ENTWICKLUNGSSTUDIEN FÜR
EINE ZEIT-PROJEKTIONSKAMMER AM
INTERNATIONAL LINEAR COLLIDER (ILC)

Jochen Kaminski

Zur Erlangung des akademischen Grades eines
DOKTORS DER NATURWISSENSCHAFTEN
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von

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aus Dortmund

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Referent: Prof. Dr. Thomas Müller, Institut für Experimentelle Kernphysik
Korrevent: Prof. Dr. Wim de Boer, Institut für Experimentelle Kernphysik
Für Barbara und Karl Domenico
Dass ich erkenne, was die Welt
Im Innersten zusammenhält.

[Goethe]
Deutsche Zusammenfassung


Aufgrund des umfangreichen Physikprogrammes werden höchste Anforderungen an den Detektor und alle seine Komponenten gestellt. So muss z.B. der zentrale Spurdetektor eine Impulsauflösung von $\frac{dE}{dx} \leq 1.4 \times 10^{-4}$ (GeV/eV)$^{-1}$ ermöglichen. Desweiteren sind ausgezeichnete Ortsauflösung und gute Teilchenidentifizierung gefordert.


Bisher verwendete TPCs wurden mit Vielrahrtkammern ausgelesen und hatten nach jedem aufgezeichneten Ereignis eine längere Totzeit, um die bei der Gasverstärkung entstandenen Ionen zu neutralisieren. Da die zeitliche Strahlstruktur des ILC dieses Vorgehen nicht zulässt, soll die Zeit-Projektionskammer mit Hilfe mehrerer *Gas Electron Multiplier* (GEM) ausgelesen werden. Eine GEM besteht aus einem dünnen Isolator (Kapton), der auf beiden Seiten mit
Zusammenfassung


Um Detektoren in einer realistischen Umgebung zu testen, wurde am DESY in einen supraleitenden Solenoidmagnet eingebaut und mit der im Technical Design Report von TESLA vorgeschlagenen Gasmischung Ar(CH$_3$)$_2$CO$_2$ (93:5:2) betrieben. Das Detektorverhalten wurde in magnetischen Feldern bis zu 5 T mit Teilchenspuren von kosmischer Höhenstrahlung getestet. Dabei wurde der Einfluß verschiedener starker Magnetfelder und weiterer Parameter auf Diffusion und Ortsauflösungsvermögen der TPC untersucht (siehe Abb. 1c). Es wurde beobachtet, dass die Rekonstruktion der einzelnen Spurpunkte mit Hilfe der Schwerpunkt-
Zusammenfassung

Abbildung 1: a) Prototypdetektor, b) Driftgeschwindigkeit von Elektronen in verschiedenen Gasmischungen in Abhängigkeit des elektrischen Feldes, c) transversale Ortsauflösung in Abhängigkeit des magnetischen Feldes und der Driftstrecke.

Bestimmung unzulänglich ist. Deshalb wurde ein verbessertes Modell entwickelt, der insbesondere bei kleinen Ladungsausdehnungen, wie sie in hohen magnetischen Feldern und bei kurzen Driftstrecken auftreten, deutlich genauere Ergebnisse liefert. Damit konnte in einem magnetischen Feld von \( B = 4 \) T für Spuren mit geringer Neigung Ortsauflösungen von \( 46 \pm 1 \) \( \mu m \) gemessen werden. Die Impulsauflösung \( \frac{\Delta p}{p} \) ist ungefähr 5 mal schlechter als erwartet. Diese Verschlechterung konnte mit Hilfe von magnetischen Feldverzerrungen erklärt werden.

Um den Einfluss verschiedener Parameter genauer untersuchen zu können, wurde das Verhalten des Detektors am CERN mit einem hadronischen Teststrahl ohne Magnetfeld untersucht. Protonen, Pionen und Elektronen mit Energien zwischen 3 GeV und 9 GeV wurden benutzt, um eine hohe Anzahl von parallelen Spuren zu erzeugen. In Abb. 2a ist die graphische Darstellung eines Ausleseyzyklus mit 29 Spuren zu sehen. Während des Teststrahles wurden drei verschiedene Gasmischungen verwendet, die sich vor allem in Driftgeschwindigkeit und Diffusionskoeffizienten unterscheiden: Ar:CO\(_2\) (70:30) - niedrige Diffusion und Driftgeschwindigkeit; Ar-CH\(_3\):CO\(_2\) (93:5:2) - mittlere Diffusion und hohe Driftgeschwindigkeit; Ar-CH\(_4\) (95:5) - hohe Diffusion und Driftgeschwindigkeit. In allen drei Fällen wurde die Ortsauflösung in Abhängigkeit von Cluster- und Spureneigenschaften untersucht. Auch hier konnte im Falle geringer Diffusion eine sehr gute Ortsauflösung von \( 52.6 \pm 0.9 \) \( \mu m \) erzielt werden. Mit Hilfe eines einfachen Modells wurden die Messresultate auf das Verhalten in dem ILC-Detektor extrapoliert, und es wurde gezeigt, dass die Vorgaben des TESLA-TDRs erreicht werden können. Mit 10 cm langen Spurausschnitten des monoenergetischen Teststrahles wurden desweiteren Untersuchungen zur Energieauflösung \( \frac{\Delta E}{E} \approx 18 \% \) und Impulsauflösung \( \frac{\Delta p}{p} \) gemacht. Aufgrund der hohen Teilchenrate konnten außerdem Experimente zu Ionenrückdrift durchgeführt.

Zusammenfassung

Abbildung 2: a) Auslesezyklus mit 29 Spuren, b) Padgeometrien, die während des Teststrahles am DESY untersucht wurden, c) transversale Ortsauflösung der rechteckigen Pads, bei denen jede 2. Reihe verschoben ist.


DEVELOPING STUDIES FOR
A TIME PROJECTION CHAMBER AT THE
INTERNATIONAL LINEAR COLLIDER (ILC)

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Abstract

The International Linear Collider (ILC) is a future electron-positron collider project with a center-of-mass energy range from 91 GeV to 1 TeV. The vast physics program of this accelerator stretches from precision measurements of electroweak parameters at the Z pole to the search for new particles at the highest possible energies. Because of the excellent signal-to-background ratio, the high luminosity and the well-known initial states, detailed studies on many parameters are possible. For example the mass of the Higgs particle can be measured with a precision of around 30 MeV independent of the decay channels.

This puts stringent requirements on the performance of the main tracking device such as high granularity and homogeneity of the sensitive volume, good momentum and spatial resolution, good multi-track separation, precise measurement of the specific ionization $dE/dx$ and a minimum amount of material. A time projection chamber (TPC) with a wire-based readout fulfills most of these requirements. However, the long dead times needed for neutralizing ions generated in the gas amplification stages prevent an efficient use of this detector type. In contrast, Gas Electron Multipliers (GEM) have an intrinsic ion feedback suppression of down to 0.2%, making possible a continuous running mode. In addition GEMs have many features which are favorable for use in a TPC. For example, the small pitch between areas of gas amplification improve the spatial resolution and minimizes $E \times B$ effects.

In order to study the combination of a TPC with a GEM-based readout with a view to an ILC-detector, a small cylindrical prototype was designed and constructed. Special attention was given to achieve a maximum degree of flexibility, good electric field homogeneity and to avoiding outgassing of any material. Equipped with two Gas Electron Multipliers (GEMs) and front-end electronics similar to those used in the TPC of the STAR experiment (Brookhaven, USA), this detector has been operated successfully in a number of different environments. Initial tests were performed with different radioactive sources and cosmic rays in the Karlsruhe laboratory. Here the performance of the prototype detector was evaluated, for example, by comparing the drift velocity and the diffusion coefficient with calculations from the MAGBOLTZ program. Good agreement was found.

To study the tracking performance of the detector under real operational conditions, the detector was tested in high magnetic fields of up to 5 T at DESY. For this study cosmic rays were used to generate particle tracks in the sensitive volume and detector properties such as spatial resolution, energy and momentum resolution were determined.

High-rate hadronic particle beams pose a special challenge for the reliability of a detector. Therefore, the prototype was operated for 4 weeks in hadronic beams at the Proton Synchrotron of CERN. A large amount of statistics was collected and different gas mixtures were studied. Excellent single-pad-row efficiencies and spatial resolutions were demonstrated already at moderate gas gains.

Finally, further improvements of the transverse spatial resolution in low-diffusion condi-
Abstract

tions were achieved by optimizing the geometry of the micro-pads. Seven different micro-pad geometries, including as rectangular pads, chevron and diamond shaped pads, were designed and tested with a theoretical model, a Monte Carlo simulation and, after construction, in a test beam. The experimental study was conducted at DESY, where a test beam with 6 GeV electrons and a 1.0 T magnetic field can be simultaneously used. The best pad geometry was found to be rectangular pads with every second row shifted by one-half the pitch.

All studies showed that the combination of a TPC with a GEM-based readout works reliably and the results are within expectations. It was shown that all requirements stated in the TESLA technical design report can be achieved with rectangular pads of $1.27 \times 12.5$ mm$^2$ in size.
Chapter 1

Introduction

During the last decades a coherent picture of sub-nuclear physics has emerged. An intense interplay between experimental and theoretical progress has led to numerous discoveries, and a theory describing most processes, the Standard Model of Particle Physics (see Fig. 1.1), was formulated.

According to this theory, the 12 fundamental constituents of matter are grouped into two classes of particles, leptons and quarks, with three generations each. The three generations differ only with respect to the masses of their particles. Since the more-massive particles of the second and third generations decay into particles of the first generation, the latter make

![Table of Particles](image)

Figure 1.1: Standard Model of Particle Physics [Co99p].
up all the known normal matter. Interactions between the fundamental particles take place via four forces: gravity, electromagnetism, weak force and strong force, which are mediated by different bosons. While gravity and the weak force act upon all particles, the gluons of the strong force couple only to quarks, while the photon, mediator of the electromagnetic force, couples to charged particles.

To date, no experimental contradictions to the Standard Model have been found. Nevertheless, it is clear that the Standard Model is not an all-embracing theory, but leaves several questions unanswered:

1. Why are there three generations?
2. Can the four forces be unified to a single fundamental force?
3. What mechanism determines the masses of all the particles?
4. What is the reason for the matter-antimatter asymmetry in the universe?
5. What does the dark matter in the universe consist of?

To answer these questions, different theoretical models such as supersymmetry, extra dimensions or string theory have been developed. To verify any one of these theories, and to restrict its parameter space, new experimental tests are under way. At CERN\(^1\) the Large Hadron Collider (LHC) will be commissioned in 2007; it will bring two proton beams to collision. Because of the high center-of-mass energy of 14 TeV, the LHC will have a large discovery potential and many new particles expected in these models should be found. A complementary project, the International Linear Collider (ILC), is currently being designed, and commissioning is planned for the year 2015. In it, electrons and positrons will be accelerated to energies of up to 500 GeV. For reasons stated in the next section, the accelerator will be an ideal tool for precision measurements. In the following, a short overview of the ILC physics program, the accelerator layout and the detector will be given.

1.1 Physics at the International Linear Collider

The Linear Collider has a number of desirable features that facilitate the precise study of new physics processes [Am01p]:

- The production cross sections of interesting Standard Model or exotic physics processes are at most 3 orders of magnitude smaller than the total cross section (see Fig. 1.2) resulting in a high signal-to-background ratio, if suitable selection requirements are introduced.

- The initial state of all processes has a simple two-body kinematics, well-known total energy and momentum, and defined quantum numbers.

- The cross sections of most processes can be predicted theoretically to part-per-mil accuracy, since they are based on electroweak processes.

- Electron and positron beams can be polarization, giving an additional handle with which to suppress undesirable background.
Cross sections

![Cross sections diagram](image)

\[ \sqrt{s} \text{ (GeV)} \]

Figure 1.2: cross section for a variety of physics processes at ILC [Am01p].

The physics reach of the ILC is described in references [A1011p, Am01p], and in the following subsections some of the main physics processes are discussed.

### 1.1.1 Higgs Boson

The Higgs mechanism is the last part of the Standard Model which has not yet been confirmed experimentally. It is responsible for breaking the electroweak symmetry and for giving mass to the W and Z bosons. The Higgs mechanism also predicts an additional particle, the Higgs boson, which has not yet been discovered. Even though the mass of the Higgs boson (\(H\)) can not be predicted from the Standard Model, global fits to all precision electroweak data give \(m_H = 126_{-48}^{+73} \text{ GeV}\) and require that the Higgs boson has a mass below 280 GeV (95% CL)(see Fig. 1.3a and reference [Le04p]). The four experiments at the Large Electron Positron Collider LEP2 at CERN excluded masses up to 114.4 GeV [Le03p], but gave a tantalizing hint of a Higgs signal at a mass of 115 MeV [Le03p].

If discovered, the properties of the Higgs boson can be measured at the ILC in great detail,

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Figure 1.3: a) $\Delta \chi^2 = \chi^2 - \chi_{\text{min}}^2$ versus $m_H$. The solid line is the result of the fit using all data; the band represents an estimate of the theoretical error due to missing higher order corrections [Lo04]. b) The two main production channels at the ILC, c) dependence of Higgs production cross section on $M_H$ for $\sqrt{s} = 350$ GeV, 500 GeV and 800 GeV [Ag01].

since a large number of Higgs particles will be produced ($\mathcal{O}(10^5)$ per year, Higgs factory). The main production channels are the Higgs-strahlung process $e^+e^- \rightarrow Z^* \rightarrow ZH$ and the $WW$ fusion process $e^+e^- \rightarrow W^*W^* \rightarrow \nu\bar{\nu}H$ (Feynman graphs see Fig. 1.3b). The production cross sections of these processes are given for various center-of-mass energies in Fig. 1.3c. The Higgs-strahlung process also gives a very distinct decay signature if the $Z$ boson decays into two leptons $e^+e^- \rightarrow Z^* \rightarrow ZH \rightarrow l^+l^-X$. By studying the recoil mass spectrum of the two leptons only, a very precise determination of the Higgs mass of down to 110 MeV is possible, even if it decays predominantly in invisible particles (see Fig. 1.4a). Since this method does not require a reconstruction of the Higgs particle, it allows an absolute measurement of the cross section $e^+e^- \rightarrow ZH$ and hence also of the coupling of $H$ to $Z$. This tests whether only the observed Standard Model Higgs boson generates the mass of the $Z$, or whether heavier bosons suggested by theories beyond the Standard Model contribute to the $Z$ mass. These heavier Higgs bosons will also appear in the spectrum of the recoil mass. For specific decay channels, such as $H \rightarrow b\bar{b}$, a precision of 50 MeV can be achieved.

The branching ratio and the partial decay widths of various decay channels are also important tests of the Standard Model, since summing over all partial decay widths and comparing the result to the total decay width (see Fig. 1.4c) gives information about the existence of undiscovered particles. Because the coupling to massive fermions is proportional to the mass of the respective particle, the branching ratios are predefined. The ILC can determine these branching ratios with uncertainties of a few percent (see Fig. 1.4b), and any deviations from these ratios could also indicate new physics beyond the Standard Model.

Finally, the spin and CP eigenvalues of the Higgs particle can be determined. In addition, the Higgs trilinear coupling can be measured with an uncertainty of 20%.

1.1.2 Electroweak Gauge Bosons

The electroweak interaction is a central part of the Standard Model and a precise determination of the electroweak parameters has led to a confirmation of the theory as well as to a prediction of the top-quark mass. Further precision measurements and tests of the theory can be performed at the ILC. For example an energy scan at the $WW$ production threshold with a
polarized electron and positron beam will reduce the uncertainty of the \( W \) mass to \( \Delta m_W = 6 \) MeV (see Fig. 1.5a). The \( WW \) production (Feynman graphs of Fig. 1.5b.i-iii) decreases with \( 1/s \) for higher energies, while the single \( W \) production increases (see Feynman graphs see Figs. 1.5b.iv and Fig. 1.6a). The high degree of polarization is an especially powerful tool to suppress background processes and to enhance or suppress either one of the four main production channels. All of these production processes are sensitive to triple-gauge couplings \( WWV \) with \( V = Z, \gamma \), and the real parts of these couplings \( \kappa_V , \lambda_V \) can be measured with a precision in the order of \( 10^{-4} \) (see Fig. 1.6b).

Figure 1.4: a) Results of a Monte Carlo simulation: \( \mu^+ \mu^- \) recoil-mass distribution on the Higgs-strahlung process (\( M_H = 120 \) GeV, \( \sqrt{s} = 350 \) GeV and \( \mathcal{L} = 500 \) fb\(^{-1} \) [Ag01p], b) Determination of Higgs boson branching ratios in a variety of channels. (The bands show the theoretical errors in the Standard Model prediction.) [Am01p], c) total decay width of the Standard Model Higgs boson as a function of its mass [Ag01p].

Figure 1.5: a) Monte Carlo simulation of sensitivity of the \( W \)-production at threshold to the \( W \)-mass: \( y \)-axis is the ratio of ‘measured’ cross section over the predicted cross section [Ag01p]. b) The four main production channels of \( W \) bosons: i) \( WW \) via \( \nu \)-exchange in \( t \)-channel, ii) \( WW \)-production via \( \gamma \) in \( s \)-channel, iii) \( WW \)-production via \( Z \) in \( s \)-channel, iv) \( W\nu\bar{\nu} \)-production via \( W \gamma \)-fusion.
Figure 1.6: a) Dependence of $W$ production cross section on the center-of-mass energy \cite{Ag01p}, b) measurement of coupling parameter $\Delta \kappa$, at different accelerators \cite{Ag01p}, c) dependence of $\Delta \chi^2$ on the Higgs mass with precision data collected in the year 2000 and after Giga-Z \cite{Ag01p}.

With a Giga-Z option, an operation mode where a high statistics of $Z$ decays is studied at a center-of-mass energy of 91 GeV (see Section 1.2), the ILC can improve the measurement of the Standard Model electroweak parameters by at least a factor of two to three. For example, the weak mixing angle $\sin^2 \theta^d_{eff}$ can be determined with an uncertainty of 0.00021 and the strong coupling constant $\alpha_s(M^2_Z)$ with 0.0009 (as compared to present day uncertainties of 0.0017 and 0.2027). In the Giga-Z mode a large $b$ and $\tau$ sample will also be collected and many flavor-physics results can be improved with respect to todays $B$-factories.

Thanks to these precision measurements, the Standard Model and possible new physics will be significantly more constrained, which is demonstrated by assuming the previously mentioned precisions in the blue-band histogram of the Higgs mass (see Fig. 1.3a) resulting in a much smaller allowed region (see Fig. 1.6c).

1.1.3 Top Quark

Because the top quark is by far the heaviest known particle ($178 \pm 4.3$ GeV \cite{Le04p}), it is a unique object for studying the fundamental interactions in the attometer regime. Due to its short lifetime, it decays predominantly into $bW^+$ before hadronization. But the remnants of the toponium $S$- and $P$-wave resonances cause a steep increase in the cross section close to the production threshold.

An energy scan with moderate luminosity at the production threshold of the top quarks gives an uncertainty of about 30 MeV for the threshold-mass (see Fig. 1.7). With a somewhat higher luminosity, the decay width can be determined with a precision of 2% and a direct measurement of the top quark Yukawa coupling to the Higgs boson is possible:

$$V_{tth} = \frac{g_{tth}^2}{4\pi} \frac{e^{-m_Hr}}{r}$$

where $m_H$ is the Higgs mass and $g_{tth}$ the coupling of the top quark to the Higgs. The Yukawa coupling with a light Higgs boson enhances the cross section by 5-8% allowing establishment of this mechanism directly.
With a \textit{continuum production} of the top quark at center-of-mass energies significantly higher than $2m_t$, several hundred thousand top quarks could be produced. This allows a precise measurement of the pole mass as well as of the electroweak properties, such as the electric dipole moment (uncertainty $\leq 1.1 \cdot 10^{-3}$), the magnetic dipole moment (uncertainty $\leq 4 \cdot 10^{-19}$ ecm) and the CKM matrix elements $V_{td}, V_{ts}$ and $V_{tb}$. With polarized beams, the form factors $F_{1V}, F_{1A}, F_{2V}, F_{2A}$ can be determined.

### 1.1.4 QCD

Individual measurements of the strong coupling constant $\alpha_S$ are limited at best to a precision of several percent. This uncertainty limits the predictive power of the perturbative Quantum Chromodynamics (pQCD), especially for higher-order multi-jet events. With the experimentally clean and theoretically tractable environment of the ILC, more-precise measurements of $\alpha_S$ are possible.

Since $\alpha_S$ diminishes according to the $\beta$-function of QCD, the conventional yardstick of $\alpha_S(M_Z^2)$ is of special interest. This quantity is usually extracted from event ‘shape’ observables such as thrust, jet mass or jet rate. While the Giga-$Z$ mode naturally gives the most precise results for $\alpha_S(M_Z^2)$ because of the high statistics of Z-decays, the ILC also provides an unprecedented possibility to test the validity of QCD and especially the $\beta$-function over a wide energy range. At the ILC, $\alpha_S$ can be determined between 91 GeV and 1000 GeV using the same detector, the same techniques, and applying the same treatment to the data, thus reducing various systematic influences. A comparison of measurements at $\sqrt{s} = 91$ GeV, 500 GeV and 800 GeV with current measurements is shown in Fig. 1.7b.

### 1.1.5 Beyond the Standard Model

As mentioned in the introduction to this chapter, the Standard Model leaves several questions unanswered. As a result, a number of theories such as the supersymmetry theory, extradimensions theory, technicolor theory and superstring theory have been developed. While none of these theories has been either confirmed or excluded to date, some theories have had a
large part of their parameter space ruled out. The best motivated extension of the Standard Model is supersymmetry (SUSY), both experimentally as well as theoretically. Some of the motivations are the following:

- It is the only theory in which gravity can be incorporated naturally.
- It can explain the hierarchy of the electroweak scale ($\approx 100$ GeV), the grand unification scale ($10^{16}$ GeV) and the Planck scale ($10^{19}$ GeV).
- The Minimal Supersymmetric Standard Model (MSSM) allows a coupling of the electroweak and strong coupling constants (see Fig. 1.8a).
- It was shown that some free parameters of the Standard Model can be calculated in SUSY (compare e.g. $\sin^2 \theta_W^{\text{SUSY}} = 0.2335(17)$ with $\sin^2 \theta_W^{\text{exp}} = 0.2311(12)$[Le04p]).
- The lightest supersymmetric particle is a good cold dark matter candidate.
- Supersymmetry contains extra sources of CP violation important for explaining the matter-antimatter asymmetry in the universe.

The minimal extension of the Standard Model (MSSM) adds, in the most general formulation, another 105 free parameters to those of the Standard Model. However, if a particular supersymmetric model is used, that number of parameters can be drastically reduced. For example, in the minimal supergravity (mSUGRA) model, only five parameters remain: the common scalar mass $m_0$, the gaugino mass $m_{1/2}$ at $M_{\text{GUT}}$, the universal trilinear coupling $A_0$, $\tan \beta$ and sign $\mu$.

The MSSM introduces a supersymmetric partner for all particles of the Standard Model: sleptons $\tilde{f}^\pm, \tilde{\nu}^\pm$ for leptons, squarks $\tilde{q}$ for quarks and gauginos $\tilde{g}, \tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$ for all gauge bosons. Additionally, two Higgs doublets have to be introduced, giving rise to 5 Higgs bosons $h^0, A^0, H^0, H^\pm$. The non-strongly-interacting gauginos mix with the higgsinos to form corresponding mass eigenstates: charginos $\chi_i^\pm$ with $i = 1, 2$, and neutralinos $\chi_i^0$ with $i = 1, \cdots, 4$. 
Figure 1.9: Distribution of the reaction $e^+_Le^- ightarrow \tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^- \tilde{\chi}_1^0 \mu^+ \tilde{\chi}_1^0$ [Ag01p]: a) energy spectrum of muons at $\sqrt{s} = 320$ GeV, b) minimum mass $m_{\text{min}}(\tilde{\mu}_R)$ of smuons and c) cross section at threshold.

If supersymmetry exists, it will be of paramount importance at the ILC to understand the mechanism of breaking supersymmetry and to determine its parameters. Fig. 1.8b shows the predicted mass spectrum for a specific set of parameters in different models of breaking supersymmetry. To distinguish between the different models and to determine their parameters, a precise measurement of the particle mass spectrum is necessary. Two examples will be given showing how the individual sparticles can be identified and measured. Right-handed smuons $\tilde{\mu}_R$, the supersymmetric partners of muons, are produced in pairs via $s$-channel $\gamma/Z$ exchange and decay into neutralinos $\tilde{\chi}_1^0$: $e^+e^- \rightarrow \gamma^*/Z^* \rightarrow \tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^+ \tilde{\chi}_1^0 \mu^- \tilde{\chi}_1^0$. The decay gives a distinct signature in the detector: two muons and a large amount of missing energy. The energy spectrum of this process is flat (see Fig. 1.9a), and its endpoints are correlated to the mass of the smuon and the neutralino. Better results can be obtained if the neutralino mass is known from a different measurement and the minimum allowed energy can be reconstructed with the help of the muon momentum correlation. This is plotted in Fig. 1.9b and the maximum of the distribution gives $m_{\tilde{\mu}_R}$. The best result with $\delta m_{\tilde{\mu}_R} < 0.1$ GeV, however, can be obtained with an energy scan at the production threshold (see Fig. 1.9c), even with a low luminosity of $\mathcal{L} = 10$ fb$^{-1}$ per energy step.

The chargino is also produced by an $s$-channel $\gamma/Z$ exchange, but a $t$-channel selectron or sneutrino exchange contributes as well. An easily detectable decay channel is $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow t\bar{t} \nu \tilde{\chi}_1^0 q\bar{q} \tilde{\chi}_1^0$. The two quarks can be selected and the di-jet energy (see Fig. 1.10a) can be used to infer the chargino mass as well. The di-jet mass distribution gives additional information about the chargino-neutralino mass difference $\Delta m(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0)$ (see Fig. 1.10b) and an excellent mass resolution of 50 MeV can be obtained with a production threshold scan (see c).

Finally, not only can the mass spectrum of light fermions be precisely measured, but also their spin, branching ratios, coupling and mixing parameters can be determined. In addition the Higgs sector with its 5 Higgs particles allows a wide range of measurements.

### 1.2 Accelerator

In recent years, three different designs for a $e^+e^-$-collider have been studied: TESLA in Europe, the NLC in North America and the JLC in Japan. However, because of the immense costs, it is clear that only one linear collider facility will be built. Therefore, an international
collaboration is evaluating the present projects to select and combine the most promising ideas into a single accelerator design, the International Linear Collider (ILC).

A first step was taken during summer 2004 by choosing the basic technology of the cavities, the accelerating structures. While the NLC and JLC concepts were based on cavities made of copper operated at room temperature with an acceleration RF frequency of 11.4 MHz, the TESLA design favored superconducting niobium cavities at 2 K and an RF frequency of 1.3 MHz. The decision in favor of the superconducting technology requires that many central elements resemble those of the TESLA design. Therefore, the general layout of the TESLA accelerator is presented in Fig. 1.11. (For further details see reference [An01].) In contrast to storage rings or synchrotrons, where particle bunches can collide in many revolutions before the beam quality suffers, particle bunches in linear accelerators (linacs) can be brought to collision only once. A further drawback is that all particles have to be accelerated to the center-of-mass energy in one path. Hence, to keep the facility’s dimensions and costs reasonably small, the acceleration gradient of the cavities has to be as high as possible. Not only the maximum energy but also a high beam quality (energy spread, emittance) and high luminosity are important to allow the study of the physics processes described in the last section. Furthermore, additional features, such as production of highly polarized $e^+$ and $e^-$ beams and head-on collisions of particle bunches, are helpful tools for a detailed understanding of physics processes. These considerations have driven the TESLA design, and the main characteristics of the baseline layout with a 500 GeV center-of-mass energy, as well as an upgrade to 800 GeV, are summarized in Table 1.1. The main components of the accelerator are briefly described:

**Particle Sources:** To attain the large number of particles and a high degree of polarization, a polarized electron gun is used as the electron source. In it, a GaAs cathode is illuminated with laser light of a wavelength between 750 nm and 840 nm, resulting in peak current of up to 10 A. Positrons are produced by sending the 250 GeV electron beam through an undulator.
<table>
<thead>
<tr>
<th></th>
<th>TESLA-500</th>
<th>TESLA-800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total site length</td>
<td>33 km</td>
<td></td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>23.4 MV/m</td>
<td>35 MV/m</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5 Hz</td>
<td>4 Hz</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>950 μm</td>
<td>860 μm</td>
</tr>
<tr>
<td>No. of bunches per pulse</td>
<td>2820</td>
<td>4886</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>337 ns</td>
<td>176 ns</td>
</tr>
<tr>
<td>No. of electrons per bunch</td>
<td>$2 \cdot 10^{10}$</td>
<td>$1.4 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Bunch size at IP $(x,y,z)$</td>
<td>553 nm, 5 nm, 300 μm</td>
<td>391 nm, 2.8 nm, 300 μm</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$3.4 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$5.8 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$e^-$: 0.15%</td>
<td>$e^+$: 0.032%</td>
</tr>
<tr>
<td>Polarization</td>
<td>$e^-$: 80%</td>
<td>$e^+$: 60%</td>
</tr>
</tbody>
</table>

Table 1.1: TESLA parameters for the 500 GeV baseline design and a possible upgrade to 800 GeV [An01p].
The generated photons are converted in a thin target to electron-positron pairs, and the latter are collected and accelerated.

**Damping Ring** The small bunch sizes as well as low emittance and small beta-values of both the $e^+$ and the $e^-$ beam at the interaction point require a reduction of the phase space prior to injection in the main linac. Hence, after bunching and acceleration to 5 GeV, both beams are stored in damping rings. Due to the long pulse length of about 1 ms, corresponding to a bunch train of more than 300 km, the bunches have to be compressed to a length of 18 km by shortening the inter-bunch spacing. The 18-km-long damping ring is designed in a 'dog-bone' shape allowing a significant part to be placed parallel to the main linac and thus reducing the construction cost. The actual damping is performed by inducing synchrotron radiation with wiggler magnets and by replacing the longitudinal energy loss with the help of standard cavities.

![Damping Ring Diagram](image)

*Figure 1.11: Schematic drawing of the layout of the TESLA accelerator [An01p].*
1.3 Detector Layout

Figure 1.12: a) Photograph of two 9-cell cavities [Ka97m], b) excitation curves of 9-cell cavities [Li04f].

Main Linac: The heart of the accelerator is the main linac, which accelerates the particles from 5 GeV to more than 250 GeV. The basic structure blocks of the linac are the 9-cell cavities, which are shown in Fig. 1.12a. They are made of pure niobium, and before installation they must undergo an intense cleaning procedure of buffered chemical polishing (BCP), electropolishing (EP) and heat treatment at 1400°C. This ensures a surface roughness of less than 0.1 μm inside the cavity, which is essential for high performance. In Fig. 1.12b the excitation curves for several cavities treated with this procedure is shown. All cavities surpass the requirements of the TESLA-800 upgrade design. Single-cell cavities have been reported to reach up to 42 MV/m, which is close to the breakdown limit of ≈ 50 MV/m in pure Niobium.

The design of the TESLA accelerator allows for operation modes other than the above-mentioned $e^+$- and $e^-$- collisions. A number of ideas have been studied and promise complementary measurements, which could considerably enhance the results of some measurements. A second interaction point alongside the primary one could be supplied by alternatingly directing the beam to either experiment. Due to the intrinsic angle between the two beam directions the second experiment is an ideal place to study $e^- - \gamma$ or $\gamma - \gamma$-interactions. But also $e^- - e^-$ or a low energy $e^+ - e^-$-experiment could be carried out here.

Additional temporary operation modes are known as 'Giga-Z', 'HERA' or 'TESLA-N'. In the 'Giga-Z' mode, the center-of-mass energy could be reduced to 91 GeV and the high luminosity could be used to record the decay of up to $10^9$ Z bosons within a few months. The 'HERA' option is a collision of TESLA’s 250 GeV electron-beam with the 920 GeV proton beam of the HERA accelerator, extending the energy range of present HERA studies. Finally, 'TESLA-N' includes the use of a 250 GeV electron beam for fixed-target experiments.

1.3 Detector Layout

The wide kinematic range of center-of-mass energies between 91 GeV to 1 TeV and the large variety of physics prospects, ranging from high-precision measurement to particle discovery puts stringent requirements on the overall detector layout and the individual sub-detector systems. Four major areas of improvement compared to existing detectors have been identified.
[Al01lp]:

- **Track momentum resolution**: For the precise measurement of the Higgs mass via the di-lepton recoil mass (see Section 1.1.1) excellent momentum resolution is required. For this, a large tracking volume with good spatial resolution and high magnetic field are necessary.

- **Vertexing**: An exact reconstruction of secondary vertices is of paramount importance for many of the expected physics processes. For example, an efficient differentiation of $b\bar{b}$, $c\bar{c}$, $s\bar{s}$, $\tau\bar{\tau}$ and $gg$ pairs is of great importance to reliably quantify the Higgs boson's decay branching ratios. The determination of secondary vertices is also necessary for the study of the top quark and many SUSY particles. These demands require a good vertex detector.

- **Energy flow**: Experience from LEP and SLC have shown that the energy-flow technique is an excellent tool for studying multi-parton final states. The energy-flow combines the tracking and calorimeter information for reconstructing the original parton four-momenta. For this, both the electromagnetic and the hadronic calorimeter have to be finely segmented in 3 dimensions and have to be placed inside the magnetic coil to reduce the amount of inactive material in front of the calorimeters. This layout also allows reconstruction of the four-momentum of tracks and photons that do not originate from the interaction point.

- **Hermeticity**: Signatures of new physics include missing energy. To reliably identify these processes good hermeticity and particle detection capabilities down to the smallest angles are necessary.

To fulfill these requirements, three basic detector layouts have been developed in parallel with the three accelerator concepts: A large detector with a drift chamber and a magnetic field of 3 T (Japan), a medium-size detector with a time projection chamber and $B = 4$ T (Europe), and a small detector with an all-silicon tracker and a 5 T magnetic field (US). In [Ec96] it was demonstrated that the medium-sized detector is most promising and therefore this detector will be discussed (for more details see reference [Al01lp]).

Like most detectors in high-energy physics, it consists of different sub-detector systems arranged in shell-like structures around the interaction point. Fig. 1.13a shows an artist's conception of the medium-sized detector, while in (b) the cross section of one quadrant is shown. The individual sub-detector systems are now described below, from the inside outwards.

- **Vertex detector**: To reach the performance goal of reconstructing the particle’s vertex with a precision of $\delta(I_{P_{\phi,z}}) \leq 5 \, \mu m \oplus 10 \, \mu m \, GeV/c_{p \sin \phi}^{0 \mu m}$, the vertex detector has to be built as a multi-layer silicon pixel detector. A total of 5 layers have been planned, the first as close as 1.5 cm from the interaction point. So as to reduce the material budget to 0.06% $X_0$, the individual layers should be as thin as 50 $\mu m$. Various technologies are being investigated for this application: CCD, CMOS and hybrid pixels.

- **Intermediate tracker**: 2 to 5 additional layers of standard silicon strip detectors improve the momentum resolution of the tracking system by about 30% and help to link the particle tracks from the TPC to the vertex detector during reconstruction.
1.3 Detector Layout

Figure 1.13: a) Artist’s conception of the medium-sized detector layout, b) cross section of one quadrant of medium-sized detector. Dimensions are given in mm [Al01, p]. The numbering scheme in (a) and abbreviations in (b) correspond to the following sub-detectors: [1] = VTX/SIT = vertex detector and silicon intermediate tracker, [2] = TPC = time projection chamber, [3] = ECAL + HCAL = electromagnetic and hadronic calorimeter, [4] = COIL = coil of superconducting magnet, [5] = YOKE = iron return yoke instrumented with muon chambers.

- **Central tracker:** A large-volume time projection chamber is foreseen and a detailed discussion is given in Section 1.4.

- **Electromagnetic calorimeter:** To reach the required energy resolution of \( \frac{\delta E}{E} \leq 0.10 \frac{1}{\sqrt{E\text{(GeV)}}} + 0.01 \) and tracking capability, a calorimeter with tungsten as passive absorber and highly segmented readout layers is planned. For reading out silicon diode pads with pad sizes of 1 cm\(^2\), scintillating fibers or photodiodes are being considered.

- **Hadronic calorimeter:** Here too, two competing ideas based on stainless steel or brass absorbers exist: The *tile calorimeter* uses scintillating plates in between the absorbers. In the *digital calorimeter* gaseous detectors with cell sizes of 1 cm\(^2\) are used for digital information only, and the particle’s energy is determined by counting cells with a signal. Both versions have been demonstrated in test beams that they surpass the TDR requirement of \( \frac{\delta E}{E} \leq 0.50 \frac{1}{\sqrt{E\text{(GeV)}}} + 0.04 \) by a large margin.

- **Coil of superconducting magnet:** The design of the magnetic coil follows closely the one of CMS\(^2\). The magnetic field of \( B = 4 \) T with a uniformity of \( 10^{-3} \) should be available with present day technology. The superconducting wires will be made of NbTi and be operated at 4.5 K.

- **Fe yoke:** The 1.6 m thick iron return yoke will be instrumented with position sensitive gaseous detectors such as Plastic Streamer Tubes (PST) or Resistive Plate Chambers

\(^2\)The **Compact Muon Solenoid** is one of the four experiments at the **Large Hadron Collider** at CERN, Geneva, Switzerland
(RPC). These detectors are used as tail catchers for high-energy hadron cascades and as muon chambers.

The two endcaps consist of similar sub-detector systems, of which only the Low Angle Tagger and the Luminosity Calorimeter will be mentioned here. Together they guarantee an angular coverage of down to 4.6 mrad and are designed to detect electrons of up to 400 GeV.

Combining the information of the different sub-detector systems, an overall tracking performance of \( \frac{\delta p_T}{p_T} \leq 5 \cdot 10^{-5} \) (GeV/c)\(^{-1} \) and an energy resolution of \( \frac{\delta E}{E} \leq 0.3 \frac{1}{\sqrt{E(\text{GeV})}} \) will be achieved.

