Study of the response of the novel LAr LEM-TPC detector exposed to cosmic rays and a charged particle beam

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Study of the response of the novel LAr LEM-TPC detector exposed to cosmic rays and a charged particle beam

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Abstract

The double phase Liquid Argon Large Electron Multiplier Time Projection Chamber (LAr LEM-TPC) is a full tracking and calorimetric device with adjustable signal gain. Outperforming other detection techniques, a giant underground LAr LEM-TPC with a fiducial mass up to 100 kilotons is a proposed observatory for neutrino physics and nucleon decay searches.

When a charged particle passes through liquid argon, the deposited energy can be detected in form of produced ionization charge and scintillation light. Due to both facts that LAr is transparent to its own scintillation light and that the transport of ionization electrons is allowed over larger distances, if an electric field is applied, the TPC technology can be used for the detection of ionizing events in LAr with a very fine granularity. Unlike in the case of a single phase LAr TPC, where the charge image is typically readout with different wire planes in the liquid, the double phase readout makes use of charge multiplication in gaseous argon: drift electrons are first extracted into the gaseous phase, where charge avalanches occur under the action of a strong electric field that is produced by the Large Electron Multiplier (LEM). The amplified ionization charge is finally collected on a two dimensional anode readout, which consists of two semi-transparent sets of collection electrodes. The possibility of increasing the signal to noise ratio is very appealing, considering the fact that increasing detector sizes with longer drifts and larger readout capacitances lead to a degradation of the imaging quality of the device. Moreover, the adjustable energy threshold makes the detector sensitive to lower energies. Due to the fact that the charge is shared among the two sets of electrodes of the 2D anode, a charge gain $\gtrapprox 2$ is required in order to reconstruct minimum ionizing particles (mips) efficiently in any direction. A further increased gain of $\gtrapprox 10$ allows the reconstruction of 100 keV Bremsstrahlung photons, which occur in electromagnetic showers.

We have reported on the successful development and operation of a first LAr LEM-TPC prototype with an active area of $10 \times 10$ cm$^2$, proving that a signal to noise ratio of $> 100$ can be achieved for mips. The continuation of the research and development (R&D) program towards a giant LAr TPC and, at the same time, the main goal of this thesis was to construct, operate and study the response of larger prototypes with a readout area of $40 \times 76$ cm$^2$.

In preparation for future beam tests of large double phase LAr LEM-TPCs, we have constructed and operated a 120 L single phase LAr TPC in a low momentum charged particle beam. The beamline instrumentation allowed to tag different particles. We present a detailed
study of the reconstructed pion, kaon and proton events, mainly addressing the stopping power and the electron-ion recombination as a function of the particle type and the $dE/dx$ along the tracks. Additionally, a detailed Monte Carlo simulation, which took into account the non-uniformities of the electric field as well as a realistic noise, could reproduce the recorded data.

Finally, we report on the design, construction and operation of the so far largest double phase LAr LEM-TPC with an active area of $40 \times 76$ cm$^2$. The produced charge readout sandwich – embedding two extraction grids, the LEM, the 2D anode readout as well as the high voltage distribution and the signal routing planes in a single compact unit – was used to record cosmic ray tracks in a volume of 200 L. Reconstructed cosmic mip tracks with $\delta$-rays have been used to address the performance. We report on the purity, the uniformity of the electric field and most importantly we could demonstrate that a gain of $\sim 14$ could be achieved in a first test of a large area device.
Zusammenfassung

Die zweiphasige Argon LEM-TPC ("Large Electron Multiplier-Time Projection Chamber") ist sowohl ein Spurendetektor als auch ein Kalorimeter mit variabler Signalverstärkung. Eine gigantische Argon LEM-TPC mit einer instrumentierten Masse von bis zu 100 Kilotonnen übertrifft die Sensitivität anderer Detektoren und ist deshalb ein Vorschlag für ein zukünftiges Observatorium für Neutrinophysik und für die Suche nach möglichen Nukleonzerfällen.


Aufgrund der Ladungsaufteilung zwischen den zwei Elektrodenanordnungen braucht es eine Ladungsverstärkung von $\gtrsim 2$ um minimal ionisierende Teilchen mit maximaler Effizienz in alle Richtungen nachzuweisen. Eine weitere Erhöhung der Ladungsverstärkung auf $\gtrsim 10$ erlaubt den zusätzlichen Nachweis von 100 keV Bremsstrahlungsphotonen, die in elektromagnetischen Kaskaden produziert werden.

Wir haben bereits über die Entwicklung und den erfolgreichen Betrieb eines ersten flüssig Argon LEM-TPC Prototyps mit einer ausgelesenen Fläche von $10 \times 10 \ cm^2$ und einem Signal-zu-Rausch Verhältnis von $> 100$ für minimal ionisierende Teilchen berichtet. Die Fortsetzung dieses Forschungs- und Entwicklungsprogramms (F&E) für grossflächige Auslesesysteme und
zugleich das Hauptthema dieser Doktorarbeit, war die Studie von größeren Detektoren mit Ausleseflächen von $40 \times 76$ cm$^2$.


Schlussendlich berichten wir über das Design, die Konstruktion und den Betrieb der bis zu diesem Zeitpunkt grössten zweiphasigen LAr LEM-TPC mit einer Auslesefläche von $40 \times 76$ cm$^2$. Das produzierte Ladungsau lesesandwich, das zwei Extraktