown. It contains a regulated cascode and a pedestal subtraction unit. Furthermore two alternate current buffers help increase the readout speed. A mixed analog signal and digital hit information FIFO stores the current and a comparator results for each input channel. The depth of the analog part of the mixed signal FIFO is only one for CURO 2, which limits the zero suppression capabilities of the ASIC. The digital part contains a hit finder with parallel tree search structure, a HIT RAM, and a output multiplexer. Extensive details on the chip and its performance can be found in [31, 22].
2.2. THE DEPFET PROTOTYPE SYSTEM FOR THE ILC

the non zero-suppressed mode with the main time consumed by multiplexing each SCN two \( I_{\text{sig}} \) currents out.

A thorough study of the CURO2 performance with and without zero suppression can be found in [22]. In the final ILC design the two signals, SCN and WRT, are planned to run as a continuous clock, i.e. the system is operated in a triggerless readout mode.

Data acquisition chain

There are two transimpedance amplifiers (AD8015) on the Hybrid PCB, one for each analog CURO output where the single ended current from the CURO is converted to a differential voltage signal. To minimize stray capacitance they are in die (non package) form and are - like the DEPFET matrix and the ASICs - wire bonded. The hybrid PCB is connected to a DAQ board with a flat ribbon cable. On the DAQ board are two differential 14 bit ADCs, one for each CURO output channel. Their digital output is fed into a Spartan 3 FPGA which houses the main DAQ control unit, a programmable sequencer, as well as logic for the initialization and configuration of the ASICs, clock management, ADC and SRAM control, processing of CURO hit data, and handling of trigger and busy signal for test beam applications (details in the next chapter). The sequencer is programmed in such a fashion that enables the DAQ to be triggered externally while running in a so-called rolling shutter mode. The digitized signals from the ADCs are stored inside a 256 kB SRAM onboard of the DAQ PCB. This is enough memory for 16 consecutive, fully read out matrix frames. Once the memory is full, data taking is paused and the data is transferred to a PC via a USB interface.

Rolling shutter mode:

Since the system was designed as an ILC prototype system it was also designed to be run without a trigger. However, for laser measurements in the laboratory as well as for test beam measurements a triggered readout is desired. Therefore, a triggered, quasi continuous readout scheme, the rolling shutter mode was implemented. Figure 2.11 shows a simplified version of the rolling shutter sequence:

- Initially the system waits for a trigger input while continuously clearing the matrix. Without perpetually clearing the matrix the electrons generated by the leakage current would flood the internal gate rendering it insensitive. In this sequencer loop the time between to clears is small (7.7\( \mu s \)) and the DEPFET pixels can be seen void of any signal (and leakage current) electrons.

- When a trigger signal arrives the sequencer jumps to the actual readout sequence. Each row is sampled according to the specification for a non zero-suppressing CURO (i.e., one slow WRT signal for sampling and two faster WRT pulses for transferring the currents to the FIFO). Then the values for this row which are now stored in the analog FIFO must be multiplexed out of the CURO with 64 SCN pulses. Then the next row is processed.
### Figure 2.11: A simplified version of a DEPFET readout program for the sequencer implemented inside the FPGA of the DAQ board. The four columns denote the general activity of the sequencer, the CLEAR pulse (actually a switcher clock), and the write and scan clock of the CURO, the brackets and the according text boxes explain the main sections of the program. While the system is waiting for a readout trigger the matrix is continuously cleared (top most loop). If a trigger is signaled the sequencer jumps to the readout sequence where each row is sampled and than multiplexed out with 64 SCN cycles. Since there are 64 double rows this has to happen 64 times. The total time it takes to read out an entire matrix depends on the actual programming and is a compromise between readout speed and signal to noise.

- When the matrix has been read out completely the sequencer jumps to the beginning of the program thus starting with the continuous clearing of the matrix. If however the RAM on the DAQ board is full, i.e. after 16 triggers, the sequencer is stopped and data transfer to a PC is commenced.

The length of the readout depends on the actual sequence, e.g. on the duration of the CURO current sample, as is indicated in figure 2.11.
2.2. **THE DEPFET PROTOTYPE SYSTEM FOR THE ILC**

<table>
<thead>
<tr>
<th>name</th>
<th>description</th>
<th>[V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWITCHER 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVDD</td>
<td>analog supply</td>
<td>23</td>
</tr>
<tr>
<td>AVSS</td>
<td>analog supply</td>
<td>-0.5</td>
</tr>
<tr>
<td>VA HI</td>
<td>Clear HIGH</td>
<td>22</td>
</tr>
<tr>
<td>VA LO</td>
<td>Clear LOW</td>
<td>7 - 9</td>
</tr>
<tr>
<td>VB HI/LO</td>
<td>common clear gate</td>
<td>6 - 8</td>
</tr>
<tr>
<td>DVDD*</td>
<td>digital supply</td>
<td>5</td>
</tr>
<tr>
<td>sensor static</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BULK</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>SOURCE</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>BP</td>
<td>backplane depletion</td>
<td>-200</td>
</tr>
<tr>
<td>^ voltage can be produced by protection board</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>name</th>
<th>description</th>
<th>[V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWITCHER 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVDD</td>
<td>analog supply</td>
<td>22</td>
</tr>
<tr>
<td>AVSS</td>
<td>Analog supply GND</td>
<td>-0.5</td>
</tr>
<tr>
<td>VA HI</td>
<td>Gate OFF</td>
<td>15</td>
</tr>
<tr>
<td>VA LO</td>
<td>Gate ON</td>
<td>3</td>
</tr>
<tr>
<td>VB HI/LO</td>
<td>common clear gate</td>
<td></td>
</tr>
<tr>
<td>DVDD*</td>
<td>digital supply</td>
<td>5</td>
</tr>
<tr>
<td>CURO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVDD*</td>
<td>analog supply</td>
<td>2.5</td>
</tr>
<tr>
<td>DVDD*</td>
<td>digital supply</td>
<td>2.5</td>
</tr>
<tr>
<td>Proteccion Board</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DVDD_S1</td>
<td></td>
<td>5.5</td>
</tr>
</tbody>
</table>

* voltage can be produced by protection board

**Figure 2.12:** This is an overview over all voltages needed to operate one DEPFET-ILC prototype system. All voltages are referenced to ground GND.

**Powering scheme**

As has been mentioned before the ASICs are sensitive to wrong biasing. Furthermore, a rather large number of voltages is needed to operate the DEPFET prototype system for the ILC vertex detector. Therefore a designated add-on board for the DAQ system has been issued to protect the ASICs from misapplied voltages and to reduce the number of required power supplies. Figure 2.12 shows a table of all voltages needed to operate one DEPFET-ILC prototype system. The protection board clamps the analog steering voltages (GATE and CLEAR) between the analog supply voltages of the SWITCHER2 (AVSS and AVDD). Although it is possible to generate some of the supply voltages on the protection board this option is usually dismissed, because unlike most laboratory power supplies the protection board possesses no current limit settings. Setting the right current limit can be crucial for operating the DEPFET system especially for the start up proceedings. When operating multiple DEPFET systems the amount of lab power supplies and the complexity of the system can, especially in test beam environments, be very demanding. A test beam, conducted in 2007, did not produce data partly because of this. As a result of these problems and the experience of the test beams of 2007 and 2008 (see next chapter) a dedicated power supply for the DEPFET ILC prototype system was developed in 2009 [21]. For the test beam in 2008 this power supply however came unfortunately to late.
2. THE ILC PROTOTYPE SYSTEM