1.4 The Time Projection Chamber (TPC)

The working principle and advantages of a TPC are described in Section 2.1. Here, only the requirements of the Technical Design Report [A01_1p] are quoted in some detail, since they will be referred to often throughout this thesis.

The schematic drawing in Fig. 1.13b foresees a cylindrical drift volume with a mechanical radius of 32 cm to 170 cm and an overall length of 2 \times 273 cm. This results in a sensitive volume with an inner radius of 36.2 cm, an outer radius of 161.8 cm and a maximum drift length of 250 cm on both sides of the cathode. The material budget of the inner field cage and the gas volume should not exceed 0.03 X\(_0\) so as not to compromise the energy resolution of the electromagnetic calorimeter.

Since the high rate of bunch crossings during one pulse does not permit a conventional gating scheme to reduce the ion back flow (see Section 2.5.4), the development of a new readout stage allowing continuous data-taking for 1 ms is mandatory. For particle identification, an energy resolution of \( \sigma(dE/dx) \leq 5\% \) is necessary and has been accomplished before. The momentum resolution of the TPC alone has to be \( \frac{\delta p_T}{p_T} \leq 1.4 \cdot 10^{-4} \) (GeV/c)\(^{-1} \) for particles with \( |\cos \theta| < 0.75 \) and \( \frac{\delta p_T}{p_T} \leq 3.2 \cdot 10^{-4} \) (GeV/c)\(^{-1} \) for particles with \( |\cos \theta| \approx 0.9 \), requiring an improvement in performance by at least one order of magnitude over existing TPCs. To obtain such good momentum and energy resolution, at least 200 readout points in the radial direction are necessary. Each readout point should reach an \( r\phi \) resolution of 70 \( \mu \text{m} \) for tracks drifting only 10 cm, and 190 \( \mu \text{m} \) for tracks drifting 200 cm. In the z-direction, resolutions of 0.6 mm and 1 mm are required for the aforementioned drift distances. Last, but not least, a double-pulse resolution of less than 2.3 mm in the \( r\phi \)-direction and less than 10 mm in the z-direction are called for.

To reach these ambitious goals, the use of micro-pattern gas detectors such as Micromegas or GEMs is advocated. These devices feature intrinsic ion feedback suppression and a significantly reduced pitch between regions of possible gas amplification (for a detailed discussion of advantages, see Section 2.7).

In this thesis the combination of a TPC with GEM-based readout is studied. A special focus was put on transverse and longitudinal spatial resolution, energy resolution due to specific ionization \( dE/dx \), and momentum resolution. The performance is studied with a prototype detector (for a detector description see Chapter 3) in conditions similar to the ones described in the TESLA TDR, that is, in a magnetic field of B = 4 T and at the limit of low diffusion (Chapter 7). In addition the influence of high-rate hadronic particle beams on
the aforementioned measurement categories is studied (Chapter 8). Finally, seven different readout pad geometries are scrutinized with a view to possible improvement of the transverse spatial resolution for very small cluster sizes (Chapter 9).
Chapter 2

Time Projection Chamber and Gas Electron Multiplier

The principle of the Time Projection Chamber (TPC) was developed by D. R. Nygren in the mid-1970s [Ny74]. It is one of the most advanced types of gaseous drift detectors and has been operated successfully in a number of high-energy physics experiments. In this chapter, the fundamental laws of physics governing the operation of a TPC are summarized. Then, an overview of the performance of TPCs is given, and finally a new device for gas amplification in a TPC, the Gas Electron Multiplier (GEM), is described.

2.1 Time Projection Chamber

The Time Projection Chamber (TPC) is a tracking detector providing three-dimensional information on particle tracks by measuring a large number of space-points along with the specific energy loss $dE/dx$. The basic design of a TPC in collider experiments is shown in Fig. 2.1. The sensitive volume consists of a vessel labeled drift cylinder, which contains a gas

- $t_1$: track images at different times
- Diffusion of track image

![Diagram of TPC operation in a collider experiment](image)

Figure 2.1: Schematic drawing illustrating TPC operation in a collider experiment.
mixture chosen to meet the needs of the experiment. A certain space along the axis is spared out to accommodate items like the beam pipe and vertex detector. The front surfaces of the detector consist of the endcaps housing the readout sensors and the front-end electronics. The gas volume between the two endcaps is split into two parts by a thin metalized HV membrane. Very homogenous electric fields are applied in both drift regions. The fields are aligned parallel to the axis of the cylinder starting at the endcaps and ending on the HV membrane that serves as a cathode. The homogeneity of the electric fields is further improved by a series of equidistant ring electrodes along the drift cylinder. These electrodes make up the field cage and are kept appropriate potentials by resistive voltage dividers.

When a charged particle traverses the detector, it ionizes the gas along its trajectory. While the ions drift to the cathode and are neutralized there, the electrons drift towards the endcaps. Here, they are amplified and read out by position-sensitive gas detectors, creating a two-dimensional image of the original particle trajectory. To get the full three-dimensional information, drift velocity and drifting time of individual charge-cloud segments have to be known with high precision. The exact time at which the primary particles traverse the chamber is given by a signal either from the accelerator or from a second, much faster, detector such as a scintillator. This signal triggers the readout electronics to record the collected charge at a constant sampling rate, thus storing information on time, position and charge.

TPC readout stages have typically been built with multi-wire proportional chambers (MWPCs) for gas amplification and position measurements. The MWPCs consist of several layers of wires stretched along the $r\phi$ plane as shown in Fig. 2.2. The top layer is a gating plane, which will be described in detail in Section 2.5.4. The ground plane forms the anode of the drift region and the cathode of the MWPC. It is important for guiding the field from the drift region to the amplification region, and it shields the readout area from induction signals created by the drifting charge. The last set of wires consists of sense wires that alternate with field forming wires. The sense wires are very thin wires (typical diameter: 20 µm), and they have a positive high voltage applied so that a strong electric field forms around the wire. In that field, gas amplification can take place. A signal generated by the

![Figure 2.2: Schematic drawing of wire layers and signal creation in a TPC wire readout [Sc93t].](image-url)
gas amplification avalanche is amplified by the front-end electronics and finally digitized. In addition, an induction signal is generated in the pad plane placed underneath the wires. The pads are arranged in rows and allow precise position measurement in the $r\phi$ plane.

In many applications a magnetic field is superimposed parallel to the electric field. Its main purpose is to determine the particle’s momentum by forcing it on a curved trajectory. A second effect of the magnetic field is that the transverse diffusion of drifting electrons is suppressed, and thus the spatial resolution is improved (see Section 2.3).

The advantages of TPCs are numerous and are summarized in the following overview. (To give an idea of the magnitudes, specifications of the TESLA-TDR are included. Some values for wire-based TPCs are given in Table 2.3.):

- Tracking performance allows single space-point resolution of about 70-200 $\mu$m in the $r\phi$ direction and 500 $\mu$m in the drift direction.

- A large number of space-points allows continuous tracking: With two hundred 3D space-points, an efficiency close to 100% is ensured, even with high multiplicity and background events.

- Three-dimensional readout reduces ambiguities at reconstruction time.

- Reasonable double-track resolution: 2 mm in the $r\phi$ direction.

- High momentum resolution: In a 4 T magnetic field the TPC can reach $\partial p_T/p_T^2 \sim 1.5 \times 10^{-4}$ 1/GeV

- Specific energy loss $dE/dx$ is important for particle identification: An energy resolution of down to 4.3% seems to be achievable.

- Minimum amount of material in the active volume: A total material budget of 3 % of $X_0$ is envisaged.

- Excellent granularity: $1.5 \times 10^6$ electrical channels and a typical digitization rate of 20 MHz give more then $10^9$ 3D electronic-readout pixels (voxels).

- Good homogeneity: high efficiency and uniform tracking performances throughout the sensitive volume, together with a homogenous mass distribution, result in an almost truly $4\pi$ detector.

However, there are some challenges that have to be met to operate a TPC in a given environment. The long drift time of up to 50 $\mu$s can lead to the overlap of several events before the drift volume can be cleared of all electrons. The ions generated during the gas amplification process have to be neutralized before reaching the drift volume, because there they could cause deformations of the electric field and therefore distort the images of tracks arriving later. The challenge of collecting the ions will be discussed in more detail in Section 2.5.4.

The following sections provide an overview of the individual processes taking place in the TPC. For more detailed discussions, see standard textbooks and publications [Bl93b, Gr93b, Ki92b, Le87b, Sa77p, We02b].
2.2 Ionization by Charged Particles and Photons

**Charged Particles** Charged particles passing through matter deposit energy by various means. For moderately relativistic particles heavier than electrons, the predominant processes are ionization and atomic excitation. The mean energy loss can be derived classically and the result is given by the Bethe-Bloch equation:

\[
\frac{dE}{dx} = \frac{e^2 e^4 N_A}{4 \pi \varepsilon_0 m_e} \frac{z^2 \beta^2}{A} \left[ \ln \left( \frac{\sqrt{2 m_e c^2 E_{\text{max}} \beta \gamma}}{I_{\text{exc}}} \right) - \beta^2 - \frac{\delta(\beta)}{2} \right]
\]  

(2.1)

where \( m_e \) is the electron rest mass, \( e \) the elementary charge, \( N_A \) Avogadro’s number, \( z \) the charge of the incident particle in units of \( e \), \( Z, A \) the atomic number and weight of the absorber, \( \rho \) the density of the absorber, \( E_{\text{max}} \) the maximum energy transfer allowed \( E_{\text{max}} = \frac{2 m_e c^2 \beta^2}{1-\beta^2} \), \( I_{\text{exc}} \) the mean excitation energy (for \( Z > 1 : I_{\text{exc}} \approx 16 Z^{0.9} \text{ eV} \)) and \( \delta \) the density-effect correction.

This function is shown in Fig. 2.3 in the kinematic range from \( \beta \gamma \approx 0.5 \) to \( \beta \gamma \approx 500 \). It has a minimum at an energy \( \beta \gamma \approx 3 m_0 c^2 \). Particles with this energy are therefore called minimum ionizing particles (MIPs). The shallow logarithmic rise to higher energies is damped by the density effect, so that the energy deposition in the absorber increases only by a small amount. Particles in this energy range have the same behavior as far as energy loss is concerned, and are usually also referred to as MIPs.

Eq. 2.1 is not valid above the critical energy, since the energy loss is then dominated by radiation of photons, the Bremsstrahlung, and rises linearly with the energy of the incident particle. The critical energy can be approximated e.g. by \( E_{\text{e, crit}} \approx \frac{7.980 \text{ GeV}}{Z^{2.03} \text{ cm}} \) for electrons in gases and \( E_{\mu, \text{ crit}} \approx \frac{7.980 \text{ GeV}}{Z^{2.03} \text{ cm}} \) for muons in gases.

The Bethe-Bloch equation (2.1) gives the mean energy loss per unit absorber thickness. However, since the energy loss is a statistical process, the energy deposition in thin absorbers fluctuates strongly. The energy loss distribution is rather wide and can be approximated by the Landau distribution. In Fig. 2.3b a sample measurement of \( dE/dx \) with the prototype
2.2 Ionization by Charged Particles and Photons

detector described in Chapter 3 is shown. The long tail to high energy losses is created by high energetic knock-on electrons (δ-rays or δ-electrons) that can create electron-ion pairs on their own.

For gaseous detectors, it is important to know how many electron-ion pairs are produced by the deposited energy, since this number influences the spatial and energy resolution. In this context, one has to distinguish between the number of primary interactions \( n_C \) generating clusters of electrons and the total number of primary pairs \( n_T \). The distance between two clusters is given by the following probability distribution:

\[
f(l) dl = \frac{1}{\lambda} \exp \left( -\frac{l}{\lambda} \right) dl
\]

where \( \lambda = \frac{1}{n_c} \) is the mean free flight path and \( l \) the free flight path between two encounters. While most clusters contain only a single electron (in argon about 65% of all clusters), some clusters consist of a large number of electrons-ion pairs. These are produced by secondary processes, mainly δ-electrons, but also by excited states, photon transmission and other processes. Hence, the total number of primary pairs is given by the number of clusters and the average number of electron-ion pairs per cluster \( n_{ec} \):

\[
n_T = n_C \cdot n_{ec} = \sum_i \frac{g_{i\text{comp}} \Delta E}{W_i}
\]

where \( \Delta E \) is the energy deposited in the absorber, \( c_i \) the weight-fraction of the gas component and \( W_i \) the energy needed to create one electron-ion pair in this gas component. \( W_i \) differs from the lowest ionization potential \( I \), since some energy is transferred into exciting the absorber without ionizing it. There is also a small difference if the ionizing particle is an electron or photon \( (W_\beta) \) or an α-particle \( (W_\alpha) \).

Table 2.1 lists all relevant numbers for the gas components considered in this thesis.

**X-ray Photons** In Chapter 4 some measurements using an \( ^{55} \)Fe radioactive source will be described.

Since \( ^{55} \)Fe has a surplus proton, it decays via electron capture into the excited \( ^{55} \)Mn

\[
^{55} \text{Fe} + e^- \rightarrow ^{55} \text{Mn} \quad \tau = 2.73 \text{ y}
\]

The incomplete K-shell is filled from higher energetic shells while emitting an X-ray photon of about 6 keV:

- \( K\alpha_1 : E_K - E_{L_{\alpha}} = 5.90 \text{ keV} \quad \text{emission prob.: } 24.4\% \)
- \( K\alpha_2 : E_K - E_{L_{\beta}} = 5.89 \text{ keV} \)
- \( K\beta_1 : E_K - E_{M_{\beta}} = 6.49 \text{ keV} \quad \text{emission prob.: } 2.86\% \)

These photons are used to calibrate detectors. In gaseous detectors with argon-based gas mixtures, the X-rays are mostly absorbed via the photoelectric effect with electrons of the K-shell \((E = 3.209 \text{ keV})\). The following list shows the distribution of the energy:

- Photoeffect with K-shell electron \( W_{kin} = 2.7 \text{ keV} \)
- Auger effect \( W_{kin} = 3.2 \text{ keV} \)
- Auger probability 80%
Table 2.1: Gas properties in connection with energy deposition and ionization: atomic number Z, atomic weight A, density \( \rho \) at N.T.P., mean excitation energy \( I_{\text{exc}} \), energy loss of MIPs, \( W \) value measured with \( \alpha \)- and \( \beta \)-particles, lowest ionization potential \( I \), number of clusters \( n_C \), total number of primary electron-ion pairs \( n_T \) and the radiation length \( X_0 \) [B193b, Gr93b].

<table>
<thead>
<tr>
<th>gas</th>
<th>( \Sigma Z )</th>
<th>( \Sigma A )</th>
<th>( \rho ) (g/l)</th>
<th>( I_{\text{exc}} ) (eV)</th>
<th>( \frac{dE}{dx}) min keV/cm</th>
<th>( W_\alpha ) (eV)</th>
<th>( W_\beta ) (eV)</th>
<th>( I ) (eV)</th>
<th>( n_C )</th>
<th>( n_T )</th>
<th>( X_0 ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>18</td>
<td>39.95</td>
<td>1.78</td>
<td>188</td>
<td>2.71</td>
<td>26.4</td>
<td>26.3</td>
<td>15.76</td>
<td>29</td>
<td>94</td>
<td>110</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>10</td>
<td>16.04</td>
<td>0.72</td>
<td>41.7</td>
<td>1.75</td>
<td>29.1</td>
<td>27.1</td>
<td>12.99</td>
<td>16</td>
<td>53</td>
<td>183</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>22</td>
<td>44.0</td>
<td>1.98</td>
<td>85</td>
<td>3.62</td>
<td>34.3</td>
<td>32.8</td>
<td>13.81</td>
<td>34</td>
<td>91</td>
<td>646</td>
</tr>
</tbody>
</table>

- Photoeffect with K-shell electron
  
  K-L fluorescence
  
  L-M fluorescence
  
  probability
  
  \( W_{\text{kin}} = 2.7 \text{ keV} \)
  \( W_\gamma = 2.9 \text{ keV} \)
  \( W_\gamma = 0.3 \text{ keV} \)
  
  16%

- Photoeffect with L-shell electron
  
  L-M fluorescence
  
  probability
  
  \( W_{\text{kin}} = 5.6 \text{ keV} \)
  \( W_\gamma = 0.3 \text{ keV} \)
  
  4%

In the first and third process the energy deposition is quasi-point-like, but in the second process a fluorescence photon with an energy of 2.9 keV that can escape from the conversion location is created. The energy detected in that case is thus only 3.0 keV, and the spectrum consists of two lines: The photopeak at 5.9 keV and the escape peak at 3.0 keV. In Fig. 2.4 an oscilloscope picture with both signal types is shown.

The intensity of the photon beam from the radioactive source diminishes exponentially while traversing matter:

\[
I(x) = I_0 \cdot e^{-\mu_{\text{pho}} \rho x} = I_0 \cdot e^{-\frac{N_A \sigma_{\text{pho}} \rho x}{A}}
\]  

(2.3)

where \( I_0 \) is the initial intensity, \( \mu_{\text{pho}} \) the absorption coefficient due to the photoelectric effect and \( \rho \) the density of the absorber, \( N_A \) Avogadro’s number, \( A \) the atomic weight of the absorber and \( \sigma_{\text{pho}} \) the cross section for the photoelectric effect. Another useful definition is the mean free path of photons \( \lambda = \frac{1}{\mu_{\text{pho}}} \) indicating the penetration depth in the absorber.

If the energy deposition in the detector is predetermined, as is the case with photons or particles stopped in the medium, then the energy resolution no longer follows the Poisson statistic, but is improved by the Fano factor \( F \) [Fa47p]. This factor depends on the gas
2.3 Drift and Diffusion in Electric and Magnetic Fields

Figure 2.4: Signal of $^{55}$Fe in an argon-methane mixture: the left signal contains the full energy of 5.9 keV and the right signal only the 3.0 keV of an escape event.

mixture and the energy deposited. For Ar-CH$_4$ (90:10) and 5.9 keV photons, a factor of $F = 0.21$ was found [Gr93b].

2.3 Drift and Diffusion in Electric and Magnetic Fields

Without an external electric field, the electrons and ions generated by the passage of the incident particle thermalize quickly in the gas. They either recombine with the opposite charge or diffuse slowly by multiple collision following a Gaussian distribution:

$$\frac{dN}{N} = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\left(\frac{x^2}{2\sigma_i^2}\right)} dx$$  \hspace{1cm} (2.4)

where $dN/N$ is the fraction of charge in element $dx$ at distance $x$ from the origin after time $t$. For a point-like initial charge distribution the standard deviation $\sigma_i$ is given by $\sigma_i = \sqrt{2D_l}$ in the two-dimensional case and $\sigma_i = \sqrt{6D_l}$ in the three-dimensional case, where $D$ is the diffusion coefficient.

If an electric field is applied, the random motion of the electrons and ions is overlaid with a drift motion (anti-)parallel to the field. Due to the collisions with the surrounding gas, the net drift velocity $\bar{v}_{\text{drift}}$ is much smaller than the instant velocity. For ions, $\bar{v}_{\text{drift}}$ is linearly dependent on the electric field:

$$\bar{v}_{\text{drift}} = \frac{\mu E}{p}$$

where $\mu$ is the mobility of the ions in the gas mixture and $p$ is the gas pressure in atm.

Due to their smaller mass, electrons are accelerated more rapidly between two collisions and are thus faster by about three orders of magnitude. However, a simple correlation between $\bar{v}_{\text{drift}}$ and $E$ can not be derived, since the electron wavelengths are similar to those of the electron shells and complicated quantum-mechanical processes such as the Ramsauer effect occur.
Figure 2.5: Electron drift properties in Argon-Methane mixtures: a) drift velocity $\bar{v}_{\text{drift}}$ of different mixtures as a function of electric field $\bar{E}$, b) longitudinal diffusion coefficient $D_L$ of different gas mixtures as a function of electric field $\bar{E}$, c) transverse diffusion coefficient $D_T$ of Ar-CH₄ (90:10) as a function of electric and magnetic field. All data are calculated with the GARFIELD interface to MAGBOLTZ [Ve01m].

In Fig. 2.5a drift velocities for various Ar-CH₄ mixtures have been computed with the GARFIELD interface to MAGBOLTZ, showing the non-trivial dependence on gas mixture and electric field. In addition, the diffusion of electrons is influenced by quantum mechanical effects. Diffusion in Ar-based mixtures is anisotropic, with differing coefficients parallel and perpendicular to the electric field. As a result, the diffusions are generally considered independently. For convenience, the standard deviations of Eq. 2.4 are restated as function of the drift distance $x_{\text{drift}}$ and with transverse and longitudinal diffusion coefficients ($D_T$ and $D_L$) as follows:

$$\sigma_{T/L} = D_{T/L} \cdot \sqrt{x_{\text{drift}}}$$

with:

$$D_{T/L} = \sqrt{2} \bar{v}_{\text{drift}}$$

(2.5)

As an example the longitudinal diffusion coefficients of Ar-CH₄ mixtures are shown in Fig. 2.5b.

If in addition a magnetic field is imposed, the electrons are subjected to the Lorentz force, $F_L = q\bar{E} + q\bar{v} \times \bar{B}$. If the electrical and magnetic fields are parallel, as is the case in most TPCs, the net displacement remains largely unaltered, but transverse motion is suppressed by a factor of $1/(1 + \omega^2 \tau^2)$. Here $\tau$ is the mean time between collisions and $\omega$ the cyclotron frequency of the electrons ($\omega = 17.6 \cdot B$ MHz/Gauss). This results in a reduction of the transverse diffusion coefficient as shown in Fig. 2.5c and given by:

$$\frac{D_T(B \neq 0)}{D_T(B = 0)} = \frac{1}{1 + \omega^2 \tau^2}$$

Thus by applying a solenoidal magnetic field, two important effects can be obtained: The momentum of the primary particle can be determined by measuring its radius of curvature, and the spatial resolution is improved due to the reduction of transverse diffusion (see Section 2.5.2).

Properties such as drift velocity and diffusion coefficients, not only depend on the electric and magnetic fields, but also vary dramatically from gas to gas. Even small changes in the composition of a gas mixture can alter its behavior completely, so that the mixture must be carefully tuned to the needs of the detector type and the experiment. In Table 2.2 some gas properties have been listed for the gas mixtures used in this thesis.
### 2.4 Gas Amplification

<table>
<thead>
<tr>
<th>gas mixture</th>
<th>$E_{\text{max}}$ V/cm</th>
<th>$v_{\text{drift}}$ cm/µs</th>
<th>$\mathcal{D}_L$ µm/√cm</th>
<th>$\mathcal{D}_T(0 \text{ T})$ µm/√cm</th>
<th>$\mathcal{D}_T(4 \text{ T})$ µm/√cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-CH$_4$ (95:5)</td>
<td>95</td>
<td>4.14</td>
<td>455</td>
<td>720</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>(60)</td>
<td>3.84</td>
<td>340</td>
<td>730</td>
<td>31</td>
</tr>
<tr>
<td>Ar-CH$_4$ (90:10)</td>
<td>135</td>
<td>5.49</td>
<td>375</td>
<td>560</td>
<td>41</td>
</tr>
<tr>
<td>Ar-CH$_4$ (80:20)</td>
<td>215</td>
<td>7.03</td>
<td>290</td>
<td>435</td>
<td>41</td>
</tr>
<tr>
<td>Ar-CH$_4$-CO$_2$ (93:5:2)</td>
<td>240</td>
<td>4.56</td>
<td>270</td>
<td>460</td>
<td>72.5</td>
</tr>
<tr>
<td>Ar-CO$_2$ (70:30)</td>
<td>(250)</td>
<td>0.57</td>
<td>160</td>
<td>158</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>(310)</td>
<td>0.71</td>
<td>155</td>
<td>150</td>
<td>109</td>
</tr>
</tbody>
</table>

Table 2.2: Gas properties in connection with drift and diffusion: $E_{\text{max}}$ is the electric field at which the drift velocity is maximum (in brackets: alternative electric fields). For the electric field indicated in the second column, drift velocity $v_{\text{drift}}$, longitudinal diffusion coefficient $\mathcal{D}_L$, and transverse diffusion coefficient in $B = 0$ T and $B = 4$ T are given. All data were computed with GARFIELD interface to MAGBOLTZ [Ve01m].

2.4 Gas Amplification

In high electric fields, electrons can gain enough energy between two collisions to ionize the atom in the second collision. The number of electrons causing this kind of multiplication depends on the electric field and the mean free path between two collisions. Mathematically the process is described by the mean free path between ionizing collisions $\lambda$, or its inverse, the first Townsend coefficient $\alpha = 1/\lambda$, which gives the number of electron-ion pairs created per unit length of the drift path. In general we get:

$$dN = \alpha N dx$$

where $N$ is the initial number of electrons and $dN$ the total number of ionizing collisions during a drift distance $dx$. Since $\alpha$ depends on the electric field and therefore on the position $x$, integration gives:

$$N(x + dx) = N(x) e^{\int_x^{x+dx} \alpha(\xi) \, d\xi}$$
During the gas amplification process, the figure of merit is the gas gain $G$, which indicates how many electrons are produced on average for every primary electron generated at position $x_0$ by the incident particle:

$$G = \frac{N(x_e)}{N(x_0)} = e^{\int \alpha(x) \, dx}$$

where $x_e$ is the end of the gas amplification region e.g. the surface of the sense wire. As an example, the first Townsend coefficient of Ar-CH$_4$ (90:10) is given in Fig. 2.6a.

The proportional charge multiplication as described in the previous paragraph takes place only up to a limited electric field. If the field is further increased, secondary processes such as deformation of the electric field due to space charges, and UV photon emission will occur. The UV photons e.g. can start secondary avalanches, and thus the gain is increased by an additional factor which can not be controlled. The schematic drawing in Fig. 2.6b shows the different regions which will be explained briefly in the following list; an example of operation is also given in brackets:

**Region I - recombination**: The electric field is not strong enough to separate all electron-ion pairs - some recombine.

**Region II - ionization**: Electron-ion pairs are separated, but not amplified (ionization chambers).

**Region III - proportionality**: Primary electrons are multiplied as a function of the electric field as described above (proportional chambers).

**Region IV - limited proportionality**: Due to secondary processes, the number of electrons collected is not strongly correlated to the number of primary electrons, but the signal remains localized (streamer tubes).

**Region V - discharges**: Due to photons, the signal propagates throughout the detector: no localized signal (Geiger-Müller counter).
Region VI - continuous discharges: Gas amplification gives way to continuous discharge. Operation of detector is not possible.

The electric field strength and exact conditions at which transitions from one regime to another occur, depend strongly, among other parameters, on the gas mixture. A detailed discussion will be given in Section 2.5.1.

2.5 Design Criteria and Performance of TPCs in HEP Experiments

In this section some important questions about designing a detector for high-energy physics experiments will be addressed, and in the last subsection an overview of some TPCs successfully operated in the past will be given.

2.5.1 Gas Mixtures

In general two gas types, 'counting gases' and 'quenchers', with complementary properties are used in gaseous detectors. The first type is needed for the avalanche multiplication, and therefore it must have a large first Townsend coefficient $\alpha$ at moderate electric fields. Noble gases fulfill this requirement particularly well, since they have only a limited number of excitation modes. A low $W$-value and comparatively low cost suggest the use of argon as a main component. Excited noble gases, however, can return from the excited state to the ground state only by emitting photons. Since the ionization potential of metals (Cu: 7.7 eV) is generally lower than the minimum energy of these photons (Ar: 11.6 eV), photoelectric effects can occur releasing secondary electrons from detector components and leading to permanent discharge in the detector. As a consequence, quenchers with a large number of rotation and vibration modes are needed to dissipate these photons and protect the detector from continuous discharge.

The choice of gases for TPCs involves a number of additional considerations that are mostly concerned with the extremely long drift distances [Gr99p].

- A high drift velocity $\bar{v}_{drift}$ is required to reduce the readout time and occupancy in the detector.
- Low electric fields are necessary to avoid high-voltage problems at the cathode and the field cage.
- A plateau in the drift velocity is helpful to compensate small inhomogeneities of the electric field.
- Low transverse and longitudinal diffusion coefficients in magnetic fields are important to achieve the best possible spatial resolution.
- The attachment coefficient has to be negligible so as to avoid losses of primary electrons during the long drift time.
- The total number of primary electrons per unit length $n_T$ should be large.
- Polymerization due to irradiation (‘aging effect’) should be suppressed.
In applications with high background, a small neutron cross section $\sigma_n$ is favorable.

Typical TPC gases are based on argon and methane, and fulfill most of these requirements as demonstrated in Fig. 2.5. In the TESLA-TDR [Al01,Ip] the three-component mixture Ar-CH$_4$-CO$_2$ (93:5:2) is favored, since the small fraction of CO$_2$ largely retains the desirable properties such as low $E_{\text{max}}$ and high $\sigma_{\text{drift}}$ while decreasing longitudinal diffusion, broadening the maximum and reducing the neutron cross section (see also Table 2.2).

### 2.5.2 Spatial and Momentum Resolution

Since in most cases the TPC is used as the main tracking device, special attention has to be given to attaining the best possible spatial and momentum resolution.

**Single-Point Resolution** The single-point resolution $\sigma_x$ is mainly determined by the number of electrons and the width over which they are distributed. The theoretical limit under ideal conditions is given by:

$$\sigma_{x/z} = \frac{\sigma_{T/L}}{\sqrt{n_T}}$$  \hspace{1cm} (2.6)

where $\sigma_{T/L} = D_{T/L} \cdot \sqrt{\bar{x}_{\text{drift}}}$ is the standard deviation of the electron distribution in transverse/longitudinal direction after a drift distance $x_{\text{drift}}$ and $n_T$ is the total number of drifting electrons. However, several contributions exist that deteriorate the single-point resolution (see [Bl93b, Ca04p]).

One limiting effect is the inclination $\phi$ of a track’s projection in the readout plane with respect to the long side of the readout micro-pads. On the one hand, the track length per pad row is altered, increasing the number of primary electrons per row by a factor of $1/\cos \phi$. On the other hand, the angular pad effect comes from spreading this charge over a larger range, since the center of charge migrates from $x_1$ to $x_2$ as the track moves across the pad (see Fig. 2.7a). This results in a modification of Eq. 2.6 in the transverse case:

$$\sigma_{x,\phi}^2 = \frac{D_{\text{eff}}^2 \cdot x_{\text{drift}}}{n_T \cdot \cos^2 \phi} + \frac{L^2}{12 n_T^{\text{eff}}} \cdot \tan^2 \phi$$  \hspace{1cm} (2.7)
2.5 Design Criteria and Performance of TPCs in HEP Experiments

![Diagram of design criteria and performance of TPCs in HEP experiments.](image)

Figure 2.8: a) Declustering through diffusion: effective number of electrons divided by the total number of clusters per pad, as a function of $\sigma/l$ for two pad sizes [B193b]. b) Example of a large-scale, wire-based detector: variance of the average arrival position as a function of the drift length $L$. a) is the contribution of diffusion, b) the contribution of the angular-wire effect and c) is the sum of both [B193b]. c) squared spatial resolution for the prototype detector in a magnetic field of $B = 4$ T.

In this equation, special attention has to be given to the number of electrons $n_T$ and $n_T^{diff}$. Since electrons are generated in clusters and are not distributed homogeneously along the track path, their positions cannot be considered as independent. From the tracks on the right-hand side of Fig. 2.7a, it becomes clear that clusters with a large number of electrons will lead to an incorrectly reconstructed space-point position, degrading the spatial resolution. Thus, an effective number of electrons $n_T^{diff}$ has to be introduced taking this clustering into account. However, $n_T^{diff}$ is not constant, but depends on many parameters, namely on the average distance between clusters $\lambda$, the pad length $l$ and the standard deviation of the cluster size $\sigma$, which is increased by diffusion. In Fig. 2.8a the quantity $n_T^{diff} \lambda/l$ is plotted. Since the ratio $l/\lambda$ gives the average number of clusters generated per pad row, $n_T^{diff} \lambda/l$ is equal to the effective number of electrons per cluster. On the horizontal scale, the ratio $\sigma/l$ denotes the diffusion in units of pad lengths. The curve shows that with larger diffusion, the effective number of electrons is increased because of the declustering through diffusion effect: Only if electrons are diffused so much that they can pass from one pad row to another - breaking the cluster correlation - are they truly independent and $n_T^{diff} \approx n_T$. The influence of the angular pad effect on the transverse spatial resolution is shown in Fig. 2.8b for a wire-based TPC. Here, the spacing between wires corresponds to the pad size $l$ of the previous discussion. The dashed curve (b) corresponds to the angular-wire effect with an inclination of $\phi = 32^\circ$, a diffusion constant of $D_T = 184\mu m/\sqrt{cm}$, and $l = 4$ mm. For short drift distances this effect dominates the spatial resolution. Therefore, the influence of this effect will be determined in the following for the prototype detector in a 4 T magnetic field (see Chapter 7). As in Fig. 2.8b, the contribution of the diffusion and of the angular pad effect, as well as the sum of both were calculated for inclinations $\phi = 1^\circ$, $2^\circ$, $3^\circ$, $4^\circ$ and $5^\circ$. For this Eq. 2.7 was used with the following values: $l = 12.5$ mm, $D_T = 72\mu m/\sqrt{cm}$ and $n_T = 115$. Since the diffusion is very small compared to the pad size, the declustering through diffusion was approximated by:

$$n_T^{diff} \cdot \lambda/l = 0.2 + 3.2 \frac{D_T}{l^{1/2}}$$

giving a virtually constant value of 0.2 for all drift distances under study. The resulting spatial resolutions depicted in Fig. 2.8 show that for track inclinations...
larger than 1° the angular pad effect dominates the measurement, and the contribution of
diffusion will be negligible. Often \( n_{T}^{eff} \) is expressed by \( n_{T}^{eff} = n_{T}^{i} \), where usual values are
\( \epsilon \approx 0.5 \) [B193b, C404p]. In Eq. 2.7 \( n_{T}^{i} \) is smaller than \( n_{T} \) due to the clustering effect, but
the influence of different cluster sizes is smaller for vertical tracks than for inclined ones, and
therefore usually one finds: \( n_{T} > n_{T}^{i} > n_{T}^{eff} \).

In multi-GEM-based readouts, an additional charge-broadening in the transfer gap be-
tween the GEMs and in the induction gap between the last GEM and the readout board has
to be considered. These contributions are due to diffusion and therefore identical to Eq. 2.6,
but one has to take into account that the number of electrons is increased after every gas
amplification stage by a factor \( G_i \):

\[
\sigma_{x, gaps}^{2} = \sum_{i=1}^{\text{all GEMs}} \sigma_{x, gaps, i}^{2} = \sum_{i=1}^{\text{all GEMs}} \frac{D_{T,i}^{2} \cdot x_{gap,i}}{\left(\prod_{j=1}^{i} G_{j}\right) n_{T}}
\]  

(2.8)

Also, every GEM itself leads to a charge-broadening \( \sigma_{GEM,i}^{2} \). However, the GEMs do
not give a Gaussian shaped contribution, but lead to a concentration of the charge in locally
well-defined GEM holes.

Furthermore, the readout electronics induces electronic noise, thus requiring \( k \) electrons
out of \( n_{T} \) for the signal to rise above the noise. According to [Sa77p] this can be taken into
consideration by changing Eq. 2.6 into:

\[
\sigma_{x, el - noise}^{2} = \frac{n_{T}^{2}}{2 \ln n_{T}} \sum_{i=k}^{n_{T}} \frac{1}{i^2}
\]

Another major effect is introduced by the micro-pad readout. Due to its geometric shape
and finite sampling of the charge cloud, an additional term \( \sigma_{x, pad}^{2} \) has to be considered.
In general, this term depends on the pad geometry and pad size and becomes negligible if a
larger number of pads is hit. For a small number of pads, however, this term can dominate
the spatial resolution. If, for example, only one pad is hit, it is equivalent to the standard
deviation of a rectangular uniform distribution:

\[
\sigma_{x, pad}^{2} = \left( \frac{w_{pad}}{\sqrt{12}} \right)^2
\]

where \( w_{pad} \) is the pad width.

Usually, the constant terms such as \( \sigma_{x, GEM}^{2} \), \( \sigma_{x, el - noise}^{2} \) and \( \sigma_{x, pad}^{2} \) are summarized to form
a global systematic contribution \( \sigma_{x, sys}^{2} \) resulting in:

\[
\sigma_{x}^{2} = \frac{D_{T}^{2} \cdot x_{drift}}{n_{T}^{i} \cdot \cos^2 \phi} + \frac{L^{2} \cdot \tan^2 \phi + \sigma_{x, sys}}{12 \ n_{T}^{eff}}
\]  

(2.9)

Transverse Momentum Resolution A particle’s transverse momentum \( p_{T} \) is measured
by the radius of curvature \( \rho \) of its track in a solenoidal magnetic field:

\[
p_{T} = e B \rho
\]

To determine the transverse momentum resolution one uses the sagitta method as demon-
strated in Fig. 2.7b, and one finds for sagitta \( s \):

\[
s = \rho - \rho \cos \frac{\theta}{2} = 2 \rho \sin^2 \frac{\theta}{4} \quad \theta \ll 1 
\]

\[
s = \rho \frac{\theta^2}{8}
\]
where $\theta$ is the deflection angle. If $L$ is the length of the magnet from the inner radius ($r_i$) to the outer radius ($r_o$) of the active readout area and with $\theta \approx L/\rho$, then the resolution is given by:

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} = \frac{8 p_T \sigma_s}{e B L^2}$$

The error of the sagitta measurement usually has two components that add quadratically: one is due to spatial resolution and one to multiple scattering. In the former case, the Glückstern equation [Gl63p] for $N$ measuring points gives: $\sigma_s = \sqrt{\frac{720}{N+4}} \cdot \frac{\sigma_x}{s}$ resulting in:

$$\frac{\sigma_{p_T}}{p_T} \big|_{sr} = \sqrt{\frac{720}{N+4}} \cdot \frac{\sigma_x}{e B L^2 p_T}$$

A more convenient form is given by:

$$\frac{\sigma_{p_T}}{p_T} \big|_{sr} = \sqrt{\frac{720}{N+4}} \cdot \frac{\sigma_x}{0.3 B L^2}, \quad (2.10)$$

if $B$ is in tesla, $p_T$ in GeV/c and $L$ in m.

Multiple scattering can alter the deflection angle $\theta$. Its central contribution can be approximated by a Gaussian distribution with a width of [We02b]:

$$\theta_{plane}^{rms} = \frac{13.6 \cdot 10^{-3} \text{GeV}}{\beta c p} \sqrt{\frac{L}{X_0}} \left(1 + 0.038 \ln \left(\frac{L}{X_0}\right)\right)$$

where $\theta_{plane}^{rms}$ is the projection of the angle in a plane parallel to the trajectory and $X_0$ the radiation length of the gas alone. The error in transverse momentum due to angle deviation is given by $\sigma_{p_T}^{rms} = p \cdot \sin \theta_{plane}^{rms} \approx p \cdot \theta_{plane}^{rms}$ resulting in a momentum resolution of:

$$\frac{\sigma_{p_T}}{p_T} \big|_{rms} = \frac{13.6 \cdot 10^{-3}}{0.3 B L \beta} \sqrt{\frac{L}{X_0}} \left(1 + 0.038 \ln \left(\frac{L}{X_0}\right)\right)$$

Additional contributions to the transverse momentum resolution, such as track distortion resulting from field inhomogeneities, usually are less significant than the two mentioned above.

Two examples will be given. In the first, the TESLA-TPC is evaluated by taking the design values from [Al01p]: $B = 4$ T, $L = r_o - r_i = 1.256$ m, $N = 200$, $X_0 = 124$ m and $\sigma_x = 2 \cdot 10^{-4}$ m for a drift distance of 2 m.

$$\frac{\sigma_{p_T}}{p_T} \big|_{sr} \approx 2 \cdot 10^{-5} \frac{1}{\text{GeV/c}} \quad \frac{\sigma_{p_T}}{p_T} \big|_{rms} \approx 7.5 \cdot 10^{-4}$$

In the second example, the prototype detector described in Chapter 3 is tested in a 4 T magnetic field, as discussed in Chapter 7: $B = 4$ T, $L = 10$ cm, $N = 8$, $X_0 = 124$ m for the gas alone and $\sigma_x \approx 0.9 \cdot 10^{-4}$ m for a drift distance of 23 cm.

$$\frac{\sigma_{p_T}}{p_T} \big|_{sr} \approx 5.8 \cdot 10^{-2} \frac{1}{\text{GeV/c}} \quad \frac{\sigma_{p_T}}{p_T} \big|_{rms} \approx 1.7 \cdot 10^{-3}$$

The transverse momentum resolution of the prototype detector is determined by the width of the track curvature distribution $\delta \kappa$:

$$\frac{\sigma_{p_T}}{p_T} \big|_{exp} = \frac{e B \delta \rho}{(peB)^2} = \frac{\delta \rho}{\rho^2 e B} = \frac{\delta \kappa}{e B} \quad (2.11)$$
2.5.3 Energy Resolution

Particle identification is an important ingredient in any high-energy physics experiment. At least two different kinds of information, such as total energy $E = \gamma m_0 c^2$, momentum $p = \beta \gamma m_0 c$, velocity $\beta \gamma$ or $p/m = \beta \gamma$, are necessary to distinguish different particles, such as pions, kaons and protons. A TPC inside a magnetic field can perform this task well for moderately relativistic particles, since not only the particle momentum is measured with great precision, but also the specific energy loss per unit length, as given by Eq. 2.1. It can be shown that the latter depends only on $\beta \gamma$ and therefore these two measurements are sufficient to distinguish two particles. In Fig. 2.9 the separation power of the PEP-4 TPC is illustrated.

As discussed in Section 2.2, ionization is a statistical process and the energy loss per unit length follows approximately the Poisson statistic. The long tail to high energies in the deposited charge distribution due to $\delta$-electrons hampers the energy measurement, and therefore two possible solutions are commonly used. For detector calibration, the most probable value (MPV) of energy loss per unit length is commonly preferred to the mean energy loss. (Both values are indicated by an arrow in Fig. 2.3b).

For particle identification, however, the truncated mean is used: Depending on the gas mixture and the number of measuring samples, $n$, 20-40% of the data are removed. Three possible rules for data removal are used: The data are discarded only at the high-energy end, a fixed ratio for both ends is used (e.g. 10% and 30%), or those data samples with the largest absolute distances from the mean energy are sorted out. Often, the best energy resolution is obtained if the cut occurs only on the high-energy end. The remaining data are then used for
the $dE/dx$ determination:

$$
\frac{dE}{dx} = \frac{\sum_{i}^\text{rem. data} E_i}{\sum_{i}^\text{rem. data} L_i}
$$

where $E_i$ is the energy deposit in sample $i$ and $L_i$ its length corrected for both track inclination angles $\phi$ and $\psi$.

The energy resolution achieved by this method scales according to reference [Al80p] with:

$$
\frac{\Delta dE/dx}{dE/dx} = \frac{0.96}{2.35} \cdot N^{-0.46} \cdot l^{-0.32}
$$

where $N$ is the number of samples and $l$ the sample length. By comparing the two detectors mentioned in the last subsection, we expect a degradation by a factor of 3 with respect to the TESLA-TPC’s 4.3% energy resolution for the prototype chamber.

### 2.5.4 The Ion Feedback Challenge

During the gas amplification process, an equal number of electrons and ions is produced. While the electrons are collected very quickly by the sense wires or micro-pads, the ions start to drift towards the cathode. Since they drift much more slowly than electrons (see Section 2.3), a large space charge can be accumulated in the drift region. This can lead to field inhomogeneities and distortions of later tracks. Therefore, a large quantity of ions must be neutralized before they enter the drift region. As a rule of thumb the number of ions that is released by the gas amplification stage into the drift region should not be allowed to exceed the number of ions created by the incident particles. Therefore, the ion feedback $F$ (definition see Section 2.6.1) should be limited to the inverse of the effective gas gain $G$, that is for $G = 5 \cdot 10^3$, an ion feedback of $F \leq 0.02\%$ must be achieved.

In wire-based TPCs, the ion feedback is suppressed by introducing an additional wire plane between the drift region and the ground-wire plane (see Section 2.1 and Fig. 2.2). The principle of operation is shown in the schematic drawings in Fig. 2.10. In a) the field lines of an ’open’ gate are shown, where all gating wires are at the appropriate potential and electrons are able to pass from the drift region into the readout region. This mode is used during data taking. But when the electrons have left the drift volume, the gate is ’closed’ as shown in Fig b). The voltage on each wire is slightly higher or lower than that on its neighbors, so that field lines from the drift region end on one wire, and the field lines from the readout area end on another. Now, slowly-drifting ions coming from below will be collected by the gating grid and neutralized. Since the time between events and the drift time of electrons are both much shorter than the drift time of ions, ions survive several gating cycles following a path similar to the one indicated in Fig. 2.10b.

This scheme has been applied in many TPCs and it works well, as long as the ’gate closed’ time is long enough. However, if the rate of events becomes too high, then the ’gate open’ mode prevails, and more and more ions escape into the drift volume. Since the TESLA accelerator will deliver bunch crossings every 337 ns, it will not be possible to close the gate after every event. A bunch train, however, consists of 2820 single bunches and lasts 950$\mu$s. During this time ions created during the first events will have drifted only about 0.5 cm. Thus, gating at a distance of even a few cm is possible during the long break (199 ms) after each bunch train. Since a continuous operation without gating is favorable, the use of GEMs with their intrinsic ion feedback suppression (see Section 2.6) is considered.
2.5.5 Examples of HEP Experiments

Table 2.3 gives an overview of design and performance of a selection of TPCs that were operated successfully in high-energy physics experiments.

2.6 Gas Electron Multiplier

GEMs were invented by F. Sauli in 1996 [Sa96p] as charge preamplifiers for micro-strip gas counters (MSGCs). Soon afterwards, the full potential of GEMs was realized, resulting in numerous applications mainly based on the combination of several GEMs with a micro-pattern readout board (for example, see references [Mc99t, Ba02p_2]). Today, the GEM technology is well established, and its successful employment in a number of high-energy physics experiments demonstrates its capability.

Optimization of the GEM geometry and production procedure has resulted in a ‘standard GEM’ that is used in most applications. These GEMs consist of a 50 μm thick polymer insulator (Kapton) that is covered with 3 μm thick copper layers on both sides. In this sandwich structure, a hexagonal pattern of micro holes is etched from both sides in a photolithographic process. Due to the simultaneous etching from both sides, the holes acquire a double conical cross section as seen in Fig. 2.11. The dimensions of the hole pattern is indicated in the electron microscope picture and the schematic drawing of Fig. 2.11: The individual holes have a diameter of 70 μm in the copper and 50 to 60 μm in the Kapton. The pitch between the holes is 140 μm. The production process is described in detail in [Ho98t].

For operation, contact with upper and lower electrodes is made and a potential difference is applied. In this way strong electric dipole fields are created within the holes, as indicated for a standard configuration in Fig. 2.11c. As shown in the schematic drawings of Fig. 2.12, electrons drifting in the gas volume above a GEM are collected and guided into a GEM hole. In the strong electric field, they undergo gas amplification and are then released into the gas volume below the GEM. From there, they can either be transferred to another gas amplification stage, or be collected by a micro-pad for readout. In this way, gas amplifications of up to $10^3$ are possible with a single GEM foil. For higher gains, several GEMs can be
### 2.6 Gas Electron Multiplier

<table>
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<tr>
<th>experiment</th>
<th>1</th>
<th>$r_o$</th>
<th>$r_i$</th>
<th>gas mixture</th>
<th>$B$</th>
<th>$N_w$</th>
<th>$N_p$</th>
<th>$A_p$</th>
<th>$\sigma_r$</th>
<th>$\sigma_z$</th>
<th>$\frac{\delta p_T}{p_T}$</th>
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<tr>
<td>PEP-4</td>
<td>1.0</td>
<td>100</td>
<td>20</td>
<td>Ar: 80</td>
<td>1.3</td>
<td>2196</td>
<td>13824</td>
<td>7/7.5</td>
<td>0.15</td>
<td>0.16</td>
<td>0.009</td>
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<td>15</td>
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<td>0.85</td>
<td>144</td>
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<td>19/6</td>
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<td>0.04</td>
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<td>30</td>
<td>Ar: 90</td>
<td>1.0</td>
<td>2800</td>
<td>8192</td>
<td>12/10</td>
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<td>0.3</td>
<td>0.015</td>
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<td>31</td>
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<td>6336</td>
<td>41004</td>
<td>30/6</td>
<td>0.17</td>
<td>0.74</td>
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<tr>
<td>Delphi</td>
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<td>116</td>
<td>32</td>
<td>Ar: 80</td>
<td>1.2</td>
<td>2304</td>
<td>20160</td>
<td>8/7</td>
<td>0.18</td>
<td>0.9</td>
<td>$\approx$ 0.005</td>
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<td>GEMs</td>
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<td>6/2</td>
<td>0.07</td>
<td>0.5</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 2.3: Comparison of TPCs in HEP-experiments. Listed are maximum drift distance $l$, outer and inner radii $r_o$ and $r_i$, gas mixture, magnetic field $B$, number of sense wires $N_w$, number of pads $N_p$, pad dimension in $r$- and $r\phi$-direction, single space-point resolution in $r\phi$- and $z$-direction and momentum resolution $\frac{\delta p_T}{p_T}$ of the TPC alone [Bl93b, Ha84p, An03p, Al01lp].

Cascaded. As an example, a gain calibration curve of a double GEM structure in Ar-CH$_4$ (90:10) is shown in Fig. 2.12. Detailed explanations of signal formation, possible losses of electrons and challenges in designing GEM detectors are given in [Ka04t].
Figure 2.11: a) Micro-electron microscope photograph [Ka04t], b) schematic drawing of a GEM hole with dimensions, c) field strength inside a GEM hole [Ka04t], calculation with MAXWELL.

Figure 2.12: a) Schematic drawing of field lines inside a GEM hole and the signal formation processes: i) an electron is guided into the GEM hole, ii) gas amplification takes place in the middle of the hole, iii) electrons are released into the gas volume below the GEM, and iv) the major portion of the ions are neutralized on the upper GEM electrode, b) dependence of effective gas gain on the sum of voltages applied on a double GEM structure in various gas mixtures [Ka04t].

The multi-GEM setups have demonstrated a number of positive features of which two, the ion feedback and discharge stability, will be discussed in more detail in Sections 2.6.1 and 2.6.2. Besides these two characteristics, another important aspect is the electrical isolation of the multiplication element from the readout plane. This feature makes possible a large variety of read-out geometries, such as double layers of orthogonal, long strips with small pitches [Co96p]. Even silicon pixel sensors have been used to collect the charge released by a multi-GEM structure [Be04p, Co04p]. In addition, the good timing resolution of down to 2 ns and high efficiency have been exploited in, for example, gaseous photomultipliers [Br02p].
2.6 Gas Electron Multiplier

Figure 2.13: a) Naming convention on triple and double GEM structures, b) studies of charge transfers with a triple GEM structure in high magnetic fields [Lo04p].

[Al03p, Ka04t], aging tests with an accumulated charge up to 11.7 mC/mm² were performed and no loss in gain was observed.

Finally the naming convention in multi-GEM structures will be explained (see also Fig. 2.13a: The GEMs are enumerated (GEM1, GEM2, ...) starting with the GEM facing the drift field. The gaps between GEMs are called transfer gaps and, in the case of more than two GEMs, are enumerated starting with the gap between GEM1 and GEM2. The final gap between the GEM facing the readout board and the readout board itself is called the induction gap, since electrons drifting here induce the signal on the pads. Electric fields in the gaps are named according to the corresponding gap: transfer field 1, transfer field 2 and induction field.

2.6.1 Ion Feedback

Of particular interest for the use in TPCs is the intrinsic suppression of ions drifting back into the gas volume above the GEM. In Fig. 2.12a the path of ions is also displayed. They are created during gas amplification and due to their large mass they follow the electric field lines with little diffusion. Since the majority of field lines within the holes end on the upper GEM electrode, most of the ions are neutralized there. Only a small percentage escapes into the gas volume above the GEM.

Since a considerable fraction of the electrons is also lost due to collection on the lower electrode of the GEM, the figure of merit is the effective ion feedback, which is defined by:

$$F = \frac{\text{ions released in the gas volume above GEM}}{\text{electrons released in the gas volume below GEM}}$$

This property depends on a large number of parameters, most notably on the electric field configuration above, below and inside the GEM hole. But also dependencies on hole geometry, gas mixture and magnetic field have been studied by various groups [Ka04t, Lo04p, Lu04t].

In [Lo04p] the authors give a recommendation of how to minimize the ion feedback in triple GEM structures: The gain in GEM1 and GEM2 have a negligible influence, since the number of ions created is small due to the absolute number of electron-ion pairs. The gain in GEM3 should be highest, as ions created here have the highest probability of being neutralized by
Figure 2.14: Discharge probability due to α-particles: a) as a function of electric field and number of GEMs, b) as a function of voltage imbalance in a double GEM structure, c) propagation probability as function of field strength in induction gap [Ka04t].

GEM1 and GEM2. As far as the electric field strengths in the gaps are concerned: During the optimization it was found that the transfer field 1 and the induction field should be maximized and the transfer field 2 minimized. With these settings a minimum ion feedback of 0.2% was reached in a magnetic field of 4 T (see Fig. 2.13b).

2.6.2 Discharge Stability

Another important issue to be considered for a TPC design is operational stability. Breakdown of the gas rigidity leading to gas discharges is a major cause of concern, since it has several undesirable effects in the detector. One consequence is a dead time of the order of several ms and the release of huge numbers of ions into the drift volume. In addition, the GEM or readout electronics might be permanently damaged. Discharges are induced in high-particle-rate environments or by highly ionizing particles, because in both cases, a large amount of charge is released. This leads to intense avalanches and high charge densities inside the GEM holes possibly resulting in charge breakdowns.

Extensive studies have been performed and published in [Ba02p, Ka04t] and for illustration some results are quoted here. During these studies a radioactive $^{243}$Am source emitting low energetic α particles was used to induce discharges, which were detected by monitoring the charge collection on the readout board. The discharge probability per α particle can be seen as a function of the total effective gas gain in Fig. 2.14a for up to three cascaded GEMs. Clearly, the stability improves with the number of GEMs, since lower voltages across individual GEMs are necessary to reach the same effective gas gain. Fig. 2.14b shows the discharge probability as a function of the voltage imbalance in a double GEM structure. A minimum is visible at about 5 to 7%, meaning that the GEM facing the drift volume should have a slightly higher share of the total gain than the lower GEM. Also, the probability that a discharge propagates to the anode plane has been studied. Fig. 2.14c shows the dependence of this quantity on the field strength within the induction gap and the GEM area. As expected, stronger fields enhance the propagation, as does a larger GEM surface that results in an increased stored energy.

The results of Sections 2.6.1 and 2.6.2 lead to contradictory requirements. While the benefits and drawbacks of both optimizations have to be carefully evaluated for a large-scale
system, the preference during the studies presented in Chapter 4.9 was placed on reliability aspects. In addition, the transfer field was set to a default value of $E_t = 2.5 \text{ kV/cm}$ and the induction field to $E_i = 3.5 \text{ kV/cm}$. Also, an imbalance of 10 V between the upper and lower GEM was used.

### 2.7 Time Projection Chamber with Gas Electron Multiplier

Compared to a conventional TPC readout based on wires, a multi-GEM amplification stage offers a number of advantages:

- The electric field configuration provides intrinsic ion feedback suppression in the range of $10^{-2}$ to $10^{-3}$, offering the possibility of continuous operation without gating (see Section 2.6.1).

- The small pitch between the holes increases the granularity of the $r\phi$-readout plane by one order of magnitude.

- Since the electric field lines are parallel up to a distance of 100 $\mu$m above and below the GEM and only small deviations occur inbetween, $\mathbf{E} \times \mathbf{B}$, which were a major source of degradation in wire-based readouts, are largely eliminated.

- The gas amplification region shows no directional preference (as do the wires) and therefore the spatial resolution reduction from wire-angle effects seen in conventional TPCs is avoided.

- Furthermore, the geometry of the readout micro-pads can be chosen independently, and thus be optimized for the needs of the experiment.

- The main signal on the micro-pads is created by charge collection and not by induction. Thus the signal shape and width is dominated by the diffusion in the drift region and not by the readout geometry. This leads to fast and narrow signals improving the double-track resolution, as well in the time dimension as in the $r\phi$ plane.

- In the $z$-direction, the performance also profits from the lack of the ion tail induced by the slow movement of ions in wire-based readouts. In GEM structures, the path of ions to the neutralizing electrode is much shorter and largely shielded by the lower electrode.

A number of aspects remain to be studied before a large-scale detector can be designed and built. The most important issue is whether a gating system is necessary or not. As described in Section 2.6.1, ion feedback can be reduced to the order of $10^{-3}$. Concerning track distortions, however, the figure of merit is the space charge given by the total number of ions per unit of volume. To determine this value more parameters such as gas gain, the drift velocity of ions and the distribution of primary electron-ion pairs throughout the detector must be taken into account and simultaneously optimized. For example, if the electric field in the drift region is reduced, the ion backflow is lowered on the one hand, but on the other hand, the ion drift velocity decreases.

Another open question is the stability and long-term operation of the detector. The effects of discharges and aging in GEM structures have been studied in [Ka04t], but further studies, especially with the chosen gas mixture, are necessary to guarantee stable data taking.
The final aspect described concerns charge spreading on the pads. While it is important for good spatial resolution to have low diffusion and localized charge clusters, it is also important to always hit more than one pad so that the exact track position can be determined. Studies to date have shown that for short drift distances, the favored pad geometry of $2 \times 6 \text{ mm}^2$ rectangles is at the lower limit of this requirement.
Chapter 3

Design and Construction of the Prototype Chambers

To study the performance of a Time Projection Chamber with a readout based on Gas Electron Multipliers (GEMs) two prototype chambers were designed and built. The general design criteria were robustness and a maximum of flexibility, while ensuring high performance. In this chapter, the general detector layout is discussed and a detailed description of the individual components is given.

3.1 General Detector Layout

To allow a maximum of flexibility, a modular design with three parts, drift cylinder, cathode plane and readout area, was chosen. Several versions of each part exists and they can easily be interchanged.

The cylindrical shape for the detector was chosen to avoid corners, which are possible sources of flashovers and field inhomogeneities. The inner diameter measures 20 cm as a result of the diagonal dimensions of the GEM including its frame. The outer diameter of 26 cm is determined by the size of the flanges needed to join the detector elements. To test the influence of high drift fields of - up to 1 kV/cm - on the one hand, and long drift distances on the other hand, two drift cylinders were built. One has a maximum drift distance of 12.5 cm and the other 25 cm (see Fig. 3.1). The total gas volumes amounts to 3.9 and 7.8 l, respectively.

To reduce the radiation length seen by particles from external radioactive sources, windows with a minimal amount of material have been foreseen: In the drift cylinders, areas 30 mm in width and 5 mm in length were spared out at opposite positions, so that low energetic particles can enter and exit the detector. The 25 cm drift cylinder features five of these double windows (at 3.9 cm, 8.3 cm, 12.5 cm, 16.3 cm and 21.1 cm), whereas the short cylinder has two (at 3.9 cm and 8.3 cm). In addition one version of the cathode plane has several circular windows of 40 mm diameter.

To ensure the high level of gas purity required for long drift distances and to avoid detector aging as a result of outgassing of components, special attention was focused on the selection of materials. Experience gained with the construction of the GEM detectors [Al01_2p] for the COMPASS experiment\(^1\) has strongly influenced the design of this prototype TPC [Ka04p_1].

\(^1\)Twenty triple-GEM detectors are used in the Small-Area-Tracker (SAT) of the hadron experiment COM-
Main components facing the gas volume consist only of copper, Kapton and fiber-glass, which are well-established materials for use in gaseous detectors. For functionality reasons, smaller elements of different materials had to be introduced: O-rings for sealing and PUR\(^2\) pillars and screws for mounting of the GEMs. Everything was assembled with the non-outgassing glue Araldit AY103 plus hardener HD991. After construction, the detectors were baked out for several days at a temperature of 70\(^\circ\) C, a process which accelerates the outgassing of any residual impurities that may be present.

With the help of a system of pillars and spacers, the gas amplification stage can easily be modified for the use of GEMs, Micromegas or a multi-wire readout. For the results described in this thesis, two GEMs of standard geometry with spacings of 2 mm between the GEMs and 2 mm between the lower GEM and the readout board are used.

The detector design meets all of the aforementioned design criteria and has been operated successfully in a number of different environments. The authors of reference [Ko06p] have copied this design for studies of the use of a GEM-based TPC in the PANDA experiment\(^3\).

### 3.2 Drift Cylinder

The drift cylinder confines the gas volume while ensuring a high homogeneity of the electric field. Therefore, the main design requirements for the drift cylinder are gas tightness, no outgassing of materials and a close succession of well-defined electrical potentials. Further criteria are a low material budget, sufficient electrical insulation for operation up to 12.5 kV and robustness, which allows easy mechanical handling. For these reasons, a multi-layer design was chosen. A short overview of the various layers is given in Table 3.1, and a schematic view of the drift cylinder design is shown in Fig. 3.2a.

During construction an aluminum pipe was used as a mold, and the various layers were glued on top of each other consecutively. The field cage, which is the innermost layer, consists of two independent sets of staggered ring electrodes separated by a Kapton foil 125 \(\mu\)m thick. The ring electrodes are made of 18 \(\mu\)m thick copper, have a width of 3 mm, and are arranged

\(^{1}\)polyurethane

\(^{2}\)Proton AN\(\bar{\text{p}}\)pion Detector Array at the GSI, Darmstadt, Germany
### 3.2 Drift Cylinder

<table>
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<td></td>
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Table 3.1: Overview of drift cylinder layers.

Figure 3.2: a) Schematic oblique view and cross section of the drift cylinder, b) percentage contribution of individual layers to total material budget.

with a pitch of 4 mm. The rings of the outer layer are shifted by 2 mm with respect to the inner rings. For the long (short) drift cylinder there are a total of 60 (29) ring electrodes in the inner layer and 59 (28) in the outer layer. The homogeneity of the electric field can be estimated by a formula given in reference [Bl93b]: If inhomogeneity is defined as the ratio between the transverse and the main field components, it decays with \( e^{-2\pi t/\Delta} \), where \( t \) is the distance from the field cage and \( \Delta \) is the pitch of the ring electrodes. It follows that
inhomogeneities of $10^{-4}$ are reached at a distance of about 6 mm from the field cage. This is still far from the active area of the GEM.

A 125 μm thick Kapton foil is then added for electrical insulation. It has a dielectric strength of about 19 kV (see reference [Du97m]). For reduction of the material budget the windows mentioned in Section 3.1 consist only of the field cage and this Kapton foil; therefore, the drift cylinder may not be operated at voltages higher than 19 kV. The windows have been placed between two outer ring electrodes, and in the window areas the gap between these ring electrodes has been increased to 5 mm by thinning the adjacent rings to a width of 1 mm (see Fig. 3.2a). The field homogeneity is not affected, since the inner layer of ring electrodes remain unaffected.

Mechanical stability and additional electrical insulation is provided by a honeycomb sandwich, which consists of a 350 μm thick Ferrozell layer, a 3 mm thick Nomex honeycomb structure and a 150 μm thick Ferrozell layer.

The outermost layer is a 50 μm thick copper foil, used to define the ground potential and to shield the detector from electronic noise.

The total material budget of this multi-layer structure is 1.1% of a radiation length $X_0$. The absolute contributions of the individual layers can be seen in Table 3.1, whereas in Fig. 3.2b, the percentage contribution of the individual layers to the total material budget is given. Obviously, the copper layers contribute most, and surely have the highest potential for further optimization. In contrast, the window area consists of only 18 μm copper, 250 μm Kapton and 80 μm glue resulting in a material budget of 0.25% of a radiation length $X_0$.

To adjust the electrical potential of the ring electrodes, they are connected to two independent resistive voltage dividers, one for the inner layer and one for the outer layer. The dividers have been placed outside of the gas volume to avoid any heating of the gas, electric field inhomogeneities or induction of gas impurities due to possible outgassing of resistors or tin solder. This is why the field cage had to be folded and led through the outer layers of the drift cylinder. The resistors connecting the ring electrodes are 10 MΩ resistors with a precision of 1% and a temperature coefficient of $5 \times 10^{-5} \text{ K}^{-1}$ (type MB (207 from BComponents, further details see reference [Bc00m])). For the long (short) drift cylinder, there are 59 (28) resistors for the inner layer and 58 (27) for the outer layer. The first and last strip of the outer layer are connected via a 5.1 MΩ resistor to the corresponding strip of the inner layer and a HV connector. For safety reasons, the resistive voltage dividers were sealed with Dow Corning R4-3117 and Polyurethane (VOSS CHEMIE K6T plus K6S-T-H) (see Fig. 3.3c and d). The total resistivity of the voltage divider was verified up to 1 kV with a Keithley 6517A device [Ke96m] (resulting in $294.5 \pm 0.6$ MΩ, see Fig. 3.3a) and up to 12.5 kV with an HCN 14-12500 F. u. G. power supply (resulting in $296.2 \pm 1.3$ MΩ, see Fig. 3.3b). The total power dissipation therefore is therefore 0.34 W at a 10 kV potential difference.

### 3.3 Endcaps

The endcaps confine the gas volume at the front surfaces of the cylinder and contain the main electrodes which form the electric field. In addition, the gas amplification stage and the micro-pad readout are affixed on the anode side.
3.3 Endcaps

Figure 3.3: Calibration of resistor chain: a) current versus voltage measurement with Keithley 6517A, b) Current versus voltage measurement with HCN 14-12500 F. u.G. power supply, c) resistor chain of short drift cylinder before sealing, d) resistor chain of long drift cylinder after sealing.

3.3.1 Cathode Plane

The highest electrical voltage of the system is applied to the cathode plane, and for this reason the main design objectives are good electrical insulation and mechanical flatness to avoid field distortions. The choice of materials for the cathode plane, driven by the aforementioned criteria, fell to Stesalit, copper and Kapton only. Two versions of the cathode plane were implemented and are shown in Fig. 3.4. The first version consists of a 0.3 mm thick, polished copper plate, glued to an insulating Stesalit carrier plate. This design provides a high degree of flatness and excellent electrical insulation. In the second design, the electrode consists of a 50 μm thick Kapton foil with a 3 μm thick copper layer on one side. The Kapton foil is glued to a Stesalit carrier that features six circular irradiation windows with a diameter of 40 mm and a material budget of 0.04% X₀. This design is optimized for usage with radioactive X- or β-ray sources.

Figure 3.4: Cathode endcaps: a) photograph of the outside of the cathode endcap without windows, b) photograph of the inside of the cathode endcap without windows, c) photograph of the outside of the cathode endcap with windows.
3.3.2 Anode Plane

The anode plane functions as the readout area. From inside out, it begins with a field correction plate that prevents distortions of the electric field outside the square GEMs. A 100 x 100 mm² large opening exposes the active area of the GEMs, placed directly below the field correction plate (see Fig. 3.5). The GEMs and the field correction plate are mounted with PUR pillars, the 2 mm gaps between the GEMs (transfer gap) and between the lower GEM and the readout board (induction gap) are realized with Teflon spacers. The PUR pillars are affixed to the circuit board that contains the readout micro-pads, HV feed-throughs and the enclosing ground plate. Since several different setups were used to fulfill different demands, the layout of the circuit boards and of the remaining readout areas differ significantly. The three major designs are described in the following paragraphs.

Readout with long strips  This readout area was designed for readout electronics based on CAMAC ADCs, which will be described in Chapter 4. The readout board is shown in Fig. 3.5a. It provides one-dimensional information and consists of 126 horizontal strips with lengths of 8 cm and a widths of 0.45 mm. The strips are arranged with a pitch of 0.6 mm and have wire feed-throughs on one side alternately (see Fig. 3.5b). Two long vertical strips on each side serve as veto strips to ensure that the full signal is recorded. The wire feed-throughs are soldered to a connector for preamplifiers. To mechanically reinforce the endcap, the circuit board is mounted on a 1 cm thick Stesalit carrier on which the front-end electronics are also mounted (see Fig. 3.5c). A 0.5 mm thick copper plate gives additional shielding against electronic noise.

The HV feed-throughs and connectors necessary for operating GEMs and the field correction plate are encapsulated by a metal box that contains electronic filters, protective resistors (see Section 3.4.2) and connections for a temperature sensor inside the gas volume (see Section 3.4.4).

Readout with long rectangular micro-pads  Fig. 3.6 shows the readout board which was used, with electronics designed for the STAR experiment (for more details concerning the
3.3 Endcaps

Figure 3.6: Readout area with long rectangular micro-pads (1.27 × 12.5 mm²): a) schematic oblique view and cross section, b) photograph from rear.

electronics see Chapter 5). The readout board consists of a 1.6 mm thick fiberglass insulator (G10), which also serves as a carrier. The micro-pads and ground electrode are made of copper passivated with gold. The pads have a size of 12.4 × 1.17 mm² and are arranged with pitches of 12.5 mm and 1.27 mm. They are grouped in 8 rows of 80 columns, thus covering the total active area of the GEMs. Vias are positioned in such a way as to adapt the pitch of the signal pads to the one-tenth-inch pitch of the soldering pads on the rear (see inset of Fig. 3.6a). Since only a limited number of electronic channels were available at the time of these studies, only the central 32 rows are brought out to the connectors on the rear. The outer pads are connected and grounded via a 1 MΩ resistor to avoid floating potentials.

Flexible readout with interchangeable micro-pads In Chapter 9 the influence of various micro-pad geometries on the spatial resolution is discussed. To test these pad geometries,

Figure 3.7: Flexible readout area with various micro-pads: a) schematic oblique view and cross section, b) photograph from rear, c) insert with micro-pad readout board.
3 Design and Construction of the Prototype Chambers

Figure 3.8: General layout of readout planes: a) photograph of pad side, b) schematic drawing of areas with different readout connections, c) photograph of the back side showing connectors and 1 MΩ resistors for grounding.

A readout area was designed where the micro-pads can be quickly and easily interchanged, leaving the remaining endcap, and in particular the GEMs, unaffected. The endcap and an exemplary pad geometry are shown in Fig. 3.7. The endcap consists of a large circuit board (as ground electrode) and a 10 mm thick Stesalit plate for mechanical reinforcement. The HV feed-throughs, PUR pillars and gas inlet are implemented on the circuit board, but below the GEMs a 100 × 100 mm² large area has been spared out. Inserts with the desired pad geometry can be installed from the outside without removing the endcap or the GEMs from the detector. They are held by twelve screws and sealed with an O-ring. The inserts are manufactured with a precision of better than 0.2 mm.

The general layout of the micro-pad readout boards is shown in Fig. 3.8. To ensure a homogeneous ground density, the complete board surface was covered with the same pad geometry. These pads have been grouped into larger areas of different functionality (see Fig. 3.8b). The pads on the outside are connected with thin metalized strips to a large surface grounded via a single 1 MΩ resistor. Pads adjacent to the active readout area are grounded individually via 1 MΩ resistors to match the input impedance of the FEE cards. The active area features two different regions. While most pads are read out by a single electronic readout channel, some pads had to be combined to form pads with five times the surface.

3.4 Support and Infrastructure

In this section the infrastructure necessary for operating the prototype TPC is described.

3.4.1 Mechanical Support

When operated with the STAR electronics, the detector and front-end electronics are mounted on a support structure made of aluminum bars and perforated aluminum sheets. This construction serves several purposes: It is a mechanical support ensuring a stable setup of the detector and allows nearby placement of the electronics, reducing cable lengths and thus noise induction. In addition, the structure defines the main grounding point to which all relevant parts of the detector and readout electronics are connected. Finally, it is a good heat sink,
3.4 Support and Infrastructure

Figure 3.9: Photographs of a chamber with long drift cylinder mounted on various mechanical support structures: a) support for cosmic ray tests and beam tests at CERN, b) support for tests in high magnetic fields at DESY, c) support for beam test at DESY.

absorbing and dissipating the heat generated by the front-end electronics. Since all materials are non-ferromagnetic, the supports can also be used in magnetic fields.

Fig. 3.9 shows the detector with long drift cylinder mounted on three different support structures. In picture a) a general purpose support is shown which served for the cosmic ray study discussed in Chapter 6 and the beam test conducted at CERN (see Chapter 8). It is optimized to provide maximum mounting flexibility for the front-end electronics. In particular, it is possible to plug the electronics into the connectors of the readout board directly. In picture b) a support adapted for tests in high magnetic fields at DESY is shown (see Chapter 7). Here the setup had to fit into a small opening with a diameter of 27 cm. Picture c) shows the support designed for the beam test at DESY (see Chapter 9). Due to the small aperture of the dipole magnet used, a very flat support structure with a total height of 6 cm was designed.

3.4.2 Electrical Power

To generate an electrical drift field of high homogeneity and to allow easy adjustment of the electric potentials with a minimum number of HV power supplies, a HV box was constructed. A diagram of the circuit is shown in Fig. 3.10: The high-voltage is supplied by a C.A.E.N.

![Diagram](https://example.com/diagram.png)

Figure 3.10: a) Diagram of electric potential adjustment for electrodes, b) photograph of HV box.
SY527 HV power supply frame [Ca97m]. The frame is equipped with a module producing voltages up to 6000 V and can be computer controlled via an RS-232 connection. Alternatively, an HCN 14-12500 F.u.G. power supply for voltages up to 12.5 kV is available. This voltage is split into two lines, one being filtered and connected to the cathode plane, the other line being connected via an appropriate resistor to the ring electrode closest to the cathode (ring 1). The ring electrode closest to the field correction plate (ring 59/60) is then connected to the HV box again. Here the voltage is adjusted and filtered for the field correction plate, and finally the current path is closed via a series of resistors and potentiometers.

This scheme allows setting two parameters (drift field strength and field correction plate potential) with the help of two free variables (the HV potential and the total value of the resistors between field correction plate and ground), while taking all other boundary conditions into account (potential of upper GEM and length of drift cylinder). Whenever any modification is made, the value of the resistor between field correction plate and ground is redetermined by a ten point voltage-current measurement procedure.

Each electrode of the GEM electrodes is powered by an individual channel of the power supply, providing a maximum degree of flexibility. To reduce electronic noise, filters (see Fig. 3.11) were used with the readout board with long strips. The 50 pF capacitor close to the GEM was used only at the lower electrode of the lower GEM to decouple the signal, as will be described in Chapter 4. For space reasons the filter could not be connected to other readout areas, and 10 MΩ resistors were used instead. The current in the feed lines to every GEM-electrode is monitored by nano-Ampere meters (CUMO V3.0 see reference [Be99m]) during operation.

3.4.3 Gas

To guarantee the highest possible purity of the gas mixture in the drift volume, a high-quality gas system is required. As demonstrated in reference [Le02l], a number of precautions have to be taken to ensure a sufficiently clean gas mixture for this purpose:

- Flux of at least 80 cm³/min is recommendable.

- Supply and exhaust lines should be made of copper or stainless steel; PVC or silicon rubber pipes are pervious to water and oxygen.

- An oxidizer should be used directly in front of the gas inlet, removing oxygen and water remnants.

A permanent gas system is installed at the Karlsruhe laboratory. The system consists of stainless steel pipes and a gas mixing unit from MKS Instruments (mass flow meter Type 1179A and 4-channel control unit, Type 247D - see references [Mk97/1m, Mk97/2m]). With
this unit two gases can be mixed. In front of the chamber an oxisorber is installed, and a 15 m long exhaust pipe ending in a bubbler prevents upstream diffusion into the chamber.

In contrast, new gas systems had to be built before the beam tests or tests in high magnetic fields. For this, copper supply and exhaust lines with a length of roughly 20 m each were installed in advance and flushed for several days prior to use. A premixed gas was used and the gas flow was regulated with a mechanical flow meter (Fischer & Porter Präzisionen-Meßrohr FP 1/8-08 G-5/81) to about 200 ccm/min. As in the laboratory an oxisorber (Messer Griesheim GmbH) directly in front of the detector gas inlet was used to guarantee the high purity of the gas (less than 100 ppb O\textsubscript{2} and H\textsubscript{2}O vapor, see reference [Mem]). Bubblers filled with silicon oil were used to create an overpressure within the gas system to avoid contamination of the counting gas.

### 3.4.4 Environment

Parameters such as gas pressure and gas temperature strongly influence the measurements and have to be monitored for later calibration of the data. For the measurement of atmospheric pressure, a sensor with integrated signal conditioning and temperature compensation is used (Motorola MPX 4115A - see reference [Mo01m]). It has a maximum error of 1.5\% and a sensitivity of 45 mV/kPa for its analog output signal. The room temperature is recorded by a monolithic temperature sensor with on-chip signal conditioning (Analog Devices AD22103 - see reference [An95m]). The typical constant offset is about 0.5 K and a typical additional error of 0.75 K over the total temperature range has to be taken into account. Finally, the gas temperature inside the detector at the readout plate was measured by a temperature-dependent platinum resistor (PT1000 of Heraeus sensor M-FK 1020, class B). It has a tolerance of about 0.4 K at 293 K and was combined with a precision resistor with a very low temperature coefficient of 15 ppm/K.

The supply voltages are delivered by a low-voltage module in the C.A.E.N. power supply frame. All three measurements are digitized by a PC-based I/O-card (BMC Messsysteme PC201TR - see reference [Bm99m]). A schematic drawing of the circuit for measuring the three environment variables is shown in Fig. 3.12a.

The two chip-based sensors are calibrated by the manufacturer with sufficient precision, but the PT1000 sensor was calibrated with ice-water (mean = (273.18 ± 0.01) K) and boiling water (mean = (373.99 ± 0.01) K). The results can be seen in Fig. 3.12b and c. To reduce
Figure 3.13: Overpressure inside the detector: a) as a function of gas flux, b) as a function of exhaust line length added to the standard setup, c) overpressure per meter exhaust pipe at different gas fluxes. In (a) and (c) the function $f(x) = p_0 + p_1 \cdot x + p_2 \cdot x^2$ is fitted to the data.

Statistical effects, such as electronic noise, the measurements are normally taken 50 times and an average is calculated.

To determine the absolute pressure in the detector, the overpressure with respect to the atmospheric pressure was measured. For this, a precision pressure transducer (Sensortechnics 142SDC30A-PCB, see reference [Se63m]) was placed behind the chamber in the Karlsruhe laboratory. Fig. 3.13a shows the overpressure of the standard setup as a function of the gas flux. The data in Chapters 4 and 6 were taken at a flux of 80 cm$^3$/min., and therefore the overpressure inside the chamber was 1.5 mbar. Also, additional gas pipes with an inside diameter of 10 mm were added to measure the effect of the exhaust line length. Fig. 3.13b shows the additional pressure caused by the extra pipe lengths for various gas fluxes. A straight line is fitted to the data giving the overpressure per meter exhaust line, which is shown in c).
Chapter 4

Measurement of Basic Detector Parameters with Radioactive Sources

For evaluating the prototype chambers, and for measurements of basic detector parameters such as drift velocity, diffusion coefficients and temperature dependence, a readout electronics based on CAMAC\(^1\) was developed. Fig. 4.1 shows a photograph of the experimental setup: In the center of the picture the TPC is shown with the readout board with long strips. On the left side, the HV power supply, amplifier modules, nano-ampere meter and the CAMAC

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\(^1\)Computer Automated Measurement And Control, a computer-controlled electronics standard used in nuclear and particle physics, for details see reference [Le87b]
crate can be seen. The gas mixing unit, HV power supplies for scintillators and the NIM\textsuperscript{2} electronics for the trigger logic are mounted in the right-hand rack.

In this chapter the measurement of drift velocity is described first. A description of the complete readout chain, the analysis methods and finally the results will also be presented.

4.1 Drift Velocity of Electrons

The drift velocity measurement is a basic test of any prototype chamber. The drift velocity is sensitive to gas impurities as well as to drift field inhomogeneities. Therefore, the dependence of the drift velocity on drift distance, electric field and gas mixture was studied.

4.1.1 Experimental Setup and Analysis Method

A schematic drawing of the experimental setup is shown in Fig. 4.2. Tracks are created with a radioactive $^{90}\text{Sr}$ source that is placed on top of one of the windows of the drift cylinder. The source has a small aperture with diameter of a 1 mm and emits 2.283 MeV $\beta^-$-rays. A scintillator with an active area of $10 \times 1 \text{ mm}^2$ is placed close to the corresponding window on the opposite side of the drift cylinder. $\beta$-particles traversing the chamber create a signal in the scintillator, which is amplified (LeCroy Model 612A) and converted into a digital signal

\textsuperscript{2}Nuclear Instrument Module, an electronics standard used in nuclear and particle physics, for details see reference [Le87b]
by a discriminator (LeCroy Model 821). This trigger signal starts a time measurement with the CAMAC-TDC.

The electrons liberated by the incident particle drift through the gas volume and are finally amplified by the GEMs. A considerable fraction of the electron signal is collected on the lower side of GEM2. This signal is decoupled from the GEM electrode by a capacitor (see Section 3.4.2), amplified (Ortec 142-B preamplifier, Ortec 474 Timing Filter Amplifier) and converted into a digital signal by a constant-fraction discriminator (Ortec 934). It is then used as a stop signal for the time measurement of the CAMAC-TDC.

A time spectrum as recorded by the TDC (a modified LeCroy Model 2228) is shown in Fig. 4.3a. A Gaussian function is fitted to the peak, and the mean value is converted to a drift time by a linear correlation obtained by a TDC calibration (see Fig. 4.3b). This TDC calibration was performed by splitting a test pulse and by determining the time delay between the two signals in ADC counts when one signal was delayed for a known time period. The result of the drift time measurement must be corrected for two effects: First, the drift time of electrons in the gap between GEM1 and GEM2 has to be accounted for. Since the width of the gap and the drift velocity are known (see MAGBOLTZ calculation in Fig. 2.5) this correction is easily calculated and is several tens of nanoseconds. In addition, the different cable and electronics delays of the start and stop signals have to be considered. They are obtained by the TDC calibration, and are in the order of 200 ns.

From the corrected drift time $t_{\text{drift}}$ and the known drift distance $x_{\text{drift}}$, the drift velocity can be inferred: $v_{\text{drift}} = \frac{x_{\text{drift}}}{t_{\text{drift}}}$.

4.1.2 Results

Measurements were performed as a function of drift length and electric field. Fig. 4.3c shows as an example the drift distance as a function of the uncorrected drift time for Ar-CH$_4$ (90:10) with an electric field of $E = 135$ V/cm. The linear correlation indicates good homogeneity of the electric field and the slope of the straight line gives a drift velocity of $(5.49 \pm 0.08)$ cm/$\mu$s. The time offset can be determined to be $(253 \pm 2)$ ns, which corresponds well with the two corrections mentioned above.

With the short drift cylinder, the drift velocity was determined up to an electric field of 800-900 V/cm. Fig. 4.4 shows the result for two gas mixtures together with calculations from
Figure 4.4: Drift velocity of electrons as a function of electric field: a) Ar-CH$_4$ (90:10), b) Ar-CH$_4$ (79:21). Lines are results of calculations from the GARFIELD interface to MAGBOLTZ at $p = 1.0$ atm and $T = 300$ K.

the GARFIELD interface to MAGBOLTZ. The statistical errors in these figures are smaller than the marker sizes. Additional systematic errors have been estimated conservatively and are displayed in the figure. These errors include:

- Variations of the electric field, which have been estimated to a maximum of 3% due to uncertainties in the total cylinder length (1 mm), resistor values, the voltage applied and gas pressure in the chamber.
- Uncertainties in drift length ($\pm 1.5$ mm), cable delay (10 ns) and errors of the correlation between TDC units and time.

Both gas mixtures show good agreement with the calculation, in particular at the maximum of the drift velocity, the typical operating point of a TPC.

4.2 Experimental Setup

In further tests cluster sizes and charge depositions by X-rays from a $^{55}$Fe-source were studied. The readout board with long strips as described in Section 3.3.2 was used with a new, specially designed electronics readout chain with 128 channels. A schematic view of this electronics is given in Fig. 4.5.

The preamplifiers are based on those used in the TPC of the ALEPH$^3$ experiment. Hence, they are designed for the signal shape of a wire-based TPC readout. Due to the long ion tail of those signals, an electronic tail cancellation was implemented, leading to a quasi-Gaussian signal shape. But because the negative signal of the GEM readout has no ion tail, tail cancellation leads to a positive overshoot (see Fig. 4.7a).

To reach a sufficiently high packing density, the circuit boards had to be rearranged and placed in a new housing (see Fig. 4.6a). Special attention was given to obtaining sufficient

$^3$ALEPH is one of the four large experiments at the LEP-collider, CERN, Geneva, Switzerland.
Figure 4.5: Schematic drawing of CAMAC-based readout chain and additional temperature and pressure sensors T and p.

Figure 4.6: Close-up view of individual parts of readout chain: a) ALEPH-based preamplifier with new housing, b) photograph of a 16-channel amplifier module, c) circuit of amplification module for one channel.
thermal energy dissipation, for which a cooler was mounted on each 16-channel preamplifier.

The preamplifiers were connected via shielded twisted-pair cables to amplifier modules. These amplifiers were designed to combine the differential output signals of the preamplifiers and to additionally amplify the signal. An amplification factor of about eight was achieved with a low-noise, high-bandwidth operational amplifier (Analog Devices AD8065, see reference [An01m]). The circuit is shown in Fig. 4.6c. The output signal of the amplifier module was delayed by 64 ns to allow the trigger electronics to create a gate open signal for the CAMAC-ADCs (LeCroy 2249W).

The data of the digitized signals were collected by a PC.

The trigger signal was obtained in a manner similar to the stop signal for the drift velocity measurement: The signal from the lower side of GEM2 was decoupled by a capacitor, amplified (Ortec 142-B, 474 and LeCroy 612A) and then split in two. One part of the signal was also delayed by 64 ns and digitized by a CAMAC ADC, whereas the other part was used without a delay to generate the gate signal needed by the ADC. The length of the gate signal was adjusted to the signal shape, so that only the negative main signal was accepted and the positive overshoot was ignored (see Fig. 4.7a).

Pedestals and noise were determined in dedicated runs, and the result is depicted in Fig. 4.7: The charge distribution of a single channel during the pedestal and noise run is indicated in the inset of c). These histograms were fitted with a Gaussian function. The resulting pedestals given by the mean of the Gaussian functions are shown for all 128 channels in Fig. 4.7b and the noise levels are given by the standard deviations in Fig. 4.7c. For the readout chain of the GEM signals, similar values were found.

An inter-strip calibration was performed using a pulse generator. A pulse with fast rise time (50 ns) and slow fall time (500 μs) was fed to the circuit shown in Fig. 4.8a. The pulse height was adjusted to be similar to that of real signals. The calibration factors $c_i$ shown in Fig. 4.8b are given by:

$$c_i = \frac{p_i}{N_{ch} \sum_{j=1}^{N_{ch}} p_j}$$

where $p_i$ is the recorded test-pulse charge of the respective channel and $N_{ch}$ the number of channels.

To have a good localization of the photon beam in the drift direction, various collimators
with aperture angles between 3.3° and 24.3° were used. As a result, the primary conversion-point error in the drift direction is as small as 3 mm when the photon converts in the middle of the detector.

4.3 Analysis Method

The analysis was performed with a C++ program making use of the ROOT library [Br03m]. At first the pedestals were subtracted, and the data were corrected with the inter-strip calibration factors mentioned in the last section. Then clusters meeting the three following requirements were searched for:

- The charge collected on each of the veto-strips (see Section 3.3.2) must be less than three times the electronic noise of the strip.

- The highest charge collection on a single strip has to be ten times the electric noise of this strip.

- This strip must be between strip numbers 5 and 121.

These requirements ensure that neither edge of the reconstructed cluster is significantly cut off, i.e. that the cluster charge is completely collected. The cluster definition includes all strips that surround the strip with the highest charge collection, and that have a charge more than twice their respective electronic noise values.

During the subsequent analysis two different approaches are used to quantify the three cluster properties width, charge and position. This is done by determining the full width at half maximum (FWHM), adding up the various charges of the relevant strips and calculating the cluster’s center of gravity (COG). The second method is based on fitting a Gaussian function to the charge distribution as a function of the strip number: This gives the standard deviation (σ), integrated area below the function, and average value. While the last two values correspond directly to the cluster charge and COG of the first method, the standard deviation and full width at half maximum are related by:

\[
\text{FWHM} = 2\sqrt{2\ln 2} \sigma = 2.355 \sigma
\]
Figure 4.9: Sample histograms of analysis: a) dependence of collected charge on strip number of a single event. A fit with a Gaussian function, the FWHM and the total collected charge are indicated. In b)-f) sample distributions of these parameters are shown for a drift distance of 8 cm in Ar-CH$_4$ (90:10) and a drift field of 135 V/cm: b) FWHM of clusters, c) standard deviation of Gaussian fit to clusters, d) cluster charge by 'summing all strips', e) cluster charge according to the integral over Gaussian-fit function, and f) dependence of cluster position on strip number.

The two methods are illustrated for the same event in Fig. 4.9a: The charge distribution of strips 56 to 74 is shown, and the first method gives a FWHM of 6 strips (indicated by the dashed line), a cluster charge of 5847 ADC counts (shaded area) and a COG at a strip position 65.49. The Gaussian function indicated by a dash-dot line gives virtually identical values: a standard deviation of 2.39, integrated area of 5820 ADC counts and cluster position of 65.54.

The results are histogrammed for a large number of events, and examples are shown in Fig. 4.9: b) and c) show the distribution of the two cluster-width definitions and d) and e) show the charge spectra of the two methods. In f) the dependence of distribution on the strip number is shown. Shape and physics implications of these results and histograms will be discussed in the following sections.

The signal decoupled from the lower side of GEM2 was also analyzed. The pedestal-corrected spectrum can be seen in Fig. 4.10, where a) shows the collected charge of all events and b) only of those events where a cluster fulfilling the aforementioned requirements was reconstructed. Clearly, the spectrum with all events contains a background that is cut off around 200 ADC counts due to trigger configuration. The required coincidence with a reconstructed cluster on the readout strips completely suppresses this background, suggesting that it originates from events where only a fraction of the total primary charge was amplified by the GEM. This is the case, for example, if the cluster is very close to the edge of the GEMs'
Figure 4.10: Charge spectra of signal decoupled from GEM2: a) all events, b) events where a cluster was reconstructed on strips.

active area.

4.4 $^{55}$Fe Spectrum

The spectrum of a $^{55}$Fe source is shown in Fig. 4.9c, f and in Fig. 4.10. It has two prominent peaks. As described in Section 2.2 the larger one is the photopeak ($pp$) originating from events in which the complete energy of 5.9 keV is deposited in one place. The second peak, situated at about half the energy, is the argon escape peak ($ep$) coming from events where a fluorescence photon escapes from the primary conversion. Since both energy depositions, 3.0 keV and 2.9 keV, contribute to this peak, an average energy of 2.95 keV is assumed for further discussion.

Two Gaussian functions can be fitted to the spectrum simultaneously:

$$
 f(E) = \frac{C_{pp}}{\sqrt{2\pi} \sigma_{pp}} e^{-\frac{1}{2} \frac{(E-E_{pp})^2}{\sigma_{pp}^2}} + \frac{C_{ep}}{\sqrt{2\pi} \sigma_{ep}} e^{-\frac{1}{2} \frac{(E-E_{ep})^2}{\sigma_{ep}^2}}
$$

(4.1)

where $C_{pp}$ and $C_{ep}$ are constant multiplication factors, $E_{pp}$ and $E_{ep}$ are the mean energies and $\sigma_{pp}$ and $\sigma_{ep}$ are standard deviations of both peaks.

The photopeak of the spectrum in Fig. 4.9c, for example has a mean of $E_{pp} = (5870 \pm 2)$ ADC counts and a standard deviation of $\sigma_{pp} = (535 \pm 2)$ ADC counts. Therefore, the energy resolution of the detector for 5.9 keV photons is:

$$
\frac{\sigma_{pp}}{E_{pp}} = (9.11 \pm 0.03)\% \quad \leftrightarrow \quad \frac{FWHM_{E,pp}}{E_{pp}} = (21.45 \pm 0.07)\%
$$

Due to the lower number of primary electrons the values worsen for the escape peak:

$$
\frac{\sigma_{ep}}{E_{ep}} = (13.0 \pm 0.1)\% \quad \leftrightarrow \quad \frac{FWHM_{E,ep}}{E_{ep}} = (30.6 \pm 0.2)\%
$$

where $E_{ep} = (2900 \pm 4)$ ADC counts and $\sigma_{ep} = (377 \pm 3)$ ADC counts. The experimental resolutions are influenced by a number of parameters, some of which will be discussed in the next section. Theoretical best values are given by the Fano factor $F$ and the total number...
of primary electrons $n_T$: \[ \frac{\sigma_{\text{FWHM}_E}}{E_{\text{pp}}} \bigg|_{\text{theo}} = \sqrt{\frac{g}{n_T}} = \sqrt{\frac{0.21}{225.3}} = 3.1\% \text{ and } \frac{\sigma_{\text{FWHM}_E}}{E_{\text{pp}}} \bigg|_{\text{meas}} = 4.3\%. \] The discrepancy between the theoretical value and the measurement are partially due to the gain fluctuations across a GEM (see Section 4.5.1).

The ratio of the integrated area below both peaks is $I_{pp}/I_{pp} = (0.112 \pm 0.002)$. Hence the fraction of argon escape events compared to all events is 10.1%. The reduction of argon escape peak in comparison to a theoretical value of 16% is due to events in which the fluorescence photon converts close to the primary interaction, so that the two signals are not distinguished.

### 4.5 Various Dependencies of Gas Gain and Energy Resolution

It is important to understand the stability of gas gain and energy resolution and their dependence on various parameters to optimize the readout. Therefore, dependencies on cluster position, GEM voltage, drift field, drift distance and temperature are discussed in this section. The mean charge of the photopeak ($E_{\text{pp}}$) is chosen as a reference value, since it depends linearly on the gas gain. All data were taken with a gas mixture of Ar-CH$_4$ (90:10).

#### 4.5.1 Homogeneity of Gas Gain across a GEM

In Fig. 4.11 the mean charge of the photopeak is shown as a function of the COG. Variations of 1.5% rms can be seen in the signal on the strips (a) and of 1.6% in the signal decoupled from GEM2 (b). Variations of the energy resolution are 5.5% rms and 4.6% rms respectively, and the result for the GEM signal is shown in Fig. 4.11c. These variations are due to small variations of hole size and are well within expectations (see reference [Al01_2p]). They are also stable with time and can be corrected for.

#### 4.5.2 GEM Voltages

The influence of the voltage applied across the two GEMs was studied by keeping one GEM at a constant value while varying the voltage of the other GEM. The results are shown in Fig. 4.12a for the signal on strips and in b) for the signal on the GEMs.

\(^4\text{Please note the logarithmic scale of the y-axis}\)
4.5 Various Dependencies of Gas Gain and Energy Resolution

![Graphs showing the dependence of mean charge on voltages applied to GEMs]

Figure 4.12: Dependence of mean charge of the photopeak on voltages applied to GEMs: a) signal on strips, b) signal on GEM2; c) energy resolution of GEM signals as a function of GEM voltage.

The curves for a constant GEM1 voltage and a constant GEM2 voltage show the same exponential behavior, but the slope differs by a small amount:

\[
G \propto e^{0.0238U_{GEM1}} \quad G \propto e^{0.0272U_{GEM2}}
\]

(4.2)

where \(U_{GEM1/2}\) is the voltage varied across GEM1 or GEM2. The curves intersect when the voltages applied to both GEMs are identical. This leads to the conclusion that in asymmetric configurations, higher gas gains are achieved if the higher voltage is applied to GEM2. This difference in the gas-gain behavior results from the external field configuration. The electric field strength above and below GEM2 are higher than the corresponding values for GEM1, leading to a stronger dipole field within the GEM holes and higher total gas amplification.

Eq. 4.2 shows that the effective gas gain is doubled if the voltage on GEM1 is increased by 30 V, or the voltage on GEM2 is increased by 25 V.

4.5.3 Electric Fields and Drift Distances

Neither the electric field in the drift volume nor the drift distance show significant influence on the effective gas gain. However, gas impurities, in particular electronegative components such as oxygen, can cause a degradation of \(E_{pp}\) with drift distance. This effect is amplified by altering the drift field, so that a reduced drift velocity leads to longer drift times and therefore, to higher probabilities of electron attachment. Fig. 4.13 shows no such degradation in any configuration and therefore good gas quality can be assumed.

4.5.4 Temperature

Temperature has a strong influence on the effective gas gain. The dependency follows an exponential relation [Alt03p]:

\[
G \approx e^{5T/p}
\]

where \(T\) is the gas temperature and \(p\) is the pressure. This correlation has been verified with the help of a PT1000 temperature sensor inside the TPC gas volume (described in
Section 3.4.4). Fitting an exponential function to the data shown in Fig. 4.14 the parameter $b$ can be extracted:

$$\frac{b}{p} = 0.047 \text{K}^{-1} \quad \rightarrow \quad b = 0.047 \text{K}^{-1} \cdot 1013 \text{mbar} = 47.6 \frac{\text{mbar}}{\text{K}}$$

This result can be used for off-line calibration of various parameters, such as the effective gas gain.

### 4.6 Diffusion Coefficient

The cluster width changes with the drift distance due to diffusion processes described in Section 2.3. The diffusion coefficient $D_T$ of Eq. 2.5 strongly depends on the electric field and gas mixture. For this reason, $D_T$ was determined for various drift fields in Ar-CH$_4$ (90:10) and compared to predicted values calculated with the GARFIELD interface to MAGBOLTZ.

Fig. 4.15a shows the square of cluster width versus drift distance. As predicted, this correlation is linear and a polynomial fit with $p_0 + p_1 \cdot x$ gives the diffusion coefficient $D_T = \sqrt{p_1}$. 

Figure 4.14: Temperature dependence of mean photopeak charge a) for signals on strips, b) for signals on GEM2.
4.6 Diffusion Coefficient

\[ D_T \] is shown for drift fields up to 420 V/cm in Fig. 4.15b and the measured values are somewhat lower than the values given by MAGBOLTZ. This effect has been observed before [Bi97p] and can be traced to an approximation used in the MAGBOLTZ calculation algorithm. (In it, the Boltzmann equation is not solved with a true multi-term approach. Only two terms are considered, leading to systematic offsets of a few percent [Ro97p].)

The linear fit also gives an offset \( p_0 \) at a drift distance of 0 cm. This quantifies the charge-broadening due to systematic effects such as electronic noise, the influence of the pad geometry and the gas amplification region (see also the related discussion on the degradation of spatial resolution in Section 2.5.2). In the case of charge-broadening by a double GEM, Eq. 2.8 translates to a standard deviation of the charge distribution:

\[
\sigma_{T,GEM}^2 = \sigma_{T,GEM1}^2 + D_{T,\text{transfer}}^2 \cdot x_{\text{transfer}} + \sigma_{T,GEM2}^2 + D_{T,\text{induction}}^2 \cdot x_{\text{induction}}
\]

In the experimental setup, the following values were used: \( x_{\text{transfer}} = x_{\text{induction}} = 0.2 \text{ cm} \) and the diffusion coefficients were determined by the MAGBOLTZ program \( D_{T,\text{transfer}} = 503 \text{ } \mu\text{m/V cm} \) and \( D_{T,\text{induction}} = 538 \text{ } \mu\text{m/V cm} \). Assuming the same contribution by both GEMs, one obtains:

\[
\sigma_{T,GEM}^2 = (329 \text{ } \mu\text{m})^2 + 2(\sigma_{T,GEM,i})^2
\]

Fig. 4.15c shows the experimental values \( \sqrt{p_0} \) and two different theoretical estimates of \( \sigma_{T,GEM} \) with \( \sigma_{T,GEM,i} = \frac{\mu\text{m}}{\sqrt{2}} \) and \( \sigma_{T,GEM,i} = 100 \text{ } \mu\text{m} \). The latter value describes the data more accurately, but is too large to be explained by the GEM alone. A possible explanation for the additional charge-broadening is the initial charge spread due to Auger electrons escaping from the point of primary interaction. It can easily reach several hundred \( \mu\text{m} \) [Be04p]. Considering the angular distribution and its projection onto a single dimension, this contribution is of the correct order of magnitude.
4.7 Mean Free Path of 5.9 keV Photons in Ar-CH$_4$ Mixtures

Since the photons enter the detector parallel to the readout board and virtually perpendicular to the direction of the strips, an exponential decay of the counting rate versus the strip number is observed (see Fig. 4.16). This attenuation of a photon beam was discussed in Section 2.2. By fitting an exponential function to the data, the mean free path $\lambda$ of 5.9 keV photons can be calculated. This was done for Ar-CH$_4$ (90:10) and Ar-CH$_4$ (80:20):

$$\lambda_{90:10} = (2.54 \pm 0.06) \text{ cm} \quad \lambda_{80:20} = (2.98 \pm 0.06) \text{ cm}$$

Theoretical values of the photon cross section with a large number of elements is given in reference [St70]. By taking into account the ratio of various gas components, one finds the following mean free paths:

$$\lambda_{90:10} = 2.45 \text{ cm} \quad \lambda_{80:20} = 2.75 \text{ cm}$$

(For a detailed description of the calculation, see references [Ka00t, Le02t]). Experimental and theoretical values agree reasonably well. The small difference is due to the collimator's large opening angle in the readout plane.

4.8 Conclusion

The measurements performed with the CAMAC-based electronics have shown good agreement with expectations. The drift velocity shows no deviation from the MAGBOLTZ results and is independent of the drift distance. Furthermore no degradation of gain or energy resolution was found with longer drift distances. The dependence on several parameters, such as temperature and voltages applied on GEMs, was quantified, and no contradictions with previously published data were found. As a result, it can be stated that the detector functions well and the required field homogeneity and gas purity have been achieved.
Chapter 5

Readout Chain and Analysis Software

A complex electronic readout chain and software analysis tool are necessary to capitalize on the 3-dimensional information that can be obtained with a TPC. This kind of electronics is usually developed for large experimental setups and is tailored to the needs of such applications. For example, the STAR experiment\(^1\) uses a TPC as central tracking device and a large number of electronic channels was produced. Some of the backup electronic channels were lent to various groups studying micro-pattern readouts of TPCs. The photograph on Fig. 5.1 shows the setup used by the Karlsruhe ILC-TPC group.

First in this chapter, a description of the electronics is given, and then the analysis package

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\(^1\)Solenoidal Tracker At RHIC, one of the four detectors at the RHIC accelerator at BNL, Brookhaven, USA

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![Figure 5.1: Photograph of STAR electronics.](image-url)
used to reconstruct the position of the collected charge and tracks from the raw data is presented.

5.1 Description of STAR Electronics Readout Chain

The readout chain that was used for these studies consists of five major elements (see Fig. 5.1): The Front End Electronics cards (FEE cards) and the Readout-board (RDO-board) are standard STAR components, and a detailed description is given in reference [An03p]. The VME computer ROSIE together with the ‘gadwall’ module were developed in Berkeley for testing STAR electronics prior to installation. The clock & trigger board was custom-designed by the University of Montreal for the ILC-TPC studies, and the final element, the computer, is a standard commercial product.

**FEE Cards** The Front-End Electronics cards (see Fig. 5.2a) are either mounted directly on the endplate of the detector or connected with a short flatband cable (≈ 20 cm) to the endplate. The FEE cards consist of two pairs of custom chips: The STAR preamplifier/shaper (SAS) chip amplifies the signal by 16 mV/pC and has a two-pole shaper and tail correction. This shaping is necessary to suppress the long tail of the signal caused by the slowly moving ions in the wire-based STAR-TPC. In our application the shaping leads to an undershoot of about 10% the signal size. Also, the relatively long rise time of 150 ns and the 180 ns FWHM of the pseudo-Gaussian pulse shape are not optimized for the fast signal of a GEM-based readout and degrade the double-track resolution. The second component is the SCA/ADC chip, containing a 512-capacitor array and a 12-bit Wilkinson rundown ADC. To improve the linearity, the dynamic range was limited to 10 bits and the output voltage to 2 V. Since the positive, induced signal of the wire-readout requires a low baseline, the FEE cards had to be modified to accommodate the negative electron signal from the GEM. In a first approach two resistors per FEE card were replaced, pulling the baseline up to 230 - 330 ADC counts. The data in Chapters 6 - 8 was taken in this configuration. However, it was observed that the reduced dynamic range (8 bits) was not sufficient to accommodate all signals, in particular in low diffusion regimes. A second modification was performed by D. Karlen and G. Rosenbaum at the University of Victoria, Canada. This modification allows free choice of the baseline. It was subsequently set to about 700 ADC counts. Each FEE card is designed for 32 electronic channels and a total of 10 FEE cards were
available for these studies. However, 20 of the 320 channels were found to be functioning improperly and were flagged out during the analysis.

**RDO-Board** Up to 20 FEE cards can be connected to a single ReaDOut board that is shown in Fig. 5.2b. This board is used in the ILC-TPC setup only for distributing the supply voltage, clock and trigger signals to the FEE cards, and for multiplexing the recorded data. The data are then transferred to a 1.2 GBit/s optical transmitter and sent via an optical fiber to the VME modules.

**ROSIE/gadwall** The ‘gadwall’ module is hosted on a VME computer called ROSIE (see Fig. 5.3a). If a data set is received by gadwall’s optical receiver, the information is dumped into a predefined block of ROSIE’s memory. The data acquisition software readvts.cc was developed by M. Ronan and B. Ledermann in the C-like language VxWorks. It reads the data from ROSIE’s memory and writes a binary file for every event via a 10 MBit/s Ethernet connection to an NFS-mounted disc of the PC. The number of waveform samples (time slices), the number of events and the number and location of the FEE cards can be chosen before starting data acquisition. In this way the readout can be adapted to the appropriate requirements.

Communication between the ROSIE computer and the PC is via an RS-232 serial cable.

**Clock & Trigger Board** The clock & trigger board is also implemented as a VME module and gives the necessary clock and trigger signals to the RDO-board. The frequency of waveform digitization can be varied between 10 MHz and 40 MHz by replacing an on-board oscillator. If not stated otherwise, the frequency was set to 19.66 MHz, giving 50.86 ns per time slice. The trigger signal is sent upon an external signal and a readout frequency of 4.17 Hz was achieved for reading out 100 time slices with 320 electronic channels.
Figure 5.4: The top row shows the result of the first modification: a) baseline of one electronic channel. The inset shows the fluctuations of the first time slices. b) average pedestal values of all readout channels, c) average electronic noise of all readout channels. The bottom row shows the result of the second modification: a) baseline of one electronic channel, b) average pedestal values of all readout channels, c) average electronic noise of all readout channels.

**Personal Computer** The PC is a dedicated readout computer with an AMD Athlon XP1800+ processor, 512 MByte RAM and an 80 GByte disc for data storage.

## 5.2 Performance of STAR Electronics

In this section the performance of the STAR electronics with respect to pedestal, noise, calibration and timing delay is described.

### 5.2.1 Pedestal and Noise

Fig. 5.4a shows the baseline of a single electronic channel after the first modification of the FEE cards. The pedestal is around 300 ADC counts and the noise is very low (about 1.3 ADC counts). Only at the very first time slices (see inset for magnification) can any baseline fluctuation be observed. The first seven time slices were therefore ignored during all of the analysis. In Chapter 6-8 only eight FEE cards were used and the pedestals and electronic noise of all electronic channels are shown in Figs. 5.4b and c. After the second modification, the pedestals were increased as shown in Fig. 5.4e. From the baseline example of Fig. 5.4d it becomes obvious that the fluctuations of the first time slices (≈ 0.7 μs) are increased and hence 14 time slices are ignored. The increased noise level shown in Fig. 5.4f is not due to
the modification, but to the use of a different readout pad geometry. The high noise tail in particular is caused by a feature of the readout structure: As described in Section 3.3.2, the readout planes with various pad geometries have an area, where five pads are combined and connected to only one readout channel. This increases the capacitive noise.

### 5.2.2 Calibration

Two different methods were used to test and calibrate individual channels:

- An inter-strip calibration was performed by giving test pulses on each channel. The circuit used to generate the signal and the analysis procedure are similar to the ones described in Section 4.2. The resulting calibration factors can be seen in Fig. 5.5a for the eight FEE cards used after the first modification. The deviations are less than 3%. These corrections are less than the gain fluctuations of the GEM, and therefore the inter-strip calibration of the electronic channels is negligible.

- Another test was performed during the operation of the detector by giving test pulses on the capacitor connected to the lower side of the GEM. These pulses induce a signal on the pads which is then treated like the aforementioned test pulses. The result, however, shows a much larger spread (see Fig. 5.5b). This has two causes: On the one hand, a number of feed-throughs from the pads to the connectors outside the chamber are
Figure 5.6: a) test pulses with a frequency of 276 kHz for a timing calibration. The oscillator frequency used for digitizing the waveform is 16.0 MHz. b) time slices of test pulse signal versus time, c) waveform digitization frequency versus the nominal oscillator frequency, d) time delay between trigger signal and digitization start. The values of 20 MHz were determined with higher statistics because this frequency was always used throughout data taking.

broken, resulting in very small calibration factors. These pads are either ignored during the analysis or the average of the adjacent pads is used. On the other hand, pads at the edge collect a larger induced signal due to the inadequate impedance of the surrounding ground pads (see Fig. 5.5c). Therefore, factors obtained with this method can not be used for inter-strip calibration, but they give a unique chance to check the quality of the connection from the pads to the electronics.

Calibration factors made with test pulses after the second modification are shown in Fig. 5.5d. The significant spread of about 30% around unity shows the necessity of using these calibration factors. In addition, 16 channels were found to be malfunctioning on the two additional FEE cards.

5.2.3 Signal Shape

Fig. 5.5e shows a chamber signal recorded by the STAR electronics. The aforementioned pseudo-Gaussian shape and the overshoot are clearly visible. The good signal-to-noise ratio has been indicated by additional lines showing the pedestal and noise.
5.2.4 Timing Delay

Calibrations were also performed to determine the timing behavior of the STAR electronics. For this, large pulses with a frequency of 276 kHz were used to generate a number of signals during one readout cycle of 512 time slices (see Fig. 5.6a). The beginnings of these signals were plotted versus the time after the trigger signal (see Fig. 5.6b). Fitting a straight line to the data, one obtains the digitization frequency. In addition, the axis intercept gives the time the STAR electronics needs to start digitizing after a trigger signal is given on the input of the clock and trigger board. A comparison of the measured digitization frequency with the nominal clock frequencies of the oscillator is plotted for various oscillator frequencies in Fig. 5.6c, and the time delay of the electronics in Fig. 5.6d. The time delay must be considered along with cable delays during the reconstruction of a particle's z-position.

5.3 Reconstruction and Analysis Package

A software package named JPCTCRAT was developed in JAVA 1.4.2 [Su05m] for reconstruction and analysis of the data collected with the STAR electronics. The JAVA language was chosen to maintain good compatibility with most computer platforms and to facilitate collaboration with other groups also working for the ILC-TPC. In this section the general layout of the package is described. Then reconstruction and analysis methods co-developed by the author of [Ka04t] are presented, and finally the results of cross-checks with Monte Carlo data are given.

5.3.1 Package Structure

The package is divided into two major components. The reconstruction tool is used to process the raw data. In a first step, pedestal and noise are determined, the pedestal is subtracted from the raw data, and the signal is inverted for convenience. Then charge cluster candidates are searched in all pad rows independently, and the exact position in the pad row and the drift direction is determined. These cluster candidates have to pass some final cuts and are stored in an array. In a final step the array is scanned for clusters forming a particle track and either a straight line or a parabola is fitted to them. The parameters of the clusters and tracks can be written to a file for use with the analysis tool.

All of the steps can also be visualized in three projections to closely monitor the reconstruction process and the chamber performance. Several modes of reconstruction and visualization are available and can be selected by the graphical user interface (GUI, see Fig. 5.7). Some of these modes are online monitoring, offline single-event display with projection, animated charge development during the event, animated visualization of a reconstructed multi-event selection or fast analysis of multiple events without visualization. In addition to these modes the GUI displays the noise behavior and time development of interactively selected channels.

The second component is the analysis tool that reads in a file created by the reconstruction tool and allows a detailed analysis of the data. The four categories under study are:

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\(^2\)NOTICE: From now on the term clusters will refer to the total charge that is generated by one track per pad row and collected after amplification by one pad row. This definition is not identical to the primary clusters discussed in Section 2.2
Figure 5.7: Graphical user interface of the reconstruction tool showing a multi-track event.

- **Global parameters** such as average noise or number of tracks per event

- **Cluster parameters** such as cluster charge, cluster position or cluster width

- **Track parameters** such as track position, track inclination, track curvature or number of clusters per track

- **Spatial resolution studies**

In all categories, a large variety of choices regarding the dependency on other parameters and possible cuts are available for the parameter under study.
5.3.2 Reconstruction Algorithms

In this section the reconstruction algorithms are discussed. Numerical examples were made with the readout board with long rectangular pads (see Section 3.3.2) that was used during most of the data taking (see Chapter 6-8).

5.3.2.1 Coordinate System

During reconstruction two coordinate systems are used. The first, a voxel coordinate system is based on the intrinsic form of the readout board and the data acquisition. It is described by a three-dimensional array \( A(c, r, ts) \), where \( c \) is the pad column, \( r \) the pad row and \( ts \) the time slice. In the case of the readout board with long rectangular pads, the values of the three parameters run from \( c = 0 \) to 31, \( r = 0 \) to 7 and \( ts = 0 \) to the maximum number of time slices recorded (\( \leq 511 \)). The raw data are stored in the array \( A \). Pedestal subtraction and cluster search and reconstruction are performed in this coordinate system.

After cluster reconstruction, a spatial coordinate system is introduced where the standard coordinates \( x \) and \( y \) are given in mm and \( t_{\text{drift}} \) in \( \mu s \). The origin of the new coordinate system is placed at the center of the readout board, and the transformation between the two coordinate systems is given by:

\[
\begin{pmatrix}
  x \\
  y \\
  t_{\text{drift}}
\end{pmatrix}
= \begin{pmatrix}
  p_c & 0 & 0 \\
  0 & p_r & 0 \\
  0 & 0 & p_{ts}
\end{pmatrix}
\begin{pmatrix}
  c - \frac{t_{\text{offset}}}{2} + \frac{p_c}{2} \\
  r - \frac{t_{\text{offset}}}{2} + \frac{p_r}{2} \\
  ts - \frac{t_{\text{offset}}}{2} + \frac{p_{ts}}{2}
\end{pmatrix}
\]

where \( p_c \) is the pad pitch in \( x/c \)-direction (1.27 mm), \( p_r \) the pad pitch in \( y/r \)-direction (12.5 mm) and \( p_{ts} \) the waveform sampling rate (50.86 ns). In addition, the origin of the new coordinate system is shifted by \( \frac{t_{\text{offset}}}{2} \) and \( \frac{t_{\text{offset}}}{2} \) to the center of the readout board, and the time is offset by \( t_{\text{offset}} \), which includes contributions from cable delay, the delay of the STAR electronics (see Section 5.2.4) and a delay due to the shaper’s peaking time of 150 ns.

The drift distance \( d_{\text{drift}} \) can be calculated by: \( d_{\text{drift}} = v_{\text{drift}} \cdot t_{\text{drift}} \).

5.3.2.2 Pedestal and Noise Determination

Two methods have been implemented to determine the pedestal baseline \( P \) and noise level \( N \) of each channel. In the first method, a special set of data is recorded in the absence of any track information, permitting obtention of an unbiased result. \( P \) and \( N \) are calculated from the set and are stored in a separate file, and later events are corrected using these values.

The second method determines the pedestal and noise during events, and requires that the occupancy of the detector be sufficiently low. In an iterative process \( P \) and \( N \) are determined by:

\[
P_i(c, r) = \frac{1}{t_{\text{max}}} \sum_{j=0}^{t_{\text{max}}} A(c, r, j) \quad \forall \ |A(c, r, j) - P_{i-1}(c, r)| < 2.5 \cdot N_{i-1}(c, r)
\]

\[
N_i(c, r) = \sqrt{\frac{1}{t_{\text{max}} - 1} \sum_{j=0}^{t_{\text{max}} - 1} [A(c, r, j) - P_{i-1}(c, r)]^2} \quad \forall \ |A(c, r, j) - P_{i-1}(c, r)| < 2.5 \cdot N_{i-1}(c, r)
\]
Figure 5.8: Event by event determination of pedestal baseline and noise level in a multi-hit event (78 clusters) and large diffusion setup: a) dependence of pedestal baseline on iteration number, b) dependence of noise level on iteration number c) number of voxels ignored as a function of the number of iterations. Values of an example event are averaged and summed over all channels respectively.

The starting values of the iteration were chosen as $P_0 = 0$ and $N_0 = \infty$ and they converge quickly to their final values (see Fig. 5.8). The number of voxels not passing the selection criteria and therefore destined to be left out of the pedestal and noise determination is shown in Fig. 5.8c. It converges more slowly to about 7000. This number agrees well with the voxels used by the 78 clusters found in this event, since the total transverse cluster width is about 8 and the total longitudinal cluster width is about 11 (including the overshoot, which is otherwise ignored). As a result, the number of iterations for determining the pedestal baseline and the noise level is set to 7.

The two methods of pedestal and noise determination give roughly the same results. In selected runs the noise level in the event-by-event calculation was increased by about 0.16 ADC counts and the pedestal level was lowered by about 2.5 ADC counts. Since the spatial resolution was slightly improved by this shift, the second method was used for all data.

The pedestal baseline is subtracted from the raw data according to:

$$\bar{A}(c,r,ts) = P(c,r) - A(c,r,ts)$$

As mentioned in the previous section the first 7 time slices are set to 0, the matrix elements $A(c,r,ts)$ are divided by the respective calibration factors, if needed, and values from broken channels are replaced by the mean values from the two adjacent pads.

5.3.2.3 Cluster Reconstruction

The task of reconstructing the charge deposition per pad row starts with scanning the matrix $\bar{A}$ for channels $(c,r)$ that have three successive time slices with $\bar{A}(c,r,ts) > 3.0 \cdot N(c,r)$. In the vicinity of these voxels, a local charge maximum in the c and ts coordinates is searched. If this maximum is at least one time slice or one pad width away from all edges, the cluster parameters are determined. For this, two different modes - small and large diffusion - are available. The small-diffusion mode is recommended if the expected total cluster width is about 2-3 pads (e.g. in high magnetic fields or Ar-CO$_2$ mixtures), whereas the large-diffusion mode is more appropriate if the total cluster width exceeds 4-5 (e.g. in Ar-CH$_4$ mixtures without magnetic field):
5.3 Reconstruction and Analysis Package

Figure 5.9: Two signals recorded with the 12.5 × 1.27 mm² pad readout geometry. a) small diffusion: cluster after a drift distance of 8 cm in Ar-CO₂ (70:30), b) large diffusion: cluster after a drift distance of 12 cm in Ar-CH₄ (95:5).

Small diffusion: \( \tilde{A}(c, r, ts) > 2.0 \cdot N(c, r) \) and voxels \( \tilde{A}(c, r, ts) \) further out must have a smaller collected charge than voxels closer to the maximum.

Large diffusion: to account for fluctuations in the diffusion process and small misalignments, the second requirement of the small-diffusion mode is relaxed, and single strips of lower or higher charge collection are allowed if the general tendency is preserved.

Fig. 5.9 shows two clusters suitable for the two different modes. All voxels passing the selected requirements are used to calculate the cluster charge \( Q_c \) and cluster noise \( N_c \):

\[
Q_c = \sum_{i}^{\text{all voxels}} A(c_i, r, ts_i) \quad N_c = \sqrt{\sum_{i}^{\text{all voxels}} N^2(c_i, r)}
\]  

(5.1)

The \( r \) coordinate of the cluster position is given by the center of the pad row, and the \( c \) and \( ts \) coordinates are determined by a standard center-of-gravity algorithm:

\[
\left( \begin{array}{c} x_c \\ x_{ts} \end{array} \right) = \frac{1}{Q_C} \left( \frac{\sum_{i}^{\text{all voxels}} A(c_i, r, ts_i) \cdot c_i}{\sum_{i}^{\text{all voxels}} A(c_i, r, ts_i) \cdot ts_i} \right)
\]

The transverse cluster width is expressed by the FWHM of the signal amplitude projected onto the \( c \) direction, and the longitudinal cluster width by the FWHM of the signal on the pad with the largest charge amplitude. Optionally, the \( c \) coordinate of the cluster position and transverse cluster width can be determined by fitting a Gaussian function to the projection of the signal amplitude onto the \( c \) direction.

Cluster positions are transformed from the voxel-based coordinate system into the spatial coordinate system and have to pass the following final criteria:

\[
Q_C \geq 3 \cdot N_C
\]

|longitudinal FWHM| \(\geq 2\)

|edge of readout area – COG| \(\geq 1.5\) pads

Then the cluster parameters are stored for track reconstruction together with additional information on the number of pads and voxels hit by the cluster as well as flags for clusters that are close to broken channels, or that reached the saturation of the dynamic ADC range.
5.3.2.4 Track Reconstruction

For track reconstruction track seeds are created by combining pairs of clusters that are located in the upper half of the detector separated by less than 30 mm of absolute distance and less than 10 mm in the z-direction. These seeds are developed into a candidate track by adding clusters that lie inside a 3 mm tube around the extrapolated track. If several clusters in one pad row fulfill this requirement, the candidate track is duplicated and all possibilities are pursued. When a new cluster is added to a candidate track, the track parameters are updated by fitting either a straight line or a parabola with a linear regression algorithm and the following parameterization:

\[
\begin{pmatrix}
  x \\
  y \\
  z
\end{pmatrix} = \begin{pmatrix}
  a \\
  0 \\
  A
\end{pmatrix} + \begin{pmatrix}
  b \\
  1 \\
  B
\end{pmatrix} \cdot y + \begin{pmatrix}
  c \\
  0 \\
  C
\end{pmatrix} \cdot y^2
\]

This is equivalent to fitting two independent functions in the \(xy\)- and \(yz\)-projections. The parameters \(a\) and \(A\) give the track position for \(y = 0\) in the \(x\)- and \(z\)-directions respectively. \(b\) gives the track inclination \(\phi = \frac{360^\circ \cdot b}{2\pi}\) within the \(xy\)-plane and \(B\) the track inclination \(\theta = \frac{360^\circ \cdot B}{2\pi}\) within the \(yz\)-plane. \(c\) and \(C\) are correlated to the track’s curvature \(\kappa\) and the radius of a circle \(R\). In our application, the approximation \(\kappa_x = 2c\) or \(\kappa_y = 2C\) can be used (see appendix A).

After the list of clusters has been scanned, the reduced track-\(\chi^2\) is calculated for all tracks with a minimum of four clusters according to:

\[
\chi^2_\text{r} = \chi^2_{r,x} + \chi^2_{r,z} = \frac{1}{2N - p_{3d}} \sum_{i=1}^{N} \frac{d^2_{x,i}}{\sigma^2_{x,i}} + \frac{d^2_{z,i}}{\sigma^2_{z,i}}
\]

where \(p_{3d}\) is the number of parameters in the 3d track function (\(p_{3d} = 4\) for a straight line and \(p_{3d} = 6\) for a parabola), \(d_i\) the perpendicular from the \(i^{th}\) cluster to the track, and \(\sigma_{j,i}\) the residual width of coordinate \(j\) in the pad row of cluster \(i\). From the list of track candidates, the track with the most clusters and the lowest reduced \(\chi^2\) is chosen, its clusters are deleted from the list, and the next track searched.

The process of track finding is terminated when less than four clusters remain, or no valid track was found during the last iteration.

Fig. 5.7 shows an event with ten reconstructed tracks of the test beam at the CERN PS ring (see Chapter 8). Fig. 5.10 shows some statistics for this test beam: the number of clusters per track, the reduced \(\chi^2\) and the number of tracks per event.

5.3.3 Analysis Methods

The analysis tool serves both to visualize the results and to calculate physical properties. Because the signal-to-noise ratio, transverse diffusion coefficient, \(dE/dx\) measurement and the spatial resolutions are discussed, the mathematical algorithms to determine these quantities are given in the following subsections.

For all studies, the track-fit to the cluster space-points can be done by using a straight line or a parabola with a fit algorithm based either on a linear regression or a \(\chi^2\)-based algorithm which accounts for the individual errors of the measured space-points. Harsh track-quality criteria can be established, and cuts that are applied routinely for studies of the spatial resolution, include:
5.3 Reconstruction and Analysis Package

Figure 5.10: Reconstructed tracks of the CERN test beam of Chapter 8: a) number of clusters per track, b) reduced $\chi^2$ of tracks, c) number of tracks per event. The data were taken with Ar-CH$_4$ (95:5) and an effective gas gain of about $3 \cdot 10^8$.

No cluster of the track should reach the limit of the ADC’s dynamic range.

All clusters of the track should be more than 1.5 times the pad width away from broken channels.

No cluster of the track should exceed 3.5 times the average cluster charge of the remaining clusters or 2 times their average cluster width. This requirement was introduced to avoid a negative biasing by $\delta$-electrons that are emitted perpendicular to the track and pull the space-points of this pad row away from the track.

At least 5 space-points per track.

A reduced $\chi^2$ smaller than 3.

Additional requirements on the cluster position, track inclination or curvature are possible, but a strong reduction in statistics has to be considered.

5.3.3.1 Signal-to-noise Ratio

The signal-to-noise ratio is the ratio of a cluster charge $Q_c$ over the cluster noise $N_c$ as given by Eq. 5.1.

5.3.3.2 Transverse Diffusion Coefficient

To calculate the transverse diffusion coefficient, cosmic rays were recorded generating clusters throughout the chamber. A Gaussian function was fitted to the clusters and the squared standard deviation given versus the drift distance. A straight line is then fitted to the data giving the square of the diffusion coefficient and a constant offset resulting from various constant cluster-broadening factors (see Section 4.6).

5.3.3.3 $dE/dx$ Measurements

The $dE/dx$ performance was studied by using the truncated mean as described in Section 2.5.3. In the case of the readout board with long rectangular pads, a signal on all 8
pads was required and the smallest 6 signals were used to calculate the average energy deposition. Corrections for both track inclinations $\phi$ and $\theta$ were made and histogrammed. A Gaussian function was fitted to the peak in a region of $\pm 1.5 \cdot RMS$ around the highest bin of the histogram. The final result is given by the definition $\frac{\sigma}{E}$.

5.3.3.4 Spatial Resolution

To study the spatial resolution of the detector, a number of different algorithms were implemented. Since the detector serves as a test object as well as a reference device, one has to be careful to avoid biasing. Therefore, the algorithms were tested with Monte Carlo data and the results compared to the input values.

**Residuals** The residual of the clusters relative to the reconstructed track is determined by choosing a target row for testing. The cluster in this target row is taken from the list of track clusters and a straight line or parabola is fitted to the remaining clusters. Then the vector $\hat{d}$ of shortest distance between the cluster in the target row and the track is determined. The $x$- and $z$-components of this vector are called the residuals of the cluster in the respective directions. Both distributions have a Gaussian shape, and their standard deviation can be used to measure the spatial resolutions of the detector.

If the residual distributions are plotted for various rows, small offsets of the mean values are observed for some rows. These offsets are due to some systematic deviations of the cluster centers resulting from field inhomogeneities due to unevenness in the readout board or GEMs such as sacking of the GEMs’ centers. To quantify the overall performance of the detector, the residuals of the central 6 pad rows are corrected for these offsets and combined in one histogram. The standard deviation of the final fit gives the residual width $\sigma_{\text{res},x/y}$ of the detector in the respective operating condition. As an example, the distribution of residuals is shown in Fig. 5.11a for set 1 of the fast Monte Carlo simulation as described in Section 5.3.4.1.

However, the residual width $\sigma_{\text{res},x/y}$ is not equivalent to the spatial resolution $\sigma_{x/y}$, since the reconstructed track itself is not determined with infinite precision, but has an uncertainty $\sigma_{\text{track},x/y}$:

$$\sigma_{\text{res},x/y}^2 = \sigma_{x/y}^2 + \sigma_{\text{track},x/y}^2$$

Therefore, the resulting residual width value is too large.

**Distance to Track** Alternatively, the target row may not be excluded while refitting the track clusters. Analog to the residual determination, the shortest vector $\hat{d}$ between the cluster in the target row and the track is calculated, and the standard deviations of the $d_x$ and $d_z$ are obtained (see Fig. 5.11a).

$\sigma_{\text{dist},x/z}$ are smaller than the expected spatial resolution, since by including the cluster in the track fit, the resulting track is pulled towards the cluster.

**Constant Factor** An approximation for track uncertainty is suggested in [Ka04t]. It is based on the fact that tracks under study are vertical and therefore the $x$ and $z$ values are similar for clusters in one track. Therefore, the error in the $x$- and $z$-position of the track is given by the errors of the cluster positions $\sigma_{x/z}$ and the average number of space-points per track $N$:

$$\sigma_{\text{track},x/z}^2 \approx \frac{\sigma_{x/z}^2}{N}$$
Inserting this approximation in Eq. 5.2 gives the spatial resolution:

\[
\sigma_{f,x/z}^2 = \sigma_{\text{res},x/y}^2 - \sigma_{\text{track},x/z}^2 \approx \sigma_{\text{res},x/y}^2 - \frac{\sigma_{x/z}^2}{N} = \frac{\sigma_{\text{res},x/y}^2}{1 + \frac{1}{N}}
\]

**Track-by-Track Estimation of Track Error** Another determination of the track error is done on a track-by-track basis according to:

\[
\sigma_{\text{track},x/z}^2 \approx \frac{1}{N} \sum_{i=1}^{N} \frac{\sigma_{x/z,i}^2}{N - p_{2d}}
\]

where \( N \) is the number of track points without the target row, \( \sigma_{x,y,i} \) is the spatial resolution of the pad row of cluster \( i \) and \( p_{2d} \) the number of parameters in the 2d track function (e.g. \( p_{2d} = 2 \) for a straight line, \( p_{2d} = 3 \) for a parabola). The mean of these track errors is determined and the spatial resolution \( \sigma_{\text{lb},x/z} \) calculated according to Eq. 5.2.

**Geometrical Mean** In [Ca04p] it was demonstrated that the spatial resolution can be approximated by the geometrical mean of the residual and the distance to the track:

\[
\sigma_{\text{gm},x/z}^2 \approx \sigma_{\text{res},x/z} \cdot \sigma_{\text{dist},x/z}
\]

\( \chi^2 \) Method In [Ja04t] two methods are described to extract the spatial resolution from the \( \chi^2_{x/z} \):

\[
\langle \chi^2_{x/z} \rangle = \left\langle \sum_{i=1}^{N} \frac{d_{x/z,i}^2}{\sigma_{x/z,i}^2} \right\rangle = N - p_{2d}
\]

where \( N \) is the number of all clusters in the track. If the spatial resolution of all clusters is equal (\( \sigma_{x/z,i} = \sigma_{x/z} \)) a pseudo-\( \chi^2 \) can be defined for each track:

\[
\chi^2_{x/z} = \sum_{i=1}^{N} \frac{d_{x/z,i}^2}{\sigma_{x/z,i}^2} = \frac{1}{\sigma_{x/z}^2} \sum_{i=1}^{N} d_{x/z,i}^2 = \frac{1}{\sigma_{x/z}^2} \chi^2_{x/z,p}
\]

Thus, the spatial resolution can be calculated by averaging the pseudo-\( \chi^2 \) divided by the number of degrees of freedom (\( n\text{df} = N - p_{2d} \)) of each track:

\[
\sigma_{\chi,x/z}^2 = \frac{\langle \chi^2_{x/z,p} \rangle}{n\text{df}}
\]

Alternatively the \( \chi^2 \) function \( P(\chi^2, n\text{df}) \) can be fitted to the \( \chi^2_{\lambda} \) distribution:

\[
P(\chi^2, n\text{df}) = H \cdot \left( \frac{\chi^2_{\lambda}}{\sigma_{\chi,x/z}^2} \right)^{\frac{n\text{df}}{2} - 1} e^{-\frac{\chi^2_{\lambda}}{2\sigma_{\chi,x/z}^2}}
\]

(5.3)

where \( H \) is an arbitrary scale factor. The spatial resolution \( \sigma_{\chi,x/z} \) is determined by the fit. Results of using both methods with Set 1 of the fast Monte Carlo simulation as described in Section 5.3.4.1 are shown in Fig. 5.11. In b) the distribution of \( \chi^2_{\lambda} / n\text{df} \) is shown and the average equivalent to the spatial resolution is indicated. In c) the \( \chi^2_{\lambda} \) distribution is shown together with the function of Eq. 5.3 fitted to the distribution.
5.3.4 Performance Checks with Monte Carlo Simulations

To test the performance of the reconstruction and analysis package, two Monte Carlo simulations were developed. A fast Monte Carlo simulation tool is implemented in the JAVA code. It generates tracks consisting of a limited number of space-points that are randomly distributed around the track. These tracks and space-points were used to test the track-fitting of the analysis package and to evaluate the various methods of determining the spatial resolution presented in the previous subsection.

A detailed Monte Carlo simulation was developed by B. Ledermann [Let]. This simulation takes into account the following properties of the detector:

- Primary ionization in clusters along the track
- 3D diffusion in the drift volume and between the GEMs
- Hexagonal spatial quantization with a pitch of 0.14 mm by the GEMs
- Landau-distributed amplification factor of GEM
- Geometrical layout of the readout structure

The influence of the STAR electronics is included by generating the appropriate pedestal baseline and noise level and by accounting for signal shaping. The output data are written in the same file format as data collected by the STAR electronics. With this simulation the cluster and track reconstruction algorithms were verified.

5.3.4.1 Fast Monte Carlo

With the fast Monte Carlo program, three sets of data were generated with 100,000 tracks each. Each track consists of eight clusters that are spread around the track following a Gaussian distribution with a standard deviation of 0.2 mm in the x-direction and 0.3 mm in the z-direction. The three sets of data differ in the following track properties:

Set 1: vertical tracks without curvature
<table>
<thead>
<tr>
<th>Set</th>
<th>fit</th>
<th>$\sigma_{\text{res},x}$ [(\mu\text{m})]</th>
<th>$\sigma_{\text{dist},x}$ [(\mu\text{m})]</th>
<th>$\sigma_{\text{cf},x}$ [(\mu\text{m})]</th>
<th>$\sigma_{\text{tbt},x}$ [(\mu\text{m})]</th>
<th>$\sigma_{\text{gm},x}$ [(\mu\text{m})]</th>
<th>$\sigma_{\chi^2,x}$ [(\mu\text{m})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>lin. reg.</td>
<td>233.7 ± 0.2</td>
<td>173.4 ± 0.1</td>
<td>218.6 ± 0.2</td>
<td>208.7 ± 0.2</td>
<td>201.3 ± 0.1</td>
<td>192.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200.1 ± 0.1</td>
</tr>
<tr>
<td>Set 2</td>
<td>lin. reg.</td>
<td>233.8 ± 0.2</td>
<td>173.5 ± 0.1</td>
<td>218.7 ± 0.2</td>
<td>207.8 ± 0.2</td>
<td>201.4 ± 0.1</td>
<td>192.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200.1 ± 0.1</td>
</tr>
<tr>
<td>Set 2</td>
<td>lin. $\chi^2$-f.</td>
<td>234.2 ± 0.2</td>
<td>174.1 ± 0.1</td>
<td>219.0 ± 0.2</td>
<td>209.3 ± 0.2</td>
<td>201.9 ± 0.1</td>
<td>192.7 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200.6 ± 0.1</td>
</tr>
<tr>
<td>Set 2</td>
<td>par. reg.</td>
<td>260.4 ± 0.2</td>
<td>154.0 ± 0.1</td>
<td>243.4 ± 0.2</td>
<td>222.4 ± 0.2</td>
<td>200.1 ± 0.1</td>
<td>186.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>195.2 ± 0.1</td>
</tr>
<tr>
<td>Set 2</td>
<td>par. $\chi^2$-f.</td>
<td>262.5 ± 0.2</td>
<td>160.9 ± 0.1</td>
<td>245.5 ± 0.2</td>
<td>225.1 ± 0.2</td>
<td>205.5 ± 0.1</td>
<td>193.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>204.5 ± 0.1</td>
</tr>
<tr>
<td>Set 3</td>
<td>par. reg.</td>
<td>259.8 ± 0.2</td>
<td>153.9 ± 0.1</td>
<td>243.0 ± 0.2</td>
<td>222.0 ± 0.2</td>
<td>200.1 ± 0.1</td>
<td>186.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>195.0 ± 0.1</td>
</tr>
</tbody>
</table>

Table 5.1: Comparison of various spatial resolution definitions with a fast Monte Carlo simulation. Shown are transverse residual width $\sigma_{\text{res},x}$, the standard deviation of the transverse distance from target cluster to the reconstructed track $\sigma_{\text{dist},x}$, transverse spatial resolutions estimated with a constant factor $\sigma_{\text{cf},x}$, with a track-by-track error $\sigma_{\text{tbt},x}$, with the geometric mean $\sigma_{\text{gm},x}$ and with the two different $\chi^2$ methods $\sigma_{\chi^2,x}$. Track fitting has been performed with different mathematical functions (straight line or parabola) and using different methods (linear regression or $\chi^2$-based fit) as indicated.
Set 2: tracks without curvature, but a Gaussian-distributed inclination with respect to \( x \) and \( z \) with \( \sigma_{\theta, \phi} = 8.6^\circ \)

Set 3: parabolic tracks with Gaussian-distributed inclination \( \sigma_{\theta, \phi} = 8.6^\circ \) and Gaussian-distributed track parameter \( c \), \( \sigma_c = 0.001 \)

The six different methods for calculating the spatial resolution were tested. For this, a straight line was fitted to the clusters of Sets 1 and 2 and a parabola to those of Sets 2 and 3. In Table 5.1 the resulting transverse spatial resolutions are shown. As expected, the residual width \( \sigma_{\text{res,}x} \) is too large and the \( \sigma_{d\text{est,}x} \) is too small. The spatial resolution based on a constant-fraction approximation of the track error \( \sigma_{cf, x} \) as well as its modification by calculating the track error track-by-track \( \sigma_{d\text{bl,}x} \), show an improvement with respect to the first two methods. The best agreement with the expected spatial resolution of 0.2 mm is reached with the \( \chi^2 \) method and the geometric mean method. The first gives better results for fitting a straight line, while the latter is best for fitting a parabola. Since the overall performance of the geometric mean method was better than the \( \chi^2 \) method, it was used for analyzing the data presented in Chapters 6–9. In addition it also proved to be more stable in cases of deviations from the ideal Monte Carlo case and more flexible by allowing consideration of individual rows, whereas the \( \chi^2 \)-method gives information only about the complete track.

The different fitting algorithms were also compared. Both linear regression and \( \chi^2 \)-based algorithms showed only little difference (< 3%) if a straight line or a parabola was fitted to Set 2 or a parabola to Set 4.

5.3.4.2 Detailed Monte Carlo

The detailed Monte Carlo simulation was used to test cluster and track reconstruction. For the tests presented in this subsection, 20,000 tracks were generated with a uniformly distributed track inclination \( \phi \) between \(-15^\circ \) and \(+15^\circ \). The track position in \( z \) was fixed with a drift distance of 19 cm and the track inclination \( \theta \) was set to 0. For drift velocity and diffusion, the values for Ar-CH\(_4\) (95:5) were taken from the GARFIELD interface to MAGBOLTZ.

The reconstructed track positions at \( y = 0 \) mm in \( x \) - and \( z \)-direction as well as both reconstructed track inclinations are compared to the respective input parameters of the Monte Carlo. The results are shown in Fig. 5.12. In a) the difference between the start parameters of the Monte Carlo simulation and the track parameters reconstructed by the JAVA reconstruction tool is shown for all tracks and in b) the results are shown as a function of the track inclination \( \phi \). The mean difference for most angles is less than \( 15 \mu m \) and in the overall distribution \( 6.8 \pm 0.5 \mu m \). Similarly small deviations were found for the track inclinations \( \phi \) and \( \theta \) (see d-f). A constant offset of about 250 \( \mu m \) \((\approx 4.5 \text{ ns})\) was found for the reconstructed \( z \)-position. It is due to the simulation and correction of the preamplifier shaping time, it can be removed from real data by the timing calibration.

The good agreement between the start parameters and the reconstructed parameters shows that no bias was introduced by the reconstruction. Even tracks with large inclinations are well reconstructed.

5.3.5 Modification of Analysis for Small Cluster Sizes

The center-of-gravity method (see Section 5.3.2.3) works well if the charge distribution is close to constant with respect to a pad. This means that best results could be obtained if
5.3 Reconstruction and Analysis Package

![Graphs showing results of comparison between start parameters of detailed Monte Carlo simulation and track parameters reconstructed by the reconstruction tool.](image)

Figure 5.12: Results of comparison between start parameters of detailed Monte Carlo simulation and track parameters reconstructed by the reconstruction tool: a) x-position of track at y = 0, b) x-position of track at y = 0 as a function of track inclination \( \phi \), c) z-position of track at y = 0, d) track inclination \( \phi \), e) track inclination \( \phi \) as a function of track inclination \( \phi \), f) track inclination \( \theta \).

the charge distribution on a pad row is rectangular. This condition can be approximated if a Gaussian charge distribution is significantly wider than single pads. However, if diffusion is strongly reduced either by magnetic fields or gas mixtures with low diffusion coefficients, cluster sizes become significantly smaller than the pitch of the readout pads \( p_r \). In this case, the reconstruction of the cluster position based on the center-of-gravity algorithm shows some shortcomings because it artificially shifts the reconstructed position towards the center of the pad with the highest charge collection. This effect is especially prominent with some of the readout pad geometries described in Chapter 9. As an illustrating example, the results of the readout pad geometry with staggered rectangular pads 2 mm \( \times \) 6 mm will be used in this subsection. If the unmodified COG method is used with this pad geometry, the distribution of the transverse spatial resolution is wide and shows a two-peak structure (see Fig. 5.13a). With the theoretical model described in Section 9.1.2 it will be demonstrated that a unique correlation between the reconstructed cluster position and the artificial shifting exists. To measure and correct the cited effect, the cluster position on a single pad is determined. To this effect, each pad is divided into segments 100 \( \mu \)m wide running from the left pad border (-1 mm) to the right pad border (+1 mm). Then the residuals are determined separately.
for clusters in different pad segments. Fig. 5.13b shows such a residual distribution for the pad segment between +0.4 mm and +0.5 mm. This Gaussian-shaped distribution has a small standard deviation and is shifted by about 300 µm from the center. Fig. 5.14 shows the results of all pad segments: In a) the dependence of transverse spatial resolution on the cluster’s x-position on a pad is shown. It has low values of 120 µm to 150 µm for clusters close to the pad edge. These good results are achievable due to sufficient charge sharing. Close to the middle of the pad, the transverse spatial resolution degrades up to 400 µm. This degradation is strongest for short drift distances and low gas gains, since here the reduced diffusion and suppressed tail of the charge cloud make a precise reconstruction of the cluster position impossible. In b), the offsets previously described are shown and in c) the number of tracks per pad segment. For easier comparison the total number of tracks has been normalized to 100 000 for each parameter setting. Here, too, a strong increase towards the pad’s center can be seen, indicating that clusters with low charge sharing are artificially pulled towards the center.

In a second iteration of the analysis, the cluster position is corrected for the offsets as a function of the pad segment; the resulting residuals distribution is shown in Fig. 5.13c. This distribution can be well described by the superposition of two Gaussian functions:

\[
\sigma_x(x) = \frac{N_n}{\sqrt{2\pi}\sigma_n} \exp\left(-\frac{(x - \bar{x}_n)^2}{2\sigma_n^2}\right) + \frac{N_w}{\sqrt{2\pi}\sigma_w} \exp\left(-\frac{(x - \bar{x}_w)^2}{2\sigma_w^2}\right)
\]

where \(N_i\) is a constant factor correlated to the number of tracks, \(\sigma_i\) the standard deviation and \(\bar{x}_i\) the offset of the Gaussian function \(i\). \(i = n, w\) denotes the narrow and the wide Gaussian functions, which describe the better transverse spatial resolution of clusters close to the pad edges and the poorer spatial resolution of clusters at the center of a pad, respectively. As examples, the values of the the function fitted in Fig. 5.13c are given:

\[
\begin{align*}
N_n &= (1006 \pm 13) & \sigma_n &= (0.103 \pm 2) \text{ mm} & \bar{x}_n &= (0.004 \pm 0.001) \text{ mm} \\
N_w &= (205 \pm 8) & \sigma_n &= (0.335 \pm 5) \text{ mm} & \bar{x}_n &= (0.007 \pm 0.004) \text{ mm}
\end{align*}
\]
The two results are combined to a final value of the residual width by calculating the weighted average:

$$\sigma_{res,x} = \frac{N_h}{N_h + N_w} \sigma_n + \frac{N_w}{N_h + N_w} \sigma_w$$

For the abovementioned example, a final value of $\sigma_{res,x} = (0.1422 \pm 0.0006)$ mm is calculated. If the same calculation is performed for the distance of the clusters to the tracks, the result is $\sigma_{dist,x} = (0.1137 \pm 0.0006)$ mm. The geometric mean of $\sigma_{res,x}$ and $\sigma_{dist,x}$ yields the final result of the transverse spatial resolution: $\sigma_x = (0.1272 \pm 0.0004)$ mm.

Obviously, the quality of the corrections strongly depends on two factors: Firstly, the cluster position on the pad must be determined as precisely as possible. Secondly, the offset correction has to be well known. For the first task, two methods are possible: One can use the cluster position as reconstructed with the COG method, or a cluster position can be estimated by using the track parameters. Then after correcting the cluster position, improved track parameters are calculated. Naively, the second method seems preferable, since a large amount of information (up to 10 clusters) enters the track-fit algorithm and therefore a more precise determination of the cluster position is expected. The resulting scatter plots for both methods are shown with a data set containing a high number of statistics in Fig. 5.15a,b. Here also, the offsets used for later corrections are given. The two methods show a different behavior: If clusters hit only one pad, they are reconstructed at the same position giving a thin vertical line at 0 mm in plot a). Since the cluster position estimated by the track parameters varies across the whole pad, the residuals are a bisecting line from (-1, +1) to (+1, -1) pulling the offset corrections towards this line. Furthermore clusters with charge sharing are distributed throughout the plot in a) whereas they are restricted to outer areas closer to the pad edges in b). Hence, an unbiased, more-precise offset correction can be performed if the cluster position based on the COG method is used (see Fig. 5.15c).

The correction also improves with the number of segments the pad is split into (see Fig. 5.15c). However, due to the low statistics in most data sets, only 20 segments were used, resulting in the aforementioned width of 100 μm per segment. Results could be improved by as much as 10 μm if finer sampling were used. Ideally, an algebraic expression can be fitted to the data of the scatter plot or the theoretical model, and thus a continuous quantification
Figure 5.15: Dependence of transverse spatial resolution on the cluster’s $x$-position on a pad: a) cluster position on pad calculated with COG method, b) cluster position on pad calculated from track parameters, c) number of events recorded as a function of the pad position. The data was taken with the staggered rectangular pad geometry $2\times6 \text{ mm}^2$, track inclinations $\phi = -2.0^\circ$ at a drift distance of 7.5 cm and an effective gas gain of $4.5 \times 10^9$.

of the offsets would be available. As an example, the following function was fitted to the 60 offset values in Fig. 5.15a:

$$f(x) = a_0 \cdot \sin(\pi x) \cdot \exp(a_1|x| + a_2x^2)$$

where $a_0$, $a_1$ and $a_2$ are free parameters.
Chapter 6

Tracking Studies with Cosmic Rays

Tracking studies were conducted with cosmic rays in the laboratory at the Forschungszentrum in Karlsruhe. The results are presented in this chapter: First the distribution of various cluster and track parameters is given and then the diffusion coefficients, energy resolutions and the spatial resolutions are discussed.

For the studies, standard TPC gas mixtures of Ar-CH_, usually (90:10) were used. As shown in Table 2.2 these mixtures have a large diffusion coefficient if no magnetic field is applied. Therefore, the limit of large transverse cluster sizes was studied with this setup, and a fine transverse sampling of clusters was possible.

6.1 Experimental Setup

A trigger telescope (see Fig. 6.1) consisting of two scintillators connected to fast photomultipliers (Valvo XP 2020) was built for triggering on high-energy cosmic rays. The active area

![Figure 6.1: Photograph of cosmic ray detection setup in Karlsruhe.](image)
of the scintillators was $4 \times 31$ cm$^2$ each, and the scintillators were positioned at a distance of about 15 cm above and below the drift volume of the TPC. A 5 cm thick layer of lead was placed directly above the lower scintillator to absorb low-energy particles. With this setup, coinciding signals from the upper and lower scintillators were detected with a rate of about 0.068 Hz. Upon every coincidence, a digital trigger signal was given to the clock and trigger board starting a readout cycle. Only one out of three such events contained a track with more than four clusters, and the rate of reconstructed tracks was reduced to only 1.3 per minute.

As discussed in Section 3.3.2, the readout board with long rectangular pads of size 1.27 x 12.5 mm$^2$ was used together with the general-purpose support described in Section 3.4.1. The FEE cards were mounted directly on the readout board, and the resulting noise level was very low (see Fig. 6.2a).

For the gas mixture of Ar-CH$_4$ (90:10) a drift field of 1.40 V/cm was used and for Ar-CH$_4$ (95:5) a drift field of 90 V/cm. In both cases the transfer field was set to 2.5 kV/cm and the induction field to 3.5 kV/cm.

### 6.2 Cluster Properties

The cluster properties in Figs. 6.2 and 6.3 are given for all reconstructed clusters as well as for clusters that could be associated with a particle track. The small and homogeneously distributed differences between both cases in all parameter distributions are the result of incomplete tracks (three clusters or less) and a small number of noise hits.

The spatial distribution of the reconstructed clusters in the $x$-direction is shown in Fig. 6.2b. The quasi-symmetric distribution around the detector's center indicates the good alignment of the two scintillators with respect to the TPC. The drift-time distribution in Fig. 6.2c shows two sharp edges at around 1.0 $\mu$s and 4.6 $\mu$s. Clusters with shorter drift times could not be detected because of the electronics' dead time after the trigger (55 ns due to delay cable, 220 ns internal delay of the electronics and 14 x 50.86 ns due to the slow pedestal rise - see also Section 5.2). The end of the distribution is marked by particles passing through the cathode plane creating charge depositions directly at the end of the detector. These charges have the longest drift time traversing the complete detector and can be used to determine the drift velocity. The exact drift time is given by the mid-point of the falling edge, as indicated in the
inset of Fig. 6.2c, which shows a drift time distribution with the drift time enlarged. If the modified drift velocity in the transfer and induction gap is taken into account, a drift velocity of $v_{\text{drift}} = (5.43 \pm 0.04) \text{ mm/μs}$ is obtained.

Fig. 6.3a shows the cluster charge collected in each row. It has the Landau shape as described in Section 2.2. The darker distribution of all clusters has an additional thin peak at very small values. Here some noise fluctuations have been misinterpreted as clusters. None of these 'fake' clusters was used in the track reconstruction. Due to the low noise of individual channels, the signal-to-noise ratio is high - the most probable value is around 120 and thus far larger than the cluster requirement of 3. In Fig. 6.3c the value of the most probable charge deposition is shown versus the sum of both GEM voltages. In combination with Fig. 2.12b, it can be shown that the effective gas gain corresponds to the position of the most probable value times four. With this, the gas gain can be determined for each data set individually. The relative uncertainties of this method are estimated at 10 percent of the gain values.

### 6.3 Track Properties

The track parameters are given by the geometrical arrangement of the scintillators. Fig. 6.4 shows that the acceptance of the track inclination $\theta$ is large (up to $\pm 40^\circ$), whereas the one of $\phi$ is less than $\pm 6^\circ$.

If a parabola is fitted to the data instead of a straight line, the curvature is given by $\kappa = 2 \cdot c = \frac{1}{\lambda}$. Values of $c$ are shown in Fig. 6.4c. They are centered around zero and have a standard deviation of $(2.13 \pm 0.02) \text{ mm}$. In an imaginary 4 T magnetic field that serves only for momentum determination, but not for diffusion suppression, this curvature distribution can be converted with Eq. 2.11 into a transverse momentum resolution of $\frac{\delta p_T}{p_T} = 0.35 \sqrt{\frac{c}{\lambda v/c}}$.

### 6.4 Transverse Diffusion Coefficient

The transverse diffusion coefficient was determined as described in Section 5.3.3.2. Fig. 6.5a shows the squared cluster size versus the drift distance and the straight line fitted to the data. The first and last data points were not included in the fit, because deviations due
to low statistics were observed. Results obtained for Ar-CH$_4$ (90:10) with a drift field of 140 V/cm are a diffusion coefficient of $(491 \pm 1) \mu$m$^2$/cm and a constant cluster broadening of $(454 \pm 16) \mu$m. For Ar-CH$_4$ (95:5) with a drift field of 90 V/cm, a diffusion coefficient of $(628 \pm 3) \mu$m$^2$/cm and a constant cluster broadening of $(473 \pm 50) \mu$m were measured. Both values of the diffusion coefficient are significantly lower than the predictions of the MAGBOLTZ program (570 $\mu$m$^2$/cm and 724 $\mu$m$^2$/cm respectively). The constant cluster broadening, in contrast, is larger than expected.

6.5 Energy Resolution of Energy Loss dE/dx

Fig. 6.5b shows the truncated mean of the energy loss $dE/dx$ as described in Section 5.3.3.3. The data were taken in Ar-CH$_4$ (90:10) at an effective gas gain of $5.4 \cdot 10^3$. A Gaussian function is fitted to the peak, and a result of $\frac{\sigma}{E} = (23.6 \pm 0.5)\%$ is obtained for 10 cm long tracks (8 data samples).

Figure 6.5: a) Squared cluster size as a function of drift distance. The rise of the straight line fitted to the data gives a diffusion coefficient of 491 $\mu$m$/\sqrt{\text{cm}}$ for a drift field of 140 V/cm in Ar-CH$_4$ (90:10). b) truncated mean of the energy loss $dE/dx$. The Gaussian function fitted to the data gives an energy resolution of 23.6%. c) energy resolution of the energy loss $dE/dx$ as a function of effective gas gain in Ar-CH$_4$ (95:5) and (90:10).
6.6 Spatial Resolution

Figure 6.6: Dependence of spatial resolution on cluster position in Ar-CH₄ (90:10) with an effective gas gain of 5.4·10^2: a) longitudinal and transverse spatial resolution in dependence on cluster x-position at a drift distance of 9 - 13 cm, b) transverse spatial resolution and offset of transverse residuals as a function of row number at a drift distance of 9 - 13 cm, c) longitudinal and transverse spatial resolution as a function of cluster x-position. The solid lines are fitting results of the model described in the text. The dashed-dotted line represents the theoretical limit for this configuration.

No changes were observed when the effective gas gain was varied, and identical values were also measured in Ar-CH₄ (95:5) (see Fig. 6.5c).

6.6 Spatial Resolution

The spatial resolution was determined as described in Section 5.3.3.4 using the geometric mean method. In this section the dependence of the spatial resolution on various parameters is described. Fig. 6.6 shows the spatial resolution as a function of the position of the track in the detector. The dependency on the x-position (see a) shows a degradation of longitudinal and transverse spatial resolution in the left (negative) part of the chamber, where 8 channels were malfunctioning. Despite the corrections and flags mentioned in the previous chapter, the performance of the detector is slightly degraded. In addition, at the border of the readout area, the broad clusters are influenced by a one-sided charge cut-off. In the transverse direction, this leads to an apparent improvement in spatial resolution, since most clusters of the track are subject to this systematic charge loss, which leads to an artificial alignment of the reconstructed clusters. In the longitudinal case, the loss of information leads to a degradation of the spatial resolution. Therefore, a more stringent requirement has to be used. If large diffusion is encountered, the cluster position has to be at least 3 mm away from the edge.

The dependency on the row number (see b) shows a constant transverse spatial resolution around 0.3 mm in the center rows, but larger values are observed in the border rows. Therefore, these two rows are ignored throughout the analysis. The offsets of the transverse residuals are of interest, since they would indicate systematic track distortions. All offsets (except row 1) are smaller than ±30 µm and therefore a good homogeneity can be assumed.

The dependency on the drift distance (see c) shows a square-root behavior that is due to the cluster enlargement by diffusion. Therefore, the following function was fitted to the data
points:

\[
\sigma_{x/z} = \sqrt{\sigma_{x/z,\text{const}}^2 + \sigma_{x/z,\text{diff}}^2 \cdot z}
\]  

(6.1)

where \(\sigma_{x/z,\text{const}}\) is a constant contribution to the spatial resolution resulting from the cluster broadening of the gas amplification stage and \(\sigma_{x/z,\text{diff}}\) is the parameter of the \(z\)-dependent diffusion contribution. Results of the fitting procedure are:

\[
\sigma_{x,\text{const}} = (0 \pm 26) \ \mu\text{m} \quad \sigma_{x,\text{diff}} = (88.9 \pm 0.2) \ \frac{\mu\text{m}}{\sqrt{\text{cm}}}
\]

\[
\sigma_{z,\text{const}} = (355 \pm 3) \ \mu\text{m} \quad \sigma_{z,\text{diff}} = (57 \pm 1) \ \frac{\mu\text{m}}{\sqrt{\text{cm}}}
\]

showing that the transverse spatial resolution is dominated by diffusion and, due to the fine sampling of the signal, the constant contribution is negligible. For the longitudinal spatial resolution the constant contribution is much larger, resulting from the long shaping time, and the degradation due to diffusion is reduced. The theoretical limit, also shown in the figure, is based on Eq. 2.6, where \(D_T\) was set to the aforementioned measured value of 490 \(\frac{\mu\text{m}}{\sqrt{\text{cm}}}\) and the number of primary electrons is 115. This leads to \(\sigma_{x,\text{const}} = 0\) and \(\sigma_{x,\text{diff}} = 46.3 \frac{\mu\text{m}}{\sqrt{\text{cm}}}\).

Fig. 6.7 shows the dependence of the spatial resolution on the track parameters. As discussed in Section 2.5.2 the spatial resolution degrades if the track is inclined in the direction of interest (see a for transverse case and b for longitudinal). However, inclinations \(\phi\) and \(\theta\) show no influence on the spatial resolution in the respective orthogonal directions.

Fig. 6.7c shows that the quality of the track fitted to the remaining clusters also influences the spatial resolution, and that the choice of \(\chi^2 < 3\) is justified.

In Fig.6.8a the spatial resolution is plotted versus the transverse cluster width. Since clusters of all drift distances are used, the expected square-root-rise of the diffusion-induced cluster broadening is clearly visible in both directions of the spatial resolution. The spatial resolution degrades also, however, with small cluster sizes. This effect is due to clusters that are cut off on one side resulting in a shifted cluster reconstruction.
Figure 6.8: a) Longitudinal and transverse spatial resolution as a function of cluster width (standard deviation), b) transverse spatial resolution as a function of drift distance and various effective gas gains in Ar-CH₄ (90:10) c) and in Ar-CH₄ (95:5). The dashed lines are to guide the eye, the solid lines are fitting results of the model described in the text and the dashed-dotted line represents the theoretical limit of this configuration.

Finally, the transverse spatial resolution was studied for various effective gas gains and in two different gas mixtures. Fig. 6.8b shows the transverse spatial resolution as a function of the z-position and for different effective gas gain in Ar-CH₄ (90:10). Fitting the same function as mentioned before, similar values are obtained for all effective gas gains. On average, the contributions are:

\[ \sigma_{x,\text{const}} = (0 \pm 20) \, \mu m \quad \sigma_{x,\text{eff}} = (86.3 \pm 0.2) \, \mu m / \sqrt{\text{cm}} \]

The data taken with Ar-CH₄ (95:5) (see c) shows two different results. At low gas gains the detector does not operate efficiently and the spatial resolution degrades to \( \sigma_{x,\text{eff}} = (125 \pm 1) \, \mu m / \sqrt{\text{cm}} \), whereas at higher gas gains the performance is stable with:

\[ \sigma_{x,\text{const}} = (0 \pm 40) \, \mu m \quad \sigma_{x,\text{eff}} = (102 \pm 1) \, \mu m / \sqrt{\text{cm}} \quad \sigma_{x,\text{theoretical}} = 58.6 \, \mu m / \sqrt{\text{cm}} \]

For both gas mixtures, the theoretical limit resulting from \( D_T \sqrt{d_{\text{drift}}/\sqrt{n_T}} \) is shown in Figs. 6.8b and c. However, no degradation effects, such as the angular pad effect, were considered.

### 6.7 Conclusion

The studies of the tracking performance of the TPC with cosmic rays and Ar-CH₄ gas mixtures were performed successfully. Expectations for basic parameters such as the drift velocity could be confirmed. Because of the large diffusion and the excellent signal-to-noise ratio, the transverse cluster position was limited by diffusion only, and no degradation due to the gas amplification stage or the readout pad geometry was observed. The transverse spatial resolution in Ar-CH₄ (90:10) for a drift distance of 11 cm was \((295 \pm 3) \, \mu m\). An extrapolation based on the cluster size (see Eq. 8.1) shows that these operating conditions correspond to a drift distance of 6.8 m under TESLA-TDR conditions and the transverse spatial resolution is below the extrapolated TDR-requirements (339 \( \mu m \)).
Chapter 7

Studies in High Magnetic Fields

One question under study was whether a GEM-based TPC can be operated in a magnetic field as high as 4 T. It is true that the transverse diffusion is greatly suppressed in magnetic fields, but in high magnetic fields it was feared that the drifting electrons might be forced on tracks so straight that the Lorentz force would prevent them from entering the GEM holes. As a result a large amount of primary electrons could be lost on the front side of the GEM facing the drift volume and the tracking performance would degrade significantly. To study the influence of magnetic fields up to 5 T, the Karlsruhe prototype TPC was placed in a superconducting magnet at DESY (see Fig. 7.1). Cosmic rays were used to study the tracking behavior of the detector in various magnetic field strengths aligned parallel to the electric field. A particular focus was put on the transverse spatial resolution study at the

Figure 7.1: Photograph of setup in the superconducting magnet at DESY.
limit of short drift distances and narrow cluster sizes.

7.1 Experimental Setup

At DESY a former compensation magnet of the ZEUS experiment is set up as detector test facility. The superconducting magnet has an overall length of 186 cm and a bore of 27 cm. It creates a solenoidal magnetic field of up to 5.5 T (see schematic drawing in Fig. 7.2a). The TPC was placed in the center of the magnet, since there the best field homogeneity can be expected, as shown in Fig. 7.2b. The FEE cards were mounted directly on a cylindrical support custom-made for this setup (see Fig. 3.9b), and long flatband cables (about 70 cm) connected the FEE cards with the RDO-board. A fan was used to blow fresh air through a pipe into the bore to guarantee sufficient cooling of the electronics.

Two scintillators with a length of 108 cm and a width of 17 cm were placed on top of and below the cryostat. Because of the limited angular acceptance, they give trigger signals with a rate between 0.74 and 0.63 Hz, varying with the magnetic field. Due to the large scintillator size, however, only few of the recorded events contain a track of a particle passing through the region of interest of the detector. A software filter sorts out events in which two or more clusters could be reconstructed, reducing the amount of data by 88.5-94.5%. Of these filtered events about 75% contain a track with more than 5 clusters. A track rate of 0.026 Hz was thus achieved with a 5 T magnetic field and one of 0.062 Hz without a magnetic field. Obviously, this low rate strongly limits the volume of statistics that could be collected during the test.

To complete a realistic test setup, the gas mixture suggested in the TESLA-TDR, Ar-CH₄-CO₂ (93:5:2) was used. The characteristic parameters for an electric drift field of 240 V/cm are given in Table 2.2.

Properties of clusters are shown in Figs. 7.3 and 7.4. The electronic noise is very low (see Fig. 7.3), and the signal-to-noise ratio has a maximum of 120. The distribution of clusters in the x-direction is rather flat, but it shows many peaks (see Fig. 7.4a). This is an artifact of
7.1 Experimental Setup

Figure 7.3: a) Average electronic noise of each channel, b) cluster charge of all clusters and of clusters associated with a track, c) signal-to-noise ratio. All data were taken with a magnetic field of $B = 4$ T and an effective gas gain of about $4 \cdot 10^3$.

The reconstruction algorithm and indicates the centers of pads. This effect will be discussed in more detail later. The drift time spectrum in (b) shows two edges resulting from the start of data taking and the detector end marked by the cathode (see Section 6.2). The drift velocity of the electrons can be deduced from the inset of Fig. 7.4b and is $(4.56 \pm 0.03)$ cm/$\mu$s. Due to the low diffusion coefficient, the charge is not distributed over many pads, but a large fraction is collected by only one or two pads. Therefore, even at moderate effective gas gains of $4 \cdot 10^3$, the dynamic range of the ADC after the first modification of the FEE cards (see Chapter 5.1) was insufficient (see Fig. 7.4c). Hence a considerable number of clusters have at least one voxel (one time-sample of one pad) in which the ADC reaches saturation.

The track properties are shown in Fig. 7.5. Both track inclinations have distributions similar to those seen in Chapter 6.

Figure 7.4: Cluster properties of tracks at a magnetic field of 4 T: a) cluster distribution in $x$-direction, b) drift time spectrum, c) fraction of clusters with at least one voxel in saturation of the ADC’s dynamic range (‘overshoot’) versus the magnetic field. The data were taken with a constant voltage applied to the GEMs. Corresponding to an effective gas gain of about $4 \cdot 10^3$. 
7.2 Transverse Diffusion Coefficient

In Fig. 7.6a the influence of the magnetic field on the transverse diffusion is illustrated. The left image shows a track after drifting 10 cm in Ar-CH₄-CO₂ (93:5:2) without magnetic field, whereas the track on the right-hand side was recorded with identical parameter settings, but with a magnetic field of 5 T.

The transverse diffusion coefficient is determined as described in Section 5.3.3.2. As an example of the analysis, the square of the cluster size is shown as a function of the drift distance in a 2 T magnetic field in (b).

The linear fit to the data gives the transverse diffusion coefficient, which is shown in (c) for various magnetic fields. The measurements agree qualitatively well with results of calculations from the GARFIELD interface to MAGBOLTZ, but are, as observed in Section 6.4, systematically below the calculation by about 15 to 20%.

Figure 7.6: Determination of the transverse diffusion coefficient $D_T$ as a function of the magnetic field: a) influence of magnetic field on transverse diffusion. left: track at B = 0 T, right: track at B = 5 T. Both tracks were created at a drift distance of about 10 cm. b) square of cluster size as a function of drift distance in a magnetic field of B = 2 T, c) transverse diffusion coefficient as a function of magnetic field: measurements and calculations from GARFIELD interface to MAGBOLTZ. The dashed line is to guide the eye.
Figure 7.7: Energy resolution with $dE/dx$: a) truncated mean of charge collected by each pad row ($B = 3\,\text{T}$), b) most probable value of truncated mean as a function of magnetic field at a constant voltage applied to both GEMs, c) energy resolution with $dE/dx$ as a function of magnetic field.

### 7.3 Energy Resolution with $dE/dx$

The energy resolution is determined with a truncated mean of the $dE/dx$ measurement (see Section 5.3.3.3). Fig. 7.7 show the truncated mean of all tracks recorded in a magnetic field of $B = 3\,\text{T}$ with an effective gas gain of about $4 \cdot 10^3$. The most probable value of the truncated mean is indicated in the figure. If it is plotted as a function of the magnetic field (see (b)), one observes an increased charge collection at higher magnetic fields. The effect of magnetic fields on the charge transfer within a GEM structure was studied by S. Lotze et al. in great detail [Lo04p]. They come to the conclusion that the magnetic field improves the extraction efficiency from the GEM hole, and therefore, more electrons are collected. However, with the $dE/dx$ method no influence of the magnetic field on the energy resolution could be observed with the electric field configuration under study (see Fig. 7.7c).

### 7.4 Transverse Spatial Resolution

While studying transverse spatial resolution, large offsets of the residuals were observed in the first and the last pad row (see Fig. 7.8a). These offsets could be traced to an attenuation of the magnetic field in the radial direction (see results of a field simulation in Fig. 7.8b). These offsets are corrected for and have no further influence on the measurements. Only in row 3 is there a significant degradation of the spatial resolution, but it is due to an increased number of broken connections between readout pads and the front-end electronics.

The transverse resolution is shown in Fig. 7.9a as a function of the drift distance and of the magnetic field. A valley of best resolution is clearly visible stretching from a magnetic field of 5 T and a drift distance of 23 cm to a magnetic field of 1 T and a drift distance of 3 cm. The spatial resolution is about 90-95 $\mu$m and degrades on the one side towards lower magnetic fields and longer drift distances and on the other side towards higher magnetic fields and shorter drift distances. In the first case, diffusion increases the cluster sizes and spatial resolution degrades according to Eq. 2.6. In the latter case, the cluster sizes become so small that only a very limited number of pads collects charge (see Fig. 7.8c) and the center of gravity algorithm described in Section 5.3.2.3 does not reconstruct the cluster
Figure 7.8: a) Transverse spatial resolution and offset of residuals as a function of the row number with a magnetic field of $B = 4$ T. b) Deviation of radial component of the magnetic field [F04m], c) average number of pads per pad row with a collected charge larger than 10 ADC counts ($\approx 7 \cdot N_i(c, r)$).

position correctly under such circumstances. Therefore, cluster positions in magnetic fields of $B = 1$ T or higher have to be corrected according to the method described in Section 5.3.5. To summarize briefly, that method is based on correcting each cluster as a function of its reconstructed center-of-gravity position on an individual pad. In order to do this, the cluster position is determined in fractional pad-size units (i.e. the pad is divided into segments). The correction is then applied based on the segment, independent of pad row and column. The quality of the correction strongly depends on the number of segments, but because of the very low statistics available, the number of segments was limited to 15. For each segment the distribution of residuals is determined individually. While the transverse spatial resolution is constant throughout the pad, the offsets of the residuals are as large as 150 $\mu$m. These offsets are shown as a function of drift distance, magnetic field and track inclination $\phi$ in

Figure 7.9: Dependence of transverse spatial resolution on drift distance and magnetic field: a) before additional correction, b) after additional correction. In both figures the track inclinations are limited to $-5^\circ < \phi < +5^\circ$ and $-20^\circ < \theta < +20^\circ$. The effective gas gain is about $4 \cdot 10^8$. 
Figure 7.10: Offset of residuals versus the x-position on pad: a) as a function of drift distance at a magnetic field of $B = 4$ T, b) as a function of magnetic field for a drift distance of 5-9 cm, c) as a function of the track inclination $\phi$ for drift distances 6-19 cm and with a magnetic field $B = 4$ T.

Fig. 7.10. The maximum value of these offsets is correlated with the cluster size. For long drift distances (23 cm) and low magnetic fields (1 T) the offsets become negligible, since the increased cluster size allows a good reconstruction of the cluster position. Track inclination also has a significant influence on the offsets, but due to limited statistics, only one parameter can be varied at a time.

If cluster positions are corrected for these offsets before the transverse spatial resolution is determined, the results are improved significantly (see Fig. 7.9b). The best resolution is now around 85 $\mu$m and the degradation towards higher magnetic fields and shorter drift distances is notably reduced.

The influence of ADC saturation is visible in the data of Figs. 7.11a and b. For effective gas gains above $3 \cdot 10^3$ the spatial resolution degrades by about 10 $\mu$m because of the limited

Figure 7.11: a) Dependence of transverse spatial resolution on the drift distance. The results before and after the additional corrections are shown, and the effect of the ADCs’ saturation is also displayed for an effective gas gain of $4 \cdot 10^3$. b) Dependence of transverse spatial resolution on the effective gas gain for $x_{\text{drift}} = 18 - 22$ cm. c) Dependence of transverse spatial resolution before and after correction on the track inclination $\phi$ for various drift distances. All data shown are with $B = 4$ T.
dynamic range. However, the limited volume of statistics prevents eliminating this effect for all results.

For a magnetic field of $B = 4 \, \text{T}$, the dependence of the transverse spatial resolution on the track inclinations $\phi$ and $\theta$ was also studied. Fig. 7.11c shows the transverse spatial resolution as a function of $\phi$ for two different drift distances before the additional correction. Both dependencies show qualitatively different curve progressions. While the data resembles the prediction of Eq. 2.9 for longer drift distances, the results for short distances show a rapid degradation at very small inclinations and a saturation at about $120 \, \mu\text{m}$. Only at inclinations larger than $5.5^\circ$ does the spatial resolution degrade again. This behavior is illustrated in Fig. 7.12a, where the transverse spatial resolution is shown for all drift distances between $3 \, \text{cm}$ and $25 \, \text{cm}$. The explanation for the behavior at short drift distances is based on the offsets shown in Fig. 7.10c. The offsets are negligible for very small track inclinations, since here the same charge distribution is obtained in all rows. Therefore, all clusters and the reconstructed track are shifted by the same distance towards the respective pad center, and the transverse spatial resolution remains unchanged. For larger track inclinations the clusters are shifted towards the center of a pad. But since these pads are not aligned in one column for all pad rows, the distances between the clusters and the tracks are increased artificially. Due to the angular pad effect (2nd term in Eq. 2.9) a large track inclination $\phi$ leads to a broader charge spread within one pad row reducing the magnitude of the offsets. Since the angle between the diagonal of a pad with the $y$-coordinate is $5.8^\circ$, the track passes across at least two pads for larger inclinations. Unfortunately, due to limited statistics the offsets could not be determined as a function of the drift distance and the track inclination at the same time. Therefore, the data in Fig. 7.12b was corrected with offsets that were averaged over the complete angular range ($0 < |\alpha| < 5.5^\circ$) resulting in an exaggerated degradation of the spatial resolution at very small and large inclinations.

Fig. 7.13a shows the theoretical considerations about transverse spatial resolution (see Eq. 2.9). The parameter choice was done identically to that in Fig. 2.8c, that is $l = 12.5 \, \text{mm}$, $D_T = 72 \, \mu\text{m}/\sqrt{\text{cm}}$ and $n_T' = 115$ and $n_T'' = \lambda/l = 0.2 + 3.2 \frac{D_T \varphi + \alpha}{l}$. In addition, a
7.5 Longitudinal Spatial Resolution

![Figure 7.13](image)

Figure 7.13: a) Transverse spatial resolution according to Eq. 2.9, b) momentum resolution as a function of the magnetic field.

A systematic contribution of $\sigma_{x,sys}^2 = (60\ \mu m)^2$ was added to the diffusion and angular contribution. Comparing Fig. 7.12b with Fig. 7.13a confirms the good agreement of both results. The systematic contribution results from a number of effects, such as magnetic field inhomogeneities, ADC saturation and limited precision of offset correction.

To confirm and quantify the angular pad effect, the following function was fitted to the corrected data in Fig. 7.11c:

$$\sigma_x = \sqrt{\frac{a_0^2}{\cos^2 \phi} + a_1^2 \cdot \tan^2 \phi}$$

where $a_i$ are free fit parameters, $a_0$ gives the transverse spatial resolution for tracks without inclination. The fit result gives a value of $a_0 = (70 \pm 2)\ \mu m$. From $a_1 = \sqrt{12n_{eff}^2}$ the effective number of electrons can be deduced. The fit result of $a_1 = (1.27 \pm 0.08)$ yields $n_{eff}^2 = (8.1 \pm 0.3) = n_{eff}^2$, which is well within expectations for low-diffusion environments.

As expected, the transverse spatial resolution shows no dependency on the track inclination $\theta$ (see Fig. 7.14c).

7.5 Longitudinal Spatial Resolution

The longitudinal spatial resolution is shown as a function of the magnetic field and the drift distance in Fig. 7.14a. Good results are achieved with low magnetic fields and long drift distances. For a magnetic field of $B = 0\ T$ a diffusion-based degradation of the longitudinal spatial resolution is obtained for drift distances longer than 11 cm. However, if a magnetic field is applied, the spatial resolution degrades. Also, a degradation with shorter drift distances is observed for all magnetic fields. This result does not agree with naive expectations, since the magnetic field has no direct influence on the longitudinal diffusion. A combination of the following three possible explanations can account for this behavior:

- Fig. 7.14 describes the longitudinal spatial resolution dependency on the effective gas gain. Above a gain of $3 \cdot 10^3$ the longitudinal spatial resolution degrades rapidly due to the saturation of the ADCs. This effect is more significant in the longitudinal direction than in the transverse direction, because it is very likely that not only one time bin is
Figure 7.14: a) Longitudinal spatial resolution as a function of drift distance and magnetic field. The track inclination was limited to $-10^\circ < \theta < +10^\circ$, b) longitudinal spatial resolution as a function of the effective gas gain. Data were taken with a magnetic field of $B = 4$ T and a drift distance of 17-23 cm. c) longitudinal and transverse spatial resolution as a function of the track inclination $\theta$. For all data an effective gas gain of $4 \cdot 10^3$ was used.

affected, but several. Since the high magnetic fields focus the collected charge onto a small number of pads, more clusters will be affected.

- Table 2.2 gives a longitudinal diffusion coefficient of about $270 \, \mu m/\sqrt{cm}$ resulting in a longitudinal cluster width of 1.35 mm after 25 cm of drift. With a drift velocity of about $45.6 \, mm/\mu s$, one finds a cluster width in the time dimension of 30 ns, which is less than the 50.9 ns of the sampling clock. For reasons similar to the transverse case of short drift distances, the spatial resolution improves with more diffusion, since a better charge sharing between time bins is obtained. The influence of the magnetic field can be explained by a reduced statistics volume: Because of the small cluster size in the time dimension, the precision of the cluster position relies on combining the information of several pads. Due to the low transverse diffusion at high magnetic fields, a smaller number of pads is hit, and thus fewer pads contribute to the position determination, and the longitudinal spatial resolution degrades.

- It is well established that the COG algorithm gives biased results for the position in the drift direction if the preamplifier has an asymmetric shaping function [Ha88]. This bias results in a charge-dependent offset of the residuals. If the transverse diffusion is reduced by a magnetic field, a larger fraction of the charge is collected by fewer pads. The increased charge fluctuation per pad leads to the summing of different uncorrected offsets and therefore to a degradation of the spatial resolution.

The track inclination $\theta$ also influences the longitudinal spatial resolution as shown in Fig. 7.14c.

7.6 Momentum Resolution

Only the magnetic field $B$ and the track curvature $\kappa = 2 \cdot c$ (see Fig. 7.5c) are needed to determine the transverse momentum resolution according to:

$$\frac{\delta p_T}{p_T} = \frac{\delta \kappa}{cB}$$
7.7 Conclusion and Outlook

The resolution is shown as a function of the magnetic field in Fig. 7.13b. A $1/B$ function is fitted to the data, but does not describe it perfectly. This is due to the fact that the standard deviation of the track parameter $c$ is correlated with the spatial resolution. Since the magnetic field improves the spatial resolution, an additional improvement of the momentum resolution is also obtained.

7.7 Conclusion and Outlook

It was demonstrated that a time projection chamber with a GEM-based readout can be reliably operated in a magnetic field of up to 5 T. No indications of primary losses were observed and basic detector parameters such as drift velocity and diffusion coefficients were confirmed. The reduction of the transverse diffusion coefficient improved the transverse spatial resolution significantly. In a magnetic field of $B = 4$ T a best resolution of $(46 \pm 1) \mu m$ was obtained if harsh angular cuts were applied. For very small cluster sizes, a shortcoming of the reconstruction method was discussed, and it was shown that the improved algorithm introduced in Section 5.3.5 can correct these effects. Due to the low volume of statistics, these corrections could not be applied to all results. Also the limited dynamic range of the ADCs leads to a significant number of clusters causing ADC saturation. Therefore, a second test in the same magnetic field was performed. With an increased dynamic range and higher statistics volume, the dependency on track inclination was studied in more detail. In addition the influence of various digitization frequencies as well as some of the different pad geometries described in Chapter 9 were tested. These results are presented in [Le6p] and [Let].
Chapter 8

Studies in a High-Rate Hadronic Test Beam

Because the rate of cosmic rays is limited and therefore the statistics collected with each parameter setting are very low, the detector was also tested in high-rate hadronic beams of CERN’s Proton Synchrotron (PS) (see Fig. 8.1). There, a large number of tracks with the same orientation and ionization could be recorded within a short time. Hence, the spatial resolution of gases with low, medium and large diffusion could be studied under identical conditions. In addition, the good performance of detector and analysis tool with multi-track events could be demonstrated.

The large number of tracks also results in a considerable charge deposition inside the detector and the ion feedback could be determined.

Figure 8.1: Photograph of setup in the CERN test beam.
8.1 Experimental Setup

The detector was tested in two different test beam areas: In the T7 area, a beam of 9 GeV/c protons and pions was available. Here the gas mixtures Ar-CH₄ (95:5) and Ar-CO₂ (70:30) were tested. In the T11 area, a beam of 3 GeV/c pions and electrons was used for tests with the gas mixtures Ar-CO₂ (70:30) and Ar-CH₄-CO₂ (93:5:2). The various parameters of the

<table>
<thead>
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<td></td>
</tr>
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<td>Ar-CO₂ (70:30)</td>
<td>Ar-CO₂ (70:30)</td>
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</table>

Table 8.1: Comparison of the beam and detector parameters during the test beam at CERN. The detector parameters of the TPC described in the TESLA-TDR are also given. The beam sizes are FWHM and the ionization refers to tracks in the y-direction.
8.1 Experimental Setup

Figure 8.2: a) Time structure of the primary 24 GeV/c protons. One division of the x-axis corresponds to 100 ms. b) current on bottom electrode of GEM2, c) particle rates in the T11-area.

beam and the detector settings are listed in Table 8.1 together with the design parameters given by the TESLA-TDR.

8.1.1 Beam Conditions and Trigger Setup

The PS delivers a beam of protons with an energy of 24 GeV/c. These particles are directed on a target, where hadronic interactions take place. The secondary particles created in the target are selected by their momentum and transferred into the experimental area. The time structure of the beam consists of spills 550 ms long. Since different beam areas are provided with particle spills, on average spill rates of 0.06 Hz are available. Fig. 8.2a shows the time distribution of the primary 24 GeV/c protons within one spill and in (b) the current which is necessary to compensate the charge deposition on the bottom electrode of GEM2 during one spill is shown. In both figures the peaks of the spill’s substructure can be seen, but because of the significant RC constants in the supply lines, the current measurement indicates an overly long spill duration.

Figure 8.3: a) Time distribution of clusters during one readout cycle, b) number of tracks during one readout cycle, c) number of clusters per track. All data were taken with a gas mixture of Ar-CH₄ (95:5) and a drift distance of 12 cm.
A coincidence of two scintillators was used for triggering the readout electronics. A 4.5 × 19 cm² scintillator was aligned vertically and placed in front of the detector, while a 3 × 7.3 cm² scintillator was installed horizontally behind the detector. Because of a low readout rate, only one readout cycle could be performed during each spill. To obtain as much benefit as possible from the large number of particles per spill, two features of the setup were exploited; First, a veto signal was used to allow triggering a readout cycle only during an 80 ms long interval during which the maximum flux of the spill was reached (see Fig. 8.2b). Second, the maximum number of time samples (500) was acquired, corresponding to 25.43 μs. However, the correct drift time and drift distance could be reconstructed only for the particle triggering the readout cycle. The drift distances of all other particles arriving randomly before and after the triggering particle have to be deduced from the beam position, with an uncertainty given by the beam profile. In Fig. 8.3a the drift time spectrum is shown for particles drifting 12 cm in an Ar-CH₄ (95:5) gas mixture. As indicated in Fig. 8.3b, these arrangements ensure on average a recording of four to six particles per readout cycle.

The particle flux and the beam width in the horizontal as well as in the vertical direction are adjusted by collimators. The beam width was set to a FWHM of 7 × 13 mm² (T7) and 20 × 20 mm² (T11) for all data presented in this chapter. These dimensions were measured by the cluster distribution as indicated in Fig. 8.4. Since the vertical beam profile is important for the uncertainty of the drift distance, special attention was given to measuring it directly. With it, an uncertainty of 6 to 10 mm was determined for the drift distance.

The rate of particles passing through the detector was determined by counting the coincidences of the two scintillators or the signals that were decoupled from the bottom electrode of GEM2. With the first method a total of (40800 ± 300) tracks per spill were detected in the T7 area with standard settings. Here, the number of signals on the GEM was about 10% lower for geometrical reasons. In the T11 area the particle flux was determined as a function of the half aperture of the collimators (see Fig. 8.2). For this measurement two scintillators with large areas (≈ 12 × 20 cm²) were used and a reasonable agreement with the predicted rate was reached. Due to a wider beam width, only a fraction of the particles passed over the active area of the GEMs. Hence, for standard settings (half aperture = 0.6 cm) an average of 40 000 - 50 000 tracks per spill were amplified by the GEM.
8.1 Experimental Setup

Figure 8.5: a) Transverse cluster width for three different gas mixtures, b) longitudinal cluster width for Ar-CO$_2$ (70:30) and Ar-CH$_4$-CO$_2$ (93:5:2), c) track inclination $\phi$ and $\theta$ in Ar-CH$_4$ (95:5).

8.1.2 Detector

The detector was operated with three different gas mixtures: Ar-CH$_4$ (95:5), Ar-CO$_2$ (70:30) and Ar-CH$_4$-CO$_2$ (93:5:2). The choice was driven by the considerable differences in the drift properties, which are summarized along with other detector parameters in Table 8.1.

The transverse diffusion coefficient $D_T$ is of special interest, since it determines the transverse cluster size and therefore also the transverse spatial resolution. In Fig. 8.5 the transverse cluster sizes are displayed for all three gas mixtures. In contrast, the longitudinal diffusion coefficient $D_L$ has little influence on the longitudinal cluster size, since the latter is dominated by the shaping time of the FEE. Therefore, Ar-CH$_4$ and Ar-CH$_4$-CO$_2$ have identical cluster sizes and only Ar-CO$_2$ has a slightly higher value, which results from its low drift velocity.

The detector was aligned so that the particle beam passes through the detector along the $y$-direction. Therefore, both track inclinations $\phi$ and $\theta$ were close to zero (see Fig. 8.5c). The uncertainty of the reconstructed track inclination is based on the limited single space-point resolution and improves as the diffusion decreases.

The detector’s low noise of only 1.4 ADC counts (see Fig. 8.6a) leads to a good signal-to-noise ratio of over 70, as depicted in Fig. 8.6b. This leads to an excellent detection efficiency.

Figure 8.6: a) Average noise per channel, b) cluster charge and c) signal-to-noise ratio for tracks after a drift distance of 12 cm in Ar-CH$_4$ (95:5) with an effective gas gain of 2.7 \times 10^3.
which was determined to be (99.3 ± 0.3)% (see Fig. 8.7, and for further detail, references [Ka04p.2, Ka04t]).

8.2 Transverse Spatial Resolution

The transverse spatial resolution was studied for all three gas mixtures described in the last section. In the following discussion, three data sets are compared:

- **Large diffusion:** Ar-CH$_4$ (95:5) with a drift distance of 12.6 cm and an effective gas gain of $2.7 \cdot 10^3$
- **Medium diffusion:** Ar-CH$_4$-CO$_2$ (93:5:2) with a drift distance of 4.2 cm and an effective gas gain of $2.5 \cdot 10^3$
- **Small diffusion:** Ar-CO$_2$ (70:30) with a drift distance of 7.0 cm and an effective gas gain of $3.5 \cdot 10^3$

Fig. 8.8 demonstrates a homogeneous spatial resolution for all cluster positions. The offsets of the residuals are also presented in this figure, since they are a good parameter with which to identify systematic influences. In (a) the dependence on row number is plotted. Only on the first and the last row are small deviations observed; they are due to the fact that track parameters must be extrapolated and therefore precision is reduced. The offsets of residuals are smaller than 40 $\mu$m. If the spatial resolution is plotted as a function of the cluster’s x-position as in (b), good resolution is observed on the right-hand side of the detector. On the left-hand side of the readout board, eight broken connections between readout pads and the FEE had to be taken into account. Section 5.3 explains how the charge of these channels is corrected for, and that clusters are excluded if a broken channel is in the center part of the cluster. These measures work well for gas mixtures with small and medium diffusion, but for Ar-CH$_4$ (95:5) a degradation of up to 100 $\mu$m was observed. For this reason, the beam position was aligned so that the defective area is affected only by the beam halo (see Fig. 8.4a).
In Fig. 8.8c the spatial resolution is shown as a function of the x-position on the pad, independent of the row and column number. A good homogeneity is observed for gas mixtures with large and medium diffusion. For short drift distances and low diffusion coefficients, however, deviations similar to those in Chapter 7 are observed. Since the track inclinations are very small, the expected offsets of the residuals could not be observed, but clusters and reconstructed track positions are shifted towards the center of the pads. This artificial cluster alignment was observed only in Ar-CO$_2$ (70:30) and with drift distances shorter than 10 cm (for more details concerning this effect see Section 9.4).

Fig. 8.9a the transverse spatial resolution is shown versus the effective gas gain. As described in the previous chapters the spatial resolution improves with increasing gas gain and leads to a plateau of best resolution for high gas gains. The onset of this plateau is reached at lower gas gains if the gas mixture has a lower diffusion coefficient, since the priritary charge density is higher for small cluster size, and less gas gain is needed to lift all channels above the electronic noise.

In Figs. 8.9b and c the dependence on the cluster charge and the signal-to-noise ratio is depicted for a constant gas gain. The initial improvement of the spatial resolution can be

Figure 8.8: Transverse spatial resolution and offset of residuals as a function of the cluster position: a) as a function of row number, b) as a function of x-position and c) as a function of the x-position on the pad.

Figure 8.9: Transverse spatial resolution as a function of a) effective gas gain, b) cluster charge at constant gas gain c) signal-to-noise ratio. Dashed lines are to guide the eye.
Figure 8.10: Transverse spatial resolution as a function of a) transverse cluster size, b) drift distance. The solid lines are theoretical models fitted to the data, c) Extrapolation of the spatial resolution results to the detector described in the TESLA-TDR. The solid line shows the requirement stated in the TESLA-TDR.

The transverse spatial resolution dependence on the cluster size shows a quasi-parabolic behavior (see Fig. 8.10a) for reasons similar to those described earlier: Smaller clusters consist of fewer electrons, while larger cluster sizes indicate the presence of large charge accumulations generated, for example, by $\delta$-electrons.

For all three gas mixtures, the spatial resolution shows a square-root dependence on the drift distance, as is expected from Eq. 2.6. Therefore, the function $\sigma_x = \sqrt{\sigma^2_{x,\text{cond}} + \sigma^2_{x,\text{diff}} \cdot z}$ is fitted to the data. From the diffusion-dominated parameter $\sigma_{x,\text{diff}}$, the declustering by diffusion described in Section 2.5.2 can be observed. Since $\sigma_{x,\text{diff}} = D_T / \sqrt{n_T}$, the effective number of primary electrons can be determined for vertical tracks.

- **Large diffusion** Ar-CH$_4$: $\sigma_{x,\text{diff}} = (61 \pm 2) \frac{\mu m}{\sqrt{\text{cm}}} \rightarrow n'_T = (135 \pm 5)$

- **Medium diffusion** Ar-CH$_4$-CO$_2$: $\sigma_{x,\text{diff}} = (46 \pm 1) \frac{\mu m}{\sqrt{\text{cm}}} \rightarrow n'_T = (100 \pm 2)$

- **Small diffusion** Ar-CO$_2$: $\sigma_{x,\text{diff}} = (31 \pm 1) \frac{\mu m}{\sqrt{\text{cm}}} \rightarrow n'_T = (26.0 \pm 0.8)$

For small cluster sizes, a significantly lower $n'_T$ was observed, which is in good agreement with predictions and earlier measurements.

The results of the test beam can be extrapolated to the detector described in the TESLA-TDR by comparing the transverse cluster sizes:

$$\sigma_{\text{TESLA-TDR}} = D_{T,4T} \cdot \sqrt{\frac{x_{\text{TESLA-TDR}}}{x_{\text{test beam}}} = D_{T,0T} \cdot \sqrt{x_{\text{test beam}}}$$

Therefore, a cluster drifting $x_{\text{test beam}}$ in the test beam setup corresponds to an equivalent drift distance of $x_{\text{TESLA-TDR}} = D_{T,0T}^2 / D_{T,4T} \cdot x_{\text{test beam}}$ in the large-scale detector. For the extrapolation, the diffusion coefficients were calculated with the GARFIELD interface to MAGBOLTZ. Fig. 8.10c shows the transverse spatial resolution as a function of the equivalent drift distance. The figure demonstrates that the TESLA-TDR requirements can be met.
Figure 8.11: Spatial resolution as a function of track parameters; a) transverse and longitudinal spatial resolution as a function of track inclination $\phi$, b) transverse spatial resolution as a function of the reduced $\chi^2$ of the track without the target row.

throughout the drift distance with the pad geometry under study. However, it is also clear that the different systematic influences - such as diffusion in the transfer and induction gap or the difference in the longitudinal diffusion - limit the predictive power of the extrapolation.

The dependence of the spatial resolution on the track inclination $\phi$ was determined only for the Ar-CH$_4$ (95:5) gas mixture. The results are shown in Fig. 8.11 and a function like Eq. 7.1 is fitted to the data. The parameter $a_1 = l/\sqrt{12n_{eff}^T}$ yields an effective number of electrons $n_{eff}^T = (10.9 \pm 0.5) = n_{T,50}^T$. As expected, this result is smaller than $n_{T,50}^T$, but due to the increased diffusion, it is larger than the value measured in Chapter 7 ($n_{eff}^T = (8.1 \pm 0.3) = n_{T,44}^T$).

The transverse spatial resolution also depends on the quality of the track fitted to all clusters but the one of the target row (see Fig. 8.11b).

8.3 Longitudinal Spatial Resolution

The longitudinal and transverse spatial resolutions show identical dependencies and similar quantitative results. Therefore, only a few important examples will be given. Fig. 8.12a shows the longitudinal spatial resolution as a function of the effective gas gain. The general behavior was discussed in the last section. As observed in Section 7.5, the longitudinal spatial resolution is more sensitive to the saturation of ADCs, and a slight increase in the spatial resolution is observed for gas mixtures with low diffusion and short drift distances. But the degradation of the longitudinal resolution in the test beam data is significantly smaller than the one observed in the high magnetic field. This results from the track alignment parallel to the $y$-axis, which suppresses a stronger degradation. The dependences on the drift distance (Fig. 8.12b) and the track inclination $\phi$ (Fig. 8.11a) show square-root and constant relationships, respectively, and are therefore in good agreement with theoretical considerations.

The only deviation from expectations is observed for the dependence of the longitudinal spatial resolution on the cluster charge, where the offset of residuals varies by as much as 400 $\mu$m. These offsets support the third explanation in Section 7.5, where the degradation’s dependence on the magnetic field and drift distance is discussed.
8.4 Ion Feedback

The high particle rate leads to significant charge deposition in the detector. Since neither the field strengths in the transfer and induction gap nor the voltages applied across both GEMs were optimized for low ion feedback, primary charge deposition was increased and considerable charge accumulated inside the drift volume. This charge was used to measure ion feedback.

As described in Section 3.4.2, the current in all HV feed lines was monitored by nano-ampere meters. To determine the ion feedback, the analog output signals of two nano-ampere meters were connected to the PC-based I/O card described in Section 3.4.4. With this setup, the time profile of the current on the cathode and the bottom electrode of GEM2 could be recorded throughout a spill. These currents are plotted in Fig. 8.13a. The cathode shows a significantly longer time constant than the GEM electrode because of larger $R$ and $C$ values. The current is integrated over the complete spill, and the total charge per spill is displayed, in Fig. 8.13b for the bottom electrode of GEM2, and in (c) for the cathode.

The definition of the ion feedback $F$ used is that of Section 2.6.1, namely:

$$F = \frac{\text{ions released in the gas volume above GEM}}{\text{electrons released in the gas volume below GEM}} = \frac{I_{\text{cathode}}}{I_{\text{anode}}}$$

The current on the bottom electrode of GEM2 can be converted into the current on the anode by taking the extraction efficiency into account. This parameter has been studied by the LC-TPC group in Aschen, and their result for Ar-CH$_4$-CO$_2$ (93:5:2) and an electric field of 3.5 keV/cm below the GEM is shown in Fig. 8.14a. With this, the ion feedback for the test beam setup was calculated from the measured currents and the results are shown in Fig. 8.14b. Here, the standard configuration for data taking with Ar-CH$_4$ (95:5) was used: $E_{\text{drift}} = 95$ V/cm, $E_{\text{gem1}} = 340$ V, $E_{\text{trans}} = 2.5$ kV/cm, $E_{\text{gem1}} = 330$ V, $E_{\text{ind}} = 3.5$ kV/cm, and a result of $F = (4.5 \pm 0.5)$% was obtained. If the imbalance of the voltage across GEM1 and GEM2 is changed, the ion feedback will change too: $F = (4.2 \pm 0.6)$% for GEM1 = 320 V, GEM2 = 350 V and $F = (5.5 \pm 0.7)$% for GEM1 = 320 V, GEM2 = 350 V.

The results of measurements in Ar-CH$_4$-CO$_2$ (93:5:2) given in Fig. 8.14c show an improvement of the ion feedback with lower electric drift fields and higher voltages in the GEM. Both changes lead to a higher ratio of the electric field inside the GEM hole to the electric field.
8.4 Ion Feedback

Figure 8.13: Measurement of currents on the bottom electrode of GEM2 and on the cathode: a) time profile of both currents during one spill. Note: The cathode current has been multiplied by ten for convenience. b) charge collected by the bottom electrode of GEM2 during one spill, c) charge collected by the cathode during one spill. b) and c) were recorded in Ar-CH₄ (95:5), while a was recorded in Ar-CH₄-CO₂ (93:5:2).

above a GEM hole, meaning that an increased number of field lines end on the top electrode of the GEMs. The ions are guided by the field lines and are neutralized there.

Because the electric field configuration was not optimized for ion feedback suppression but for reliable operation, a space charge of up to 0.9 \( \mu \text{C} \) was accumulated, also leading to track distortions. A detailed analysis of the track distortion study can be found in reference [Ka05p]).

Figure 8.14: a) Extraction efficiency of electrons from GEM holes versus the voltage applied across the GEM. Results are for Ar-CH₄-CO₂ (93:5:2) and an electric field of 3.5 kV/cm below the GEM.[Lo05m], b) distribution of ion feedback in Ar-CH₄ (95:5) during one spill, c) ion feedback as a function of the sum of the voltages across both GEMs and the electric drift field in Ar-CH₄-CO₂ (93:5:2).
Figure 8.15: Measurement of drift velocity with test beam: a) schematic view of the setup: The detector is tilted so that the particle beam exits through the cathode, b) drift time spectrum of charge clusters, c) drift velocity as a function of electric field and gas mixture.

8.5 Further Results

In this section a short summary of further results obtained during the tests with the beam at CERN is given.

8.5.1 Drift Velocity

The drift velocity was measured to confirm correct operation of the detector in the setup. For this, the particle beam was directed through the cathode (see Fig. 8.15a). As in the case of measurements with cosmic rays, the time spectrum shows a sharp cutoff at the drift time the charge cluster needs to traverse the detector (see Fig. 8.15b). The drift velocity can be inferred from this value, and a good agreement with calculations from MAGBOLTZ was obtained (see Fig. 8.15c).

8.5.2 Energy and Momentum Resolution

The straight, parallel tracks of monoenergetic particles are also well suited for the study of the energy and momentum resolution of 10 cm long tracks in the detector. With the truncated-mean method described in Section 5.3.3.3, results of 18% to 19% could be achieved (see Fig. 8.16a).

For an imaginary 4 T magnetic field, the momentum resolution can be inferred from the distribution of the track parameter c in a way similar to that in Section 6.3. Since the momentum resolution depends linearly on the spatial resolution and therefore on the diffusion, it is clear that different results can be expected for the three gas mixtures under study. If a Gaussian function is fitted to the data in Fig. 8.16b, the following momentum resolutions are found:

- **Large diffusion**: \( \text{Ar-CH}_4 \) (95:5), \( d_{\text{drift}} = 4.4 \text{ cm}, \sigma_x = (0.204 \pm 0.003) \text{ mm} \),
  \[ \sigma_c = (1.97 \pm 0.02) \frac{10^{-4}}{\text{mm}} \rightarrow \frac{\delta p_T}{p_T} \approx 0.33 \frac{1}{\text{GeV/c}} \]

- **Medium diffusion**: \( \text{Ar-CH}_4-\text{CO}_2 \) (93:5:2), \( d_{\text{drift}} = 4.2 \text{ cm}, \sigma_x = (0.169 \pm 0.001) \text{ mm} \),
  \[ \sigma_c = (1.19 \pm 0.02) \frac{10^{-4}}{\text{mm}} \rightarrow \frac{\delta p_T}{p_T} \approx 0.2 \frac{1}{\text{GeV/c}} \]
8.6 Conclusion

- **Small diffusion**: Ar-CO$_2$ (70:30), $d_{drift} = 12.6$ cm, $\sigma_x = (0.114 \pm 0.01)$ mm,

$\sigma_c = (8.0 \pm 0.1) \frac{10^{-2}}{\text{mm}} \rightarrow \frac{\delta r}{r} \approx 0.13 \frac{1}{\text{GeV}/c}$

For measurements with large and medium diffusion, short drift distances were chosen to minimize the influence of the space charge, while a longer drift distance was chosen for the measurement with small diffusion to avoid the artificial alignment of clusters.

As expected, the momentum resolution scales with the spatial resolution. However, due to the space charge, results are about 2 times larger than is expected from Eq. 2.10.

8.5.3 High-multiplicity Events

By changing the collimator settings, the number of tracks per readout cycle could be increased to an average of 17 (see Fig. 8.17b). Fig. 8.17 shows the graphical user interface with 29 reconstructed tracks in one readout cycle. By increasing the particle flux, the detector's performance in a high-rate application was tested. The proper functioning of both the detector and the reconstruction and analysis software package were verified by comparing the tracking efficiency and cluster charge of data sets with high and low particle fluxes. Comparing the number of clusters per track, a good measure of the tracking efficiency, one finds a good agreement between both particle rates: $(7.71 \pm 0.01)$ for high rates and $(7.67 \pm 0.01)$ for low rates (compare Figs. 8.17c and 8.3c). Deviations in the shape of the cluster charge distribution would indicate an artificial cluster splitting (excess of clusters with low charge) or cluster fusion (excess of clusters with twice the most probable cluster charge). Comparing Figs. 8.17d and 8.6b, no such deviations are visible.

Finally, the transverse spatial resolution was determined. With a gas mixture of Ar-CH$_4$-CO$_2$ (93:5:2), a drift distance of 12.6 cm and an effective gas gain of $3.2 \cdot 10^3$ a value of $\sigma_x = (183 \pm 1)$ $\mu$m was found. This is also in good agreement with low rate results.

8.6 Conclusion

The prototype detector was operated successfully for four weeks in a high-rate hadronic test beam with a particle flux of up to $3.3 \cdot 10^5$ Hz. During operation in the test beam a large amount of statistics could be collected and three gas mixtures with different drifting properties

![Figure 8.16: a) $dE/dx$ measurement with the truncated-mean method, b) track parameter $c$ for three different gas mixtures.](image-url)
Figure 8.17: Readout cycles with a large number of tracks: a) Graphical user interface showing a reconstructed event with 29 tracks. b) number of tracks per readout cycle. c) number of clusters per track, d) cluster charge. The data was recorded with a gas mixture of Ar-CH₄-CO₂ (93.5:2).

were tested. The main focus was put on the detailed transverse spatial resolution study. In it, the influence of various parameters such as effective gas gain, drift distance, cluster size and cluster charge were studied and related to the gas mixture in use. The best resolutions of (52.6 ± 0.9) μm were reached for Ar-CO₂ (70:30) and at a drift distance of 3.5 cm.

Because of the high particle flux and an operation mode which was not optimized for suppressing the ion feedback, a significant charge accumulation in the drift volume was observed. By measuring the current in the feed lines of the electrode, the ion feedback was determined to be 4.5% to 12%, depending on the effective gas gain and the electric drift field.
Chapter 9

Studies with Various Pad Geometries

A degradation of the transverse spatial resolution for short drift distances and low diffusion coefficients was observed in Chapter 7. This behavior was explained by the small cluster sizes preventing sufficient charge sharing in a pad row. A possible improvement can be achieved by altering the pad geometry such that a charge sharing occurs despite small cluster sizes. To test the performance of several different pad geometries, a new readout area which allows easy interchange of the readout pad assembly was constructed (see Section 3.3.2). Seven pad geometries were designed according to the guidelines proposed in the Technical Design Report of the TESLA project [Al01]. To assure high statistics, these pad geometries were

Figure 9.1: Photograph of setup in the DESY test beam.
tested at the DESY test beam facility. The results of these experiments, as well as theoretical considerations and Monte Carlo simulations, are presented in this chapter.

9.1 Motivation and Theoretical Considerations

In conventional TPCs, the primary charge is collected by a wire and the signal is created by gas amplification. This process induces a wide signal on a pad plane which is typically placed at a distance of 2 to 6 mm from the wire plane (see also Section 2.1). As indicated in Fig. 9.2a the signal is recorded on several pads, and the signal position is typically determined by a center of gravity algorithm (COG).

In a GEM-based readout, the electrons are released after gas amplification and drift towards the pad plane. There, the main signal is created by direct charge collection. Compared to the induction signal of a wire-based readout, the resulting signal is faster and narrower; its size is determined mainly by diffusion before and after the GEM (see Fig. 9.2b). Therefore, better spatial resolution can be achieved.

However, if the cluster sizes become so small that the signal is collected by a single pad only, the spatial resolution degrades to

$$\sigma_x = \frac{\text{pitch of pads}}{\sqrt{12}}$$

To prevent this degradation smaller pad sizes would, in principle, be preferable. But since the number of electronic readout channels is limited for financial and geometric reasons alternative solutions have been suggested:

- With an optimized readout pad geometry, charge sharing between neighboring pads could be achieved because every track passes over at least two pads per pad row.
- Similar to the wire-based TPCs, the induction signal created by the electrons’ movement from the last GEM to the pad plane can be used for space point reconstruction (see references [Ka00f] and [Ka00p]).
9.1 Motivation and Theoretical Considerations

![Readout pad geometries](image)

Figure 9.3: Readout pad geometries under study: a) rectangular pads $2 \times 6 \text{ mm}^2$, b) staggered rectangular pad $2 \times 6 \text{ mm}^2$, c) rhombic pads, d) chevron-shaped pads, e) comb-like pads, f) '3+1'-pads and g) rectangular pads $1.27 \times 12.5 \text{ mm}^2$. The upper row shows schematic drawings of the geometries, while the lower row shows photographs of the respective prototype readout planes.

- In strong electric fields ($> 1.5 \text{ kV/cm}$) the transverse diffusion coefficient remains large even in the presence of a strong magnetic field. This can be used to spread the charge cloud after the gas amplification stage, e.g. by increasing the induction gap up to several cm (see references [Ka04f] and [Ka04p, 3]). Due to the large number of electrons $\left( \prod_{i=1}^{\text{all GEMs}} G_i \right) n_T$ this increase in cluster size is not accompanied by a degradation of the spatial resolution (see Eq. 2.8).

- Another way charge spreading after gas amplification can be achieved is by gluing a thin, high-surface-resistivity film on the readout pad plane. This arrangement forms a 2-dimensional resistive-capacitive network. Any localized charge will disperse with time and cover a larger area of the pad plane. The dispersion signal can then be seen on the neighboring pads (see reference [Di04p]).

In this chapter the first item will be studied in more detail by comparing seven geometries. For this, the theoretical model described in the next section was developed and the results of an idealized Monte Carlo simulation were studied. Finally, the pad geometries were tested in a test beam experiment.

9.1.1 Pad Geometries Studied

The geometries under study are shown in Fig. 9.3 and will be briefly introduced now. The first pad geometry is a rectangular pad with a width of 2 mm and a length of 6 mm. This
geometry is the baseline geometry suggested in the TESLA-TDR, and the dimensions are
given by the requirements stated therein: A total of 200 pad rows should be placed between
the outer radius \( r_o \) and inner radius \( r_i \) of the active readout area resulting in a fixed pad
length \( l \):
\[
l = \frac{r_o - r_i}{N_{\text{pads}}} = \frac{1618 \text{ mm} - 362 \text{ mm}}{200} \approx 6.25 \text{ mm}
\]
The area \( a \) of a single pad is given by the maximum number of electronic channels per endcap
\( N_{\text{ec}} \):
\[
a = \frac{A_{\text{ec}}}{N_{\text{ec}}} = \frac{\pi \cdot (1618^2 - 362^2) \text{ mm}^2}{0.75 \cdot 10^6} \approx 10.5 \text{ mm}^2
\]
where \( A_{\text{ec}} \) is the total active readout area per endcap. Of course, some extra space has to be
allowed for supporting elements resulting, in the aforementioned pad dimensions.

The geometry shown in Fig. 9.3b is a small modification of the baseline geometry: Every
second row is staggered by half a pitch (1 mm) with respect to the previous row. This layout
ensures charge sharing in every second row.

The rhombus-shaped pads shown in Fig. 9.3c have a width of 2 mm and an overall length
of 12 mm resulting in a total area of 12 mm\(^2\). Due to their shape, intrinsic charge sharing
is achieved between adjacent pads. However, the adjacent pads are not in the same pad row
and thus a strong interaction between rows is expected.

Chevron-shaped pads with a number of jags have been suggested as an alternative in the
TESLA-TDR. However, since the production process of the prototype readout pad planes
did not allow any precision filigree, single jags were selected (see Fig. 9.3d). The remaining
dimensions were chosen according to the TDR guidelines: a pitch of 2 mm in the \( x \)-direction
and 6 mm in the \( y \)-direction. The angle \( \alpha \) between the pad and the \( y \)-direction is \( \pm 33.7^\circ \)
displacing the middle by 2 mm with respect to the upper and lower border.

The comb-like pad geometry is based on the idea of combining fine strips, so that large
interdigitated pads are formed. For prototype production, four strips with a pitch of 500
\( \mu \text{m} \) were connected on one side (see Fig. 9.3e). The two outer strips are separated from the
two central ones by a single strip of the neighboring pad. This reduces the uninterrupted
transverse dimension to 1 mm and ensures charge sharing.

The '3+1' pad geometry shown in Fig. 9.3f is based on the idea of increasing the area of
one pad so that other pads can be made smaller. Hence, the length of one pad was increased
by a factor of three. To retain a mean pad area of 12 mm\(^2\) the width of all pads was reduced
to 1.33 mm.

Finally, rectangular pads with a width of 1.27 mm and a length of 12.5 mm were also
tested. Due to the increased pad length, the number of primary electrons collected per pad
row is increased from 55 to 115. This fact should improve the transverse spatial resolution
by a factor of \( \sqrt{\frac{115}{55}} \approx 1.45 \).

### 9.1.2 Theoretical Framework for Comparing Pad Geometries

In theory, the charge distribution will be homogeneous, continuous and Gaussian in the \( x \)-
direction and constant in the \( y \)-direction (see Fig. 9.4). Assume that the center \( \bar{x} \) of the charge
distribution is moved in steps of 10 \( \mu \text{m} \) from the left border of a pad (-1 mm) to the right
border (+1 mm). At each step the charge collected by a central pad and the four neighboring
pads is calculated separately by integrating the distribution. The \( y \)-dimension is accounted
Figure 9.4: Illustration of the theoretical model for comparing pad geometries: a) rectangular pads with a Gaussian charge distribution, integrating to the total charge collected by each pad, b) chevron-shaped pads with a Gaussian charge distribution and a track inclination $\phi = 8^\circ$.

for by repeating the integration 100 times between the lower border of the pad (-3 mm) and the upper border (+3 mm). The left and right pad borders as well as the center of the charge distribution were determined for each $y$-position according to the pad geometry and the track inclination $\phi$. Hence, the charge $Q_i$ collected by pad $i$ is given by:

$$Q_i = \sum_{y=-3}^{+3} \left( \int_{\text{left border} \ (i,y)}^{\text{right border} \ (i,y)} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{x - \bar{x}(y)}{2\sigma^2}\right) dx \right) \Delta y$$

where $\sigma$ is the standard deviation of the Gaussian distribution, which will be called 'cluster width' because of its physical meaning. With the charge information of these five pads, the center of gravity $x_{\text{COG}}$ is determined and plotted against the exact charge position (as examples see Fig. 9.11a to c). In addition the difference between the exact charge position and the center of gravity ($\delta = x_{\text{COG}} - \bar{x}$) is studied as a function of $\bar{x}$ and $x_{\text{COG}}$ (for examples see Fig. 9.11d to f and g to i).

With this model, the influence of the cluster width on the reconstruction of the charge position was studied. The cluster widths were varied between 1.0 mm and 0.1 mm. Comparing the values to the experimental setup described later in this chapter, a cluster width of 1.0 mm corresponds to a drift distance of about 55 cm, whereas a cluster width of 0.1 mm is unrealistically small. Due to the charge-spreading of the GEMs’ transfer and induction gaps, a minimal charge spread of 0.35 mm is expected. Therefore, a cluster width between 0.4 mm and 0.5 mm seems to be best suited to reflect the experimental setup, and for subsequent studies of track inclination and electronic noise, 0.4 mm was chosen.

The track inclination $\phi$ was varied in an angular range between $0^\circ$ and $16^\circ$ (as examples see Fig. 9.11b, c and h). The electronic noise was accounted for by ignoring the charge collected
by one pad if that charge does not exceed the following noise limit:

\[
\text{noise limit} = \frac{Q_{\text{tot}}}{s/n_{\text{theo}}} = \frac{Q_1 + \cdots + Q_5}{s/n_{\text{theo}}}
\]

where \( s/n_{\text{theo}} \) is the signal-to-noise ratio.\(^1\)

### 9.1.3 Monte Carlo Simulation

Since the theoretical description takes into account only one pad row, the detailed Monte Carlo simulation described in Section 5.3.4.2 and in [Let] was used to study longer track segments. A total of twelve pad rows corresponding to a track length of 7.8 cm was considered. The primary ionization was idealized by a fixed number of equidistant electrons per track length, resulting in a Gaussian charge distribution. The track inclination \( \phi \) was distributed uniformly between \(-3^\circ\) and \(-1^\circ\) and the inclination \( \theta \) was kept at \(0^\circ\). These settings resemble the experimental situation as described in the next section. But due to a number of idealizations, the predictive power of the Monte Carlo is limited, and its results are expected to be better than in the experiment. Therefore, only a small number of results will be shown.

### 9.2 Experimental Setup

The experiments were conducted at the test beam line 24 at DESY (for references see [Me03m]). This facility is well adapted to our needs. The low beam intensity prevents a large charge accumulation in the drift volume that was observed with the test beams at CERN. On the other hand, the high repetition rate allows collection of a large amount of statistics. Finally a dipole magnet was also available, and it was used for reduction of the transverse diffusion.

#### 9.2.1 Beam Properties

A schematic drawing of the beam generation is shown in Fig. 9.5a: A carbon fiber is introduced in the beam of the DESY II synchrotron creating bremsstrahlung photons. The photons are guided through a 3 mm thick aluminum plate, where they convert to electron-positron pairs. Then a dipole magnet is used to spread the beam into a horizontal fan. Positrons of a specific energy are then selected by opening a collimator. The energy of the test beam can be adjusted between 1 and 6 GeV by varying the strength of the magnetic field. For the data presented in this chapter a constant beam energy of 5.2 GeV was used.

The collimator was set to a large width in the detector’s \( x \)-direction to collect as many particles as possible. The distribution of the clusters’ \( x \)-positions is shown in Fig. 9.5b. In contrast, the beam width in the detector’s \( z \)-direction was set to a \textit{minimum}, to guarantee a well-defined drift distance. Three different methods were used to measure the beam dimensions. In the first method, the beam profile was scanned with a 4 cm wide scintillator. The number of particles per minute is shown in Fig. 9.6a. The solid line is a convolution of a 4 cm wide rectangular function and a Gaussian function with a standard deviation of 5.3 mm. In Fig. 9.6b the drift time spectrum is shown. The prominent peak at about 2 \( \mu s \)

\(^1\)NOTE: This definition deviates from the one used during the analysis of the Monte Carlo or test beam data: While in the theoretical description the ‘noise’ of only one channel is used to quantify \( s/n_{\text{theo}} \), the total noise in the analysis is determined by adding the noise of each voxel quadratically (see Section 5.3.2.2).
9.2 Experimental Setup

Figure 9.5: Properties of the test beam facility at DESY: a) beam generation [Me03m], b) cluster x-position. The light grey area indicates the clusters that could be assigned to a track, the remainder are shown in dark grey. c) number of tracks per event.

results from particles triggering the readout electronics. The standard deviation of this peak is $(1.460 \pm 0.001) \cdot 10^{-1}$ $\mu$s and corresponds to a beam width of $(5.36 \pm 0.005)$ mm. The drift time spectrum also reveals additional peaks in steps of about $1$ $\mu$s. This time structure is due to the 1 MHz revolution frequency of the bunch inside the DESY II synchrotron. Since the bunch has only a small probability of creating a secondary particle pair with the correct energy, the subsequent (and previous) peaks are much smaller than the one triggering the electronics. Finally, the beam width was measured directly by turning the chamber as described in Section 8.5.1. Here a standard deviation of $(6.25 \pm 0.02)$ mm was found. Therefore, a drift distance error of 6 mm will be used.

Fig. 9.7 shows the track properties. Both track inclinations $\phi$ and $\theta$ have a narrow distribution. $\phi$ shows a long tail to larger angles coming from a low-energetic tail of the beam energy. Also the track curvature $\kappa = 2e$ shows evidence of a low-energetic tail arising from interactions of the positrons with the triggering scintillators. The central peak has a standard deviation of $(5.49 \pm 0.08) \cdot 10^{-5}$ (mm$^{-1}$), giving a momentum resolution of $\frac{p_T}{p_T} = (0.366 \pm 0.001)$.

Only during a short period of the acceleration cycle is the energy of the DESY II beam

Figure 9.6: Measurement of the vertical beam width: a) scanning the beam profile with a 4 cm wide scintillator. The solid line is a convolution of a 4 cm wide rectangular function and a Gaussian function with a standard deviation of 5.3 mm, b) drift time spectrum, c) measurement after turning the chamber.
sufficiently high to produce a secondary beam. Therefore, 80 ms spills with a repetition rate of 3.1 Hz are available. This rate is well-matched with our readout rate (see Section 5.1), so that one event with 130 digitization samples could be recorded during every spill. The number of particles per spill varies strongly with the energy, since the bremsstrahlung spectrum decays according to a $1/E$ law. At 5 GeV an average rate of about 500 Hz can be expected. Hence, in general, only one particle was recorded per event (see Fig. 9.5e).

### 9.2.2 Magnet

Another large dipole magnet is placed inside the experimental area. It has an aperture of 55 cm, and a maximum magnetic field of $B = 1$ T can be attained. The field was tested with a Hall-effect probe, and inhomogeneities of the order of about 5% were observed in the volume occupied by the detector.

### 9.2.3 Detector Parameters

All detector parameters were chosen to minimize the transverse diffusion coefficient. A non-flammable gas mixture of Ar-CH$_4$ (95:5) was used. However, a measurement of the drift velocity similar to the one performed during the CERN tests revealed that the gas was contaminated with about 150 ppm H$_2$O (see Fig. 9.8a). In addition, the maximum magnetic field of 1 T was applied and the detector’s drift field was operated at 60 V/cm, which is below the maximum for the drift velocity. The GARFIELD interface to MAGBOLTZ gives a transverse diffusion coefficient $D_T = 117 \mu$m/$\sqrt{\text{cm}}$ for this configuration. The ratio of this value to the one of the large-scale detector described in the TESLA-TDR is 1.625. Therefore, drift distances cited for the prototype have to be multiplied by 1.625$^2$=2.64 to get the equivalent drift distances under TDR conditions (7.5 cm $\sim$ 19.8 cm and 17.5 cm $\sim$ 46.2 cm). The longitudinal diffusion coefficients differ only by a factor of 1.93, so that the results are truly comparable. All numbers have been summarized in Table 9.1. In Fig. 9.8b the number of pads per pad row with a collected charge larger than 10 ADC counts ($\approx 2 \cdot N_l(c,r)$) is plotted. It is obvious that the cluster positions throughout this chapter have to be corrected using the modified analysis technique described in Section 5.3.5. A significant number of clusters, however, shows no charge sharing at all with only one pad collecting the complete cluster charge.
### 9.2 Experimental Setup

<table>
<thead>
<tr>
<th>detector</th>
<th>gas</th>
<th>$\bar{E}$ V/cm</th>
<th>$\bar{B}$ T</th>
<th>$\bar{v}_{\text{drift}}$ mm/μs</th>
<th>$D_T$ μm/√cm</th>
<th>$D_L$ μm/√cm</th>
<th>$d_{\text{drift}}$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>prototype</td>
<td>Ar-CH$_4$-H$_2$O (95:5:1.5$\times$10$^{-4}$)</td>
<td>60</td>
<td>1</td>
<td>36.7</td>
<td>117</td>
<td>550</td>
<td>7.5 / 17.5</td>
</tr>
<tr>
<td>TESLA-TDR</td>
<td>Ar-CH$_4$-CO$_2$ (93:5:2)</td>
<td>240</td>
<td>4</td>
<td>45.0</td>
<td>72</td>
<td>285</td>
<td>19.8 / 46.2</td>
</tr>
</tbody>
</table>

Table 9.1: A comparison between detector parameters of the prototype detector in the DESY test beam and the large-scale detector described in the TESLA-TDR. Listed are the gas mixture, the electric drift field $\bar{E}$, the magnetic field $\bar{B}$, the drift velocity $\bar{v}_{\text{drift}}$ of electrons, the transverse and longitudinal diffusion coefficients $D_T$ and $D_L$ and various drift distances $d_{\text{drift}}$. All values were calculated with the GARFIELD interface to MAGBOLTZ.

Because of the small aperture of the dipole magnet, a flat mechanical support had to be used. The front-end electronics were mounted sideways, and the FEE cards were connected via 20 cm flatband cables to the readout board (see Fig. 9.9a). Even though they were shielded by an aluminum layer, additional noise was introduced by the operation of the magnet. Compared to data taken previously (see as examples Figs. 6.2a and 6.3b) an increase in noise by a factor of 3 to 4 was measured. Fig. 9.9b shows the average electronic noise of each channel and c) the signal-to-noise ratio of all clusters. While a signal-to-noise ratio peaking around 40 is still excellent performance as far as efficiency is concerned, it obscures the tails

![Figure 9.8](image-url)  
Figure 9.8: a) Drift velocity of electrons in Ar-CH$_4$ (95:5) as a function of the electric field. The solid line is a calculation with the GARFIELD interface to MAGBOLTZ, including 150 ppm H$_2$O. b) average number of pads per pad row with a collected charge larger than 10 ADC counts. Results of the staggered rectangular pads with track inclination $\phi = -1^\circ$ and a drift distance of 7.5 cm are shown.
of the Gaussian charge distribution, and therefore causes a major loss of information for a spatial resolution study.

### 9.2.4 Trigger signal

The trigger signal was generated by two scintillators placed in front of the detector. Each scintillator had an active area of $4 \times 31 \text{ cm}^2$ and is 1 cm thick, giving a good detection efficiency but introducing a considerable material budget in front of the detector. The scintillators were mounted perpendicular to each other, resulting in an active area of $4 \times 4 \text{ cm}^2$.

### 9.3 Rectangular Pads $1.27 \times 12.5 \text{ mm}^2$

Since this pad geometry does not comply with the guidelines of the TESLA-TDR, only a small set of data was taken. This data set, however, allows an easy comparison of the remaining data with previous results. The drift distance was set to 17.5 cm, resulting in cluster sizes sufficiently large to hit more than two pads. The transverse spatial resolution and the offsets of the residuals are shown in Fig. 9.10. No deviations from the ideally flat distribution were found, except at very low effective gas gains.

The transverse spatial resolution follows the same dependency on the effective gas gain as has been previously observed. Saturation sets in at a gain of about $5 \cdot 10^3$. Due to the increased noise, this is somewhat larger than the value reported at the CERN test beam. At a gain of $1.06 \cdot 10^4$ a best value of $(76 \pm 2) \mu \text{m}$ was reached. Hence, the best resolution that could be expected from the pad geometries described below is of $110 \mu \text{m}$, assuming only the pad length has a significant influence.

### 9.4 Rectangular Pads $2 \times 6 \text{ mm}^2$

The theoretical model describing rectangular pads with a width of 2 mm and a length of 6 mm is identical for the staggered and non-staggered layout. The results are shown in Fig. 9.11. In the first column (a,d,g), various noise levels are shown, corresponding to different gas gains in the experiment. The reconstructed track position versus the true track position is
Figure 9.10: Long rectangular pads 1.27 × 12.5 mm²: a) dependence of transverse spatial resolution and offset of residuals on the cluster’s x-position on the pad, b) dependence of transverse spatial resolution on the effective gas gain.

ideally a straight line between (-1,-1) and (+1,+1), bisecting the first and third quadrants. However, due to the Gaussian charge distribution, the reconstructed position deviates from the true position. This deviation is shown in (d) as a function of the true position and in (g) as a function of the reconstructed position. Both plots show good agreement with the data presented in Figs. 9.13b,e and h, and identical features can be observed: The vertical line in (g) represents the degradation of the spatial resolution when only one pad is hit. These events transform into the sloping line in plot (d).

The increase in noise extends the region in which the cluster is shifted to the center. However, the influence of the noise is much lower than that of track inclination and cluster width. The latter has a particularly strong impact, and for small cluster sizes only a small segment of the pad sees charge sharing with the neighboring pads. Deviations from the true track position can be as large as 0.8 mm. In contrast to the situation described in Section 2.5.2 the angular pad effect has a positive influence in this model: Since charge quantization is not taken into account, an inclination of the homogeneous distribution is equivalent to a larger cluster width and therefore the reconstruction improves.

The offsets of residuals calculated with the Monte Carlo simulation data (see Fig. 9.12a) agree well with the theoretical model (see Fig. 9.11g,i): The offsets increase from wider to smaller charge distributions, whereas the signal-to-noise ratio has no influence. From the absolute values of the offsets, a cluster width of 0.6 mm to 0.4 mm can be deduced. The transverse spatial resolution degrades with shorter drift distances (see Fig. 9.12b). This is true for all signal-to-noise ratios under study. However, for s/n=239 and a drift distance of 17.5 cm, the theoretical limit of 65 μm is reached, and for longer drift distances a diffusion-dominated behavior is expected.

The measurements with the DESY test beam show an overall degradation, as was expected due to the idealizations in the Monte Carlo simulations. The qualitative results, however, agree well. The transverse spatial resolution degrades towards the center of the pad. This effect is particularly strong for low effective gas gains (see Fig. 9.13a) and short drift distances (g). The function relating the offsets of residuals and the x-position on the pad varies little with the effective gas gain (b), but strongly with cluster sizes (h), i.e. with the drift distance. The corrected transverse spatial resolution, however, does not show any dependence on the drift distance (i).
Figure 9.11: Theoretical description of rectangular pads 2 × 6 mm²: reconstructed versus true track position (a,b,c), deviation of reconstructed track position from true track position versus true track position (d,e,f) and the deviation versus the reconstructed track position (g,h,i). Additionally, the s/n_theo level was changed in (a,d,g), the track inclination φ in (b,e,h) and the cluster width in (c,f,i).

The dependence on track inclination φ shows a more complex behavior. For very small inclinations (here: 0.4°) an artificial alignment of reconstructed clusters is observed. Fig. 9.12c illustrates this effect: If the track follows a single column of pads with no charge sharing in a significant number of rows, then clusters as well as tracks are aligned in the center of the pad column, resulting in a transverse spatial resolution of 0 µm. In Fig. 9.13d this effect leads to a drop of the spatial resolution from about 150 µm at the border of the pads down to (74 ± 4) µm at the middle of the pads. Also the offset of the residuals differs from the remaining track inclinations by being about 0 for all x-positions on the pad. For larger angles, the aforementioned behavior can be observed: With an increasing inclination, the spatial resolution in the middle of the pad degrades and the offsets of the residuals increase. This changes only with large inclinations of more than 10°, where the performance of the
complete pad degrades.

To avoid the 'artificial' cluster alignment and to have comparable conditions for all pad geometries, all data were taken at track inclinations $\phi \approx -2^\circ$. Only a few sets of data deviate from this standard setting; they are used to study the respective pad geometry's performance at larger and smaller track inclinations.

9.5 Rectangular Pads $2 \times 6$ mm$^2$ - Staggered

The staggered rectangular pad geometry has a behavior similar to the non-staggered geometry, but the quantitative results are about 20 to 30 $\mu$m better. This has already been demonstrated by the Monte Carlo simulation (see Fig. 9.14). The offsets of the residuals are similar to those in Fig. 9.12a and the transverse spatial resolution also shows the expected behavior. The overall performance, however, is improved, and a diffusion-dominated regime can be observed for drift distances longer than 10 cm, even in the presence of significant noise.

The main reason for introducing the staggered arrangement is to guarantee charge sharing in at least every second row. Monte Carlo and test beam data showed that a careful correction of the cluster position according to its $x$-position on the pad is of utmost importance. Otherwise, a drastic degradation of the spatial resolution will occur. The reason for this effect is similar to the 'artificial' alignment of clusters described in the last section. In contrast to the non-staggered geometry, however, the clusters are not aligned in a straight line of the column, but in a zigzag curve (see Fig. 9.15b). Therefore, as the track runs between the two cluster positions, the clusters have alternatively a positive and negative residual with respect to it. This double-peak structure of the residuals or transverse spatial resolution distribution is shown in Fig. 5.13a. The effect is also visualized in Fig. 9.15a. There, the residuals of the row under study (target row) are plotted versus the residuals of the row above it and the $x$-position on the pad. The resulting distribution shows the typical "Z"-shape expected from the offset. This "Z" is also a bisecting line if the distribution is projected onto the residual-residual plane, revealing the linear correlation between the offsets of different rows.

Results from the DESY test beam are shown in Fig. 9.16 and confirm the predicted be-
Figure 9.13: Results of measurement with rectangular pads $2 \times 6$ mm$^2$: transverse spatial resolution as a function of the $x$-position on the pad (a,d,g) and offset of residuals in dependence on the $x$-position on pad. The data are shown for various effective gas gains (a,b,c), track inclinations $\phi$ (d,e,f) and drift distances (g,h,i). If not stated otherwise, the data refer to an effective gas gain of about $4 \cdot 10^3$, a drift distance of 7.5 cm and an inclination $\phi = -2.0^\circ$. The dependency on the effective gas gain is shown for a drift distance of 17.5 cm.

At high effective gas gains the transverse spatial resolution shows values of about 110 $\mu$m to 120 $\mu$m for $x$-positions on the pads in the outer segments. This is in good agreement with the results from the long rectangular pads $1.27 \times 12.5$ mm$^2$ if the reduced statistics of primary electrons is taken into account. At the central part of the pad, the spatial resolution degrades more strongly than in the non-staggered case, resulting from the previously mentioned anti-alignment of clusters. The corrected transverse spatial resolution again shows no dependency on the drift distance (i). This is confirmed by (c), where the gain dependence for two drift distances is shown (7.5 cm and 17.5 cm): For low effective gas gains, results of the
two drift distances differ by as much as 35 μm, but for effective gas gains of more than \(1\times10^4\), both drift distances show similar spatial resolutions (119 ± 1 μm for 7.5 cm, 117 ± 1 μm for 17.5 cm).

For this readout pad geometry some additional dependencies of the transverse spatial resolution are discussed below. Fig. 9.17 shows the dependencies on properties of the reconstructed cluster itself, as for example, the row number of the cluster position (a). The transverse spatial resolution is rather homogenous between rows number 1 and 10. But the offsets of the residuals show in the same range, deviations of up to 50 μm from the expected zero-position. These deviations are presumably caused by the previously mentioned inhomogeneities of the magnetic field (see Section 9.2.2). The offset of the last row is particularly large. As a consequence, the extrapolation of the track parameters is not reliable, and the spatial resolution is also very large. Despite the vanishing offset, the first row also shows an

Figure 9.15: a) Residuals of staggered pads: dependence of residuals on the pad row under study (target row, x-axis) and residuals of the pad row above the row under study (y-axis) on the x-position on the pad (z-axis), b) illustration of alignment behavior of staggered pads.
Figure 9.16: Results of measurement with staggered rectangular pads $2 \times 6 \text{ mm}^2$: transverse spatial resolution as a function of the $x$-position on the pad (a,d,g) and offset of residuals as a function of the $x$-position on the pad. The data are shown for various effective gas gains (a,b,c), track inclinations $\phi$ (d,e,f) and drift distances (g,h,i). If not stated otherwise, the data refer to an effective gas gain of about $4 \times 10^3$, a drift distance of 7.5 cm and an inclination $\phi = -2.0^\circ$.

increased transverse spatial resolution, which is due to the extrapolation of track parameters. For this reason, the first and the last row were not considered when determining the spatial resolution. Figs. 9.17b and c show the dependence on the cluster charge and the signal-to-noise ratio. Since the data set was taken with a constant effective gas gain, the cluster charge can be converted directly into the primary ionization: The mean of the charge distribution corresponds to $1.3 \cdot 10^3$ ADC counts and is equivalent to an average of 55 electrons per pad row. At this value the transverse spatial resolution in Fig. 9.17b ends in a plateau of best resolution of about 140 $\mu$m. But at lower cluster charges, the spatial resolution degrades
rapidly due to the low statistics of primary ionization. The spatial resolution plotted over the signal-to-noise ratio shows a similar behavior. Here the area of best resolution sets in at about 60 \( \mu \text{m} \). Since clusters with lower cluster charge tend to have smaller cluster sizes, the noise of these clusters is reduced. Therefore, the large difference that was observed between the low cluster charges and the plateau is partially compensated.

Fig. 9.18 shows the dependence of transverse spatial resolution on track properties. In (a) the dependence on the number of clusters per track is shown. The spatial resolution improves with an increased number of clusters per track. This is because the larger number of clusters improves the estimates of track parameters, and therefore they become more reliable. But since more than 90\% of all tracks consist of either 10 or 11 clusters, this effect has only a marginal influence on the results presented in this chapter. In (b) the transverse dependence of spatial resolution on the \( \chi^2 \) of the track without the cluster under study is shown. Here the same argument as before holds true: The better the estimates of the track parameters, the more accurate the spatial resolution determination.
Figure 9.19: Theoretical description of rhombic pads: reconstructed versus true track position (a,b,c) and deviation of reconstructed track position from true track position versus reconstructed track position (d,e,f). In addition, the \( s/n_{\text{th}} \) level was varied in (a,d), the track inclination \( \phi \) in (b,e) and the cluster width in (c,f).

### 9.6 Rhombic Pads

The rhombic pads are intrinsically staggered, and therefore will be compared to the staggered rectangular pads described in the previous section. The theoretical model gives results identical to the ones of the rectangular pads (see Fig. 9.19). Only one single deviation was found: The difference between reconstructed and true track position has opposite signs for small and large inclination angles (see (e)).

The Monte Carlo simulation (see Fig. 9.20) shows an even more extreme behavior than with the staggered rectangular pads. For all drift distances and gains, a spatial resolution of about 40 to 60 \( \mu \)m is achieved at the border of the pads, while at the center of the pads a degradation by a factor of about 3 is observed in all configurations under study. Also, the offset of residuals shows more-pronounced deviations of up to 500 \( \mu \)m. The reason for this is a further asymmetric charge sharing of pads in one row. As described in Section 5.3.5, the deviations are due to the center of gravity algorithm that is not optimized for thin Gaussian charge distributions. The rhombic pads emphasize the asymmetric charge collection by collecting only a small fraction of the charge if the tail of the Gaussian distribution hits the border segment of the pad. In contrast, if the central part of the pad is hit, twice as much charge is collected compared to the staggered rectangular pads. This offset enlargement can be corrected for, but the central region, where insufficient charge sharing takes place, is extended, resulting in larger spatial resolutions than with staggered rectangular pads. However, Fig. 9.20c shows a clear improvement with respect to the non-staggered rectangular pads (see
Figure 9.20: Simulation results of rhombic pads: a) dependence of transverse spatial resolution on x-position on pad, drift distance and signal-to-noise ratio, b) dependence of offsets of residuals on x-position on pad, drift distance and signal-to-noise ratio. c) dependence of transverse spatial resolution on drift distance and signal-to-noise ratio.

The results of the test beam (see Fig. 9.21) again confirm the predictions. If cluster position is close to the border of the pad, the spatial resolution is as good as that with the staggered rectangular pads. For short drift distances and high effective gas gains, the performance is about 120 \( \mu \text{m} \). But for all parameter settings, the resolution degrades to more than 300 \( \mu \text{m} \) at the center of the pad. Therefore, the results averaged over the whole pad area are about 20 \( \mu \text{m} \) larger than for staggered rectangular pads. The spatial resolution also shows a larger degradation for larger track inclinations resulting from the increased pad length.

### 9.7 Chevron-shaped Pads

The theoretical model gives excellent results: The cluster width has no influence on the reconstruction and track inclinations as well as signal-to-noise ratio show deviations of less than 100 \( \mu \text{m} \) (see Fig. 9.22). The dependence on the signal-to-noise ratio, however, shows an interesting structure: the difference between reconstructed and true track position at first increases towards the center of the pads but then drops to zero before reaching it. The negative sign on the left half of the pad and the positive one on the right side show that the reconstructed clusters are not shifted towards the center, but rather towards the pad borders. However, with \( s/n_{\text{th}} \) ratios higher than 50, this effect will not be visible in the test beam data.

The Monte Carlo simulation supports these favorable results (see Fig. 9.23). The transverse spatial resolution is constant with respect to the x-position on the pad, and the offsets of the residuals are smaller than 80 \( \mu \text{m} \). The Monte Carlo simulation shows a dependence on the drift distance, however, and for a signal-to-noise ratio of 239 the transverse spatial resolution increases from \( (56 \pm 1) \mu \text{m} \) at a drift distance of 7.5 cm, to \( (74 \pm 1) \mu \text{m} \) at a drift distance of 17.5 cm. The signal-to-noise ratio also shows a significant influence throughout the pad which was not predicted by the theoretical model.

The measurements with the prototype detector verify the small offsets of the residuals, which agree in all respects well with the theoretical model and the Monte Carlo simulation. In addition, the rather constant spatial resolution for all x-positions on the pad for small
angles and sufficiently high gains ($\geq 3.5 \cdot 10^3$) reinforces both the model and the simulation. However, the absolute value of the transverse spatial resolution is considerably higher than the expected value. A best value of $(235 \pm 5) \mu m$ was reached for an effective gas gain of $9 \cdot 10^3$ at a drift distance of 17.5 cm. For shorter drift distances the spatial resolution degrades, and for effective gas gains below $4 \cdot 10^3$ and drift distances of 7.5 cm a degradation of the spatial resolution was measured if the reconstructed cluster position is close to the center of the pad. The track inclination $\phi$ shows an interestingly low influence on the spatial resolution. Between $0^\circ$ and $14^\circ$, the resolution degrades by only 20 $\mu$m.

The spatial resolution can be improved if the number of jags is increased. Then the
9.7 Chevron-shaped Pads

Figure 9.22: Theoretical description of chevron-shaped pads: reconstructed versus true track position (a,b,c) and deviation of reconstructed track position from true track position versus the reconstructed track position (d,e,f). In addition, the \( s/n_{\text{theo}} \) level was varied in (a,d), the track inclination \( \phi \) in (b,e) and the cluster width in (c,f).

...asymetry is broken, and for “high-frequency” chevrons, the pads resemble rectangular pads with interdigitated edges. In [Ka02f] it was demonstrated with a Monte Carlo simulation that the spatial resolution is equivalent to that of rectangular pads.

Figure 9.23: Simulation results of chevron-shaped pads: a) dependence of transverse spatial resolution on \( x \)-position on pad, drift distance and signal-to-noise ratio, b) dependence of offsets of residuals on \( x \)-position on pad, drift distance and signal-to-noise ratio. c) dependence of transverse spatial resolution on drift distance and signal-to-noise ratio.
9.8 Comblike Pads

The theoretical model shows a rather complex behavior of the comblike readout pad geometry (see Fig. 9.25). In addition, the main characteristic of the data from this readout geometry is unlike that of data from previously discussed pad geometries. The reconstructed track position is not shifted from the true track position towards the center of the pad, but towards its borders (see (a)). This occurs not only for low signal-to-noise ratios, as it did for the chevron-shaped pads, but also if no noise is included. If the deviation of reconstructed to
Figure 9.25: Theoretical description of comblike pads: reconstructed versus true track position (a,b,c), deviation of reconstructed track position from true track position versus true track position (d,e,f) and the deviation versus the reconstructed track position (g,h,i). The data is shown for various $s/n_{theo}$ levels (a,d,g), track inclinations $\phi$ (b,e,h) and cluster widths (c,f,i).

true track position is plotted versus the true or reconstructed position, the effect is clearly visible (see (d,g)). These deviations have a negative sign on the left half of the pad and a positive sign on the right half. In addition the curve becomes vertical at the border of the pad as seen in Fig. 9.25g, an indication of an ambiguous charge distribution on the pads. With other geometries this was only seen if narrow tracks were at the center of the pad. With a rising noise level an additional substructure similar to the ones of the chevron-shaped pads appears introducing zones of ambiguous behavior. With increasing track inclination $\phi$ the deviations decrease, since the homogeneous charge distribution balances the narrow width. The dependence on the cluster width shows the most meaningful result: For cluster widths smaller than 300 $\mu$m, the reconstructed cluster position is on the neighboring pad (see (c)), and a unique track position can not be deduced from the reconstructed track position (see
Figure 9.26: Simulation results of comblike pads: a) dependence of transverse spatial resolution on x-position on pad, drift distance and signal-to-noise ratio, b) dependence of offsets of residuals on x-position on pad, drift distance and signal-to-noise ratio. c) dependence of transverse spatial resolution on drift distance and signal-to-noise ratio.

(i). The reason for this is shown in Fig. 9.27a: Three tracks that are separated by a 500 µm thick strip give the same signal ratio on the two neighboring pads. Only if the true track position were known could a unique correction be performed (see Fig. 9.25f).

The Monte Carlo simulation shows the expected results. That is, the transverse spatial resolution degrades at the pad borders (see Fig. 9.26a)). Also, the offsets of the residuals confirm the theoretical model qualitatively as well as quantitatively (see Fig. 9.26b)). The transverse spatial resolution shows a continuous worsening with increasing drift distance, which is due to diffusion. For drift distances larger than 10 cm, the comblike pads have a transverse spatial resolution which is 20 µm larger than the one of the staggered rectangular pads.

The measurements show again a substantial degradation of the transverse spatial resolution. In addition there is no dependence on the x-position on the pad - neither of the spatial

Figure 9.27: a) Illustration of track positions leading to ambiguous charge ratios on comblike pads, b) dependence of transverse spatial resolution on the cluster’s x-position on a pad, calculated with track parameters, c) dependence of transverse spatial resolution and offset of residuals on x-position on a pad, d) ‘3+1’ pads: Illustration of splitting of the charge collected by the long pad.
9.8 Comlike Pads

resolution nor of the residuals’ offsets (see both parameters for various detector settings in Fig. 9.27c). With the theoretical model, it was shown that a unique correction could only be found if the true track position was known. To approximate this true track position, the track parameters were used to calculate the x-position of the primary charge location.

A scatter plot showing the spatial resolution distribution versus this x-position on a pad is shown in Fig. 9.27b. Here, a position-dependent offset can be observed, but no hint for resolving the above mentioned ambiguities was found. Therefore, correcting for the offsets does not improve the final transverse spatial resolution results. Fig. 9.28 shows results that were obtained with the COG method. For all gas gains the results for a drift distance of 7.5 cm are higher than the ones for 17.5 cm (see (a)). This is confirmed by Fig. 9.28c, where the transverse spatial resolution is shown versus the drift distance. The dependency on the track inclination $\phi$ shows a swift degradation at small angles, then a slight improvement at around $4^\circ$ and again a steep degradation up to $12^\circ$. This behavior could be explained by the fact that for inclinations of more than $4^\circ$ tracks pass over more than two strips, and in regions where ambiguities are possible, the wider charge distribution gives a unique charge ratio on the two pads.

The aforementioned ambiguities can be eliminated by adjusting the number of strips and the pitch to the diffusion. During the test beam, the typical standard deviation of the cluster width was 0.4 mm. With a moderate signal-to-noise ratio, the total cluster width is about 1.6 mm. Therefore, on average, only two to three strips are hit significantly above the noise, resulting in an ambiguous charge collection. If the number of strips per pad is increased and the pitch is reduced, then the basic concept of a continuous transition from one pad to the next can be approximated. In Fig. 9.29a several implementations of the comlike structure are shown. In addition to the version built, with 4 strips, pads with 9 or 16 strips have been studied. Taking into account the same total cluster width as before, the number of strips hit above noise is 5-6 or 10-11 respectively. In these cases, changing the number of strips per spike led to unique integration patterns, giving the desired resolution. To test the idea, the two improved versions were tested with the theoretical model (see Fig. 9.29b,c). As expected, there are no ambiguities for cluster widths of 0.3 - 0.4 mm. However, for smaller cluster sizes the number of ambiguities increases, and if these clusters are also to be considered, then a larger number of strips is necessary. From this, one can conclude that with comlike pads the
pitch of the strips must be less than half the standard deviation of the smallest cluster sizes expected.

9.9 ‘3+1’ Pads

For reconstructing the track position at every row, the charge collected by the long pad was split into three charges allocated to three short pads \((u, m, l)\) instead of a large one. The process is illustrated in Fig. 9.27d, where the numbering scheme of the adjacent pads is also introduced. The splitting algorithm is based on weighting the charges \(C_u\), \(C_m\) and \(C_l\) with the charge collected by the adjacent short pads:

\[
\text{Charge of upper pad:} \quad C_u = \frac{C_1 + C_6}{2C_{\text{tot}}} \cdot C_{\text{long}}
\]

\[
\text{Charge of middle pad:} \quad C_m = \frac{C_2 + C_5}{2C_{\text{tot}}} \cdot C_{\text{long}}
\]

\[
\text{Charge of lower pad:} \quad C_l = \frac{C_3 + C_4}{2C_{\text{tot}}} \cdot C_{\text{long}}
\]

where \(C_{\text{long}}\) is the charge collected by the long pad, \(C_i\) the charge collected by the adjacent short pads and \(C_{\text{tot}} = \sum_{i=1}^{6} C_i\) the charge collected by all adjacent pads. This algorithm is expected to work well if tracks with a small inclination \(\phi\) are studied. However, for larger inclinations this algorithm is expected to give an incorrect charge splitting. Fig. 9.27d illustrates that a thin charge distribution with an inclination of about 18° could pass first across pad 1, then the long pad and finally across pad 4. The splitting algorithm would then assign about half the charge collected by the long pad to \(C_u\) and the remaining charge to \(C_l\). Obviously, this does not represent the true charge distribution.

Since this pad geometry consists of rectangular pads, the theoretical model is identical to the one presented in Section 9.4 and that discussion will not be repeated here. Only the test
Fig. 9.30: Results of measurement with '3+1' pads: dependence of transverse spatial resolution on the x-position on the pad (a,d,g) and dependence of offset of residuals on the x-position on pad. The data are shown for various effective gas gains (a,b,c) and track inclinations φ (d,e,f). Dashed lines are to guide the eye. If not stated otherwise, the data refer to an effective gas gain of about 4·10³, a drift distance of 7.5 cm and an inclination φ = -2.0°.

beam results shown in Fig. 9.30 will be discussed. In (a) the dependence of transverse spatial resolution on the x-position of the pad is shown. A degradation at the center of the pads leads to the conclusion that despite the reduced pad width, some clusters still hit only one pad. The dependence on the gain shows another novelty (see (c)): For short drift distances the transverse spatial resolution degrades at high effective gas gains. This can be attributed to an increasing number of events where the charge collected by the long pads reaches the saturation of the ADC chips despite the extended dynamic range. For small track inclinations φ, the onset of an artificial cluster alignment can be seen by the improved transverse spatial resolution at the center of the pad (see (d)). For larger track inclinations φ, the spatial resolution degrades rapidly. For an angle of 10°, spatial resolutions of about 450 µm were reached. Here the suboptimal splitting algorithm certainly contributes to the unsatisfactory result.

9.10 Improved Monte Carlo Simulation

A large discrepancy between the Monte Carlo simulation used so far and the measurements is observed for all pad geometries. Also striking, is the fact that the results of the Monte Carlo simulation are rather similar for all pad geometries. For a signal-to-noise ratio of about 240, spatial resolutions between 60 µm and 80 µm were reached and for a signal-to-noise ratio
of about 50, results are around 100 \( \mu \text{m} \). The results of the measurements, however, differ significantly for various pad geometries. As an example, the staggered rectangular pads have spatial resolutions around 120 \( \mu \text{m} \), whereas the results for chevron-shaped pads are larger than 250 \( \mu \text{m} \). The reason for these differences is the simplification of assuming equidistant electrons along the track path in the Monte Carlo simulation. To estimate the influence of a clustering effect, six sets of different electron distributions along the track were tested. Since an effect similar to the angular pad effect is assumed to cause the degradation, the number of electrons and clusters were reduced. Based on results in Section 7.4 \( n_T^{eff} = 8.1 \pm 0.3 \) and Section 8.2 \( n_T^{eff} = 10.9 \pm 0.5 \) an average number of 10 electrons or clusters per cm track length have been tested:

- **Set 1**: \( 90 \frac{\text{cm}}{\text{cm}} \) are distributed equidistantly along the track path.
- **Set 2**: \( 9 \frac{\text{cluster}}{\text{cm}} \) are distributed equidistantly along the track path and each cluster consists of 10 electrons.
- **Set 3**: \( 9.5 \frac{\text{cm}}{\text{cm}} \) are distributed equidistantly along the track path. To ensure identical cluster charge, the 'electronic amplification' given by the number of electrons per ADC count was adjusted.
- **Set 4**: \( 10 \frac{\text{cluster}}{\text{cm}} \) are distributed equidistantly along the track path. The number of electrons per cluster follows the experimental distribution given in [B093b] with a mean of \( 2.9 \frac{\text{cm}}{\text{cluster}} \). Here the number of electrons per ADC count was also adjusted.
- **Set 5**: \( 10 \frac{\text{cluster}}{\text{cm}} \) are distributed equidistantly along the track path. The number of electrons per cluster follows the experimental distribution given in [B093b] with a mean of \( 8.4 \frac{\text{cm}}{\text{cluster}} \).
- **Set 6**: \( 29 \frac{\text{cluster}}{\text{cm}} \) are distributed along the track according to Eq. 2.2. The number of electrons per cluster follows the experimental distribution given in [B093b] with a mean of \( 2.9 \frac{\text{cm}}{\text{cluster}} \).

These sets were studied for two different pad geometries, the staggered rectangular pads and the chevron-shaped pads. The results are given in Fig. 9.31 for three different signal-to-noise ratios. The quoted numbers of these ratios are the mean of the respective s/n distributions, since the mean is identical for all sets. The most probable value quoted for measurements, however, changes with the various sets. E.g. for the most realistic set (\#6), the given signal-to-noise ratio of 88 (mean) corresponds to a most probable signal-to-noise ratio of about 60, which is similar to the test beam results.

In Fig. 9.31 the results of measurements and the theoretical limit according to the following equation have been added:

\[
\sigma_x^2 = \frac{D_T^2 \cdot \tau_{drift}}{n_T \cdot \cos^2 \theta \cdot 2} + \frac{(6 \text{ mm})^2}{12 n_T \cdot \tan^2 2^\circ}
\]  \hspace{1cm} (9.1)

with \( D_T = 117 \mu \text{m} / \sqrt{\text{cm}} \) and \( n_T = 55 \).

Set 1 and 2 both give results, which are close to the theoretical limit. Therefore, one can conclude that the spatial resolution is independent of the clustering of electrons if cluster sizes are identical. However, if the number of electrons is reduced (Set 3), the spatial resolution
Figure 9.31: Comparison of various electron clusterings along the track. Shown are results of the Monte Carlo simulation, measurements and the theoretical limit for the staggered rectangular pad (a,b,c) and chevron pads (d,e,f). Three different signal-to-noise ratios are given: \( \approx 240 \) (a,d), \( \approx 88 \) (b,e) and \( \approx 48 \) (c,f).

degraded considerably as is expected from Eq. 9.1 with a smaller \( n_T \). From Set 4 and 5 it becomes obvious that the variation in the number of electrons per cluster has a strong influence on the spatial resolution. For larger asymmetries (Set 5), the spatial resolution is worse and approaches, for small signal-to-noise ratios, the results of the measurement. If realistic spacing distances between clusters are introduced (Set 6), the spatial resolution degrades more strongly. For the staggered pad geometry, results of Set 6 is about 100 \( \mu m \), and for similar signal-to-noise ratios it agrees within 20 \( \mu m \) with the measurement. The chevron-shaped pads show a larger spatial resolution of about 160 \( \mu m \) for Set 6 and a signal-to-noise ratio of about 88. This results from the intrinsic pad inclination of 33.7°, which leads to an angular pad effect even if tracks are quasi-parallel to the \( y \)-direction. Here also, a discrepancy of \( \approx 90 \mu m \) remains between the measurement and simulation results, indicating that additional effects such as \( \delta \)-rays have not been accounted for, but contribute significantly to the degradation of the spatial resolution. A more detailed discussion of the influence of various parameters can be found in reference [Let].

9.11 Comparison and Conclusion

Seven different readout pad geometries were studied with respect to their transverse spatial resolutions under the requirement that the charge that is to be detected have a narrow, Gaussian distribution. The pad geometries were studied with a theoretical model and in
a Monte Carlo simulation. The results of both methods were compared to measurements performed at the DESY test beam facility. Qualitatively a good agreement of the theoretical model, the simulation study and the measurements was achieved. The intrinsic features of various pad geometries could be explained, and with the optimized analysis algorithm, the results improved. Due to idealizations in the model and in the simulation program, the quantitative results of the test beam show a larger transverse spatial resolution than predicted. Therefore, a more realistic Monte Carlo simulation was used to demonstrate that this degradation is due to the irregular clustering of electrons. The results of the measurement are summarized in Table 9.2 for two different drift distances (7.5 cm and 17.5 cm), two effective gas gains ($4 \cdot 10^3$ and $10^4$) and two track inclinations $\phi$ ($-2^\circ$ and $10^\circ$). For pad geometries complying with the guidelines of the TESLA-TDR, the staggered rectangular pads $2 \times 6$ mm$^2$ gave the best results and are to be recommended. But if longer and thinner pads are used the transverse spatial resolution improves due to the higher statistics of the primary charge collected per pad row.

The results of more complex pad geometries such as the chevron-shaped pads, comblike structures or the '3+1' pads can be further optimized either by an improved layout of the geometry, or by more sophisticated analysis algorithms. Several suggestions for improvements have been given throughout the text. Nonetheless, all complex pad geometries fulfill their original design criteria: The number of clusters without charge sharing can be lowered by a factor of 2 to 5.
<table>
<thead>
<tr>
<th>Pad geometry</th>
<th>$\sigma_x$ (7.5 cm)</th>
<th>$\sigma_x$ (17.5 cm)</th>
<th>$\sigma_x$ (gain = $10^4$)</th>
<th>$\sigma_x$ ($\phi = 10^\circ$)</th>
<th>$n_{cc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular pads 1.27 × 12.5 mm$^2$</td>
<td>75$^\dagger$</td>
<td>83.8 ± 0.8</td>
<td>75$^\dagger$</td>
<td>235$^\dagger$</td>
<td>0$^\dagger$</td>
</tr>
<tr>
<td>Rectangular pads 2 × 6 mm$^2$</td>
<td>172.3 ± 0.6</td>
<td>190 ± 2</td>
<td>158 ± 1</td>
<td>186 ± 2</td>
<td>0.150 ± 0.001</td>
</tr>
<tr>
<td>Staggered rectangular pads 2 × 6 mm$^2$</td>
<td>146</td>
<td>126 ± 1</td>
<td>119 ± 2</td>
<td>189 ± 2</td>
<td>0.211 ± 0.001</td>
</tr>
<tr>
<td>Rhombic pads</td>
<td>179 ± 2</td>
<td>150$^*$</td>
<td>130$^*$</td>
<td>232</td>
<td>0.141 ± 0.004</td>
</tr>
<tr>
<td>Chevron-shaped pads</td>
<td>265</td>
<td>250 ± 12</td>
<td>220$^*$</td>
<td>286 ± 22</td>
<td>0.078 ± 0.001</td>
</tr>
<tr>
<td>Comlike pads</td>
<td>315 ± 16</td>
<td>231 ± 9</td>
<td>260$^*$</td>
<td>437 ± 20</td>
<td>0.039 ± 0.001</td>
</tr>
<tr>
<td>'3+1' pads</td>
<td>178 ± 3</td>
<td>191 ± 3</td>
<td>174 ± 3</td>
<td>445 ± 3</td>
<td>0.074 ± 0.001</td>
</tr>
</tbody>
</table>

Table 9.2: Summary of all readout pad geometries studied in this chapter. Listed are transverse spatial resolutions $\sigma_x(7.5 \text{ cm})$ and $\sigma_x(17.5 \text{ cm})$ for a track inclination $\phi \approx -2.0^\circ$, an effective gas gain of $4 \cdot 10^3$ and a drift distance of 7.5 cm and 17.5 cm, respectively. Also transverse spatial resolutions $\sigma_x(\text{gain} = 10^4)$ and $\sigma_x(\phi = 10^\circ)$ for drift distances of 7.5 cm with a gain = $10^4$ and track inclinations of $10^\circ$ are included. $n_{cc}$ indicates the fraction of clusters without charge sharing (for this, only clusters associated with a track were considered). Values without errors are linear interpolations between measured values, $^*$ indicates extrapolations of measured values and $^\dagger$ indicates extrapolations from data previously taken.
Chapter 10

Summary and Outlook

The International Linear Collider (ILC) is being designed as a new tool to study sub-nuclear physics processes with high energetic electron-positron collisions. Because of the clean signal available in lepton colliders and the high design luminosity, this accelerator project is well-suited for precision measurements in the energy range between 90 GeV and 1 TeV.

Exploiting the high potential of this accelerator imposes challenging demands on the performance of all detector components. For the central tracking detector excellent spatial and momentum resolution, as well as good multi-track separation and a precise measurement of the specific ionization $dE/dx$ (for particle identification) are of utmost importance. A time projection chamber fulfills these requirements very well and offers additional important features, such as low material budget, excellent granularity and high homogeneity. To improve some aspects of detector operations use of micro-pattern-based readouts, such as Gas Electron Multipliers (GEMs) has been suggested. These devices have already demonstrated excellent spatial and time resolution in various detector designs. In combination with a TPC, their intrinsic suppression of the ion feedback, as well as vanishing $E \times B$ effects and the decoupling of the gas amplification stage from the readout geometry make them of major interest.

In this dissertation I have studied a TPC with GEM-based readout with regard to its application in the ILC detector. For this purpose a prototype detector with a length of 25 cm and a diameter of 20 cm was designed and built. The main design criteria were a high degree of flexibility, good homogeneity of electric fields and excellent gas purity. With them in mind a multi-layer field cage was constructed and the material choices were based on existing experience with detector aging properties. For readout, the detector was equipped with a double GEM gas amplification stage and a micro-pattern readout board. Initial tests were performed with radioactive sources and CAMAC-based readout electronics. In them basic detector properties such as drift velocity, diffusion coefficients and gain dependencies on the various parameters, such as GEM voltage, drift distance and temperature, were measured. These tests showed good agreement with expectations, and the measured gas parameters matched well calculations by MAGBOLTZ.

For subsequent tracking studies, the prototype detector was equipped with modified electronics designed for use with the TPC of the STAR experiment. A software package for reconstructing and analyzing particle tracks was developed in JAVA. A number of different reconstruction algorithms were tested with a Monte Carlo simulation, and good performance was demonstrated.

With this setup, the performance of the prototype detector in various environments was
studied. During all studies, a special focus was placed on spatial resolution; additional properties such as the energy resolution due to ionization \(\frac{dE}{dx}\), detection efficiency or momentum resolution, were also determined. In the Karlsruhe laboratory, the limit of large diffusion was explored with the help of data collected in a cosmic ray test setup without a magnetic field. At DESY, Hamburg, the detector was operated in a superconducting solenoid magnet which can create magnetic field strengths of up to 5 T. There, the suggestions in the TESLA Technical Design Report were tested: The detector was operated with Ar-CH\(_4\)-CO\(_2\) (93:5:2) in a 4 T magnetic field. Despite this high field, no degradation of performance was observed. The spatial resolution was greatly improved because of the strong reduction of diffusion, and best values of down to \((46 \pm 1)\) \(\mu m\) were reached. High-rate hadronic test beams at CERN's proton synchrotron were used to collect high statistics of parallel tracks with negligible track inclinations. Several different gas mixtures with varying properties were used and for low diffusions the predicted results could be confirmed: with Ar-CO\(_2\) (70:30) spatial resolutions of \((52.6 \pm 0.9)\) \(\mu m\) were obtained for short drift distances. Furthermore, energy resolutions of \(\frac{\Delta E}{E_{\text{true}}} = 18\%\) and momentum resolutions of \(\frac{\Delta p}{p_T} = 0.13 \frac{1}{\text{GeV/c}}\) were demonstrated for a total track length of 10 cm. Because of the high particle rate considerable charge was accumulated in the drift cylinder, and studies of ion feedback were performed. A best value of below 2\% was obtained.

Finally, the transverse spatial resolution of various readout pad geometries was studied in a 1 T magnetic field with an electron test beam at DESY. The particularity of each pad geometry was discussed with the help of a theoretical model, and the measurements were compared with the results of a Monte Carlo simulation. For rectangular pads complying with requirements of the TESLA-TDR (2 mm \(\times\) 6 mm) the spatial resolution was limited because the pad width was large compared to the cluster size. By using alternative pad geometries such as chevron-shaped or comblike pads, the number of clusters without charge sharing could be reduced. However, with these pad geometries the transverse spatial resolution degraded despite better charge spreading. The reasons for this degradation are given for each pad geometry, and possible improvements to the layout provided. In general, the staggered rectangular pads - where every second row is shifted by half a pitch - have performed best and are recommended for use in a large-scale detector. However, changing the dimensions of the pad geometry seems to be unavoidable if a resolution of 70 \(\mu m\) is to be achieved with short drift distances. Some suggestions for further improvements are given and analyzed in Chapter 9.

In conclusion, the performance of the prototype detector has proven highly reliable and within expectations in various environments, and a GEM-based TPC is proposed as the preferred candidate for a main tracking device of the ILC detector.

On the way to designing a large-scale detector, the first goal has been attained: With the small-scale prototype detector, it was demonstrated that a TPC with GEM-based readout can fulfill the requirements stated in the TESLA-TDR. Only two important aspects remain to be confirmed: The double-track resolution is still being studied in the superconducting magnet at DESY with the help of a new laser system. In addition, the electric field configuration has to be optimized for reliable operation. This has already been done for the COMPASS experiment, but results have to be conciliated with the ion feedback optimization.

In a second phase, starting at the end of this year, a medium-scale detector will be designed and built in collaboration with all ILC groups. With this prototype detector, a number of aspects will be studied that can not be addressed by small detectors. In particular ideas for
integrating large numbers of electronic channels and covering large areas with micro-pattern gas detectors are to be studied. In the end, direct comparison of a GEM-based readout with other types of gas-amplification stages will lead to the final decision as to which readout technology will be implemented in the large-scale detector. These tests are expected to last about two years. The combined results for the small-scale and medium-scale detectors will become part of the large-scale detector Conceptual Design Report, scheduled for 2007.
Appendix A

Curvature of a parabola

The curvature of a parabola is correlated to the parameter $c$ of the quadratic term. To derive the exact equation one has to use the definition of the curvature:

$$\kappa = \frac{\frac{d^2y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}$$

If the parabola is given by $y = a + b \cdot x + c \cdot x^2$ the derivates are given by:

$$\frac{dy}{dx} = b + 2c \cdot x \quad \frac{d^2y}{dx^2} = 2c$$

resulting in a curvature

$$\kappa = \frac{2c}{\left[1 + (b + 2c \cdot x)^2\right]^{3/2}}$$

Since in our application, $b$ and $c$ are small (typical values are $|b| < 0.002$ and $|c| < 0.0005$) and the region of interest is close to the origin, the contribution of $(b+2c \cdot x)^2$ is much smaller than 1 and therefore negligible:

$$\kappa \approx 2c$$

If the parameter $c$ is to be compared to a circle's bending radius $R$, one has to equate the curvatures:

$$\kappa = \frac{1}{R} = \frac{2c}{\left[1 + (b + 2c \cdot x)^2\right]^{3/2}}$$

resulting in

$$R = \left[\frac{1 + (b + 2c \cdot x)^2}{2c}\right]^{3/2} \approx \frac{1}{2c}$$
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The scientific references have been arranged in five categories. These can be distinguished by the last letter of the citation mark:
- b - text books
- p - publications
- t - diploma and doctorate theses
- f - talks
- m - technical descriptions and manuals

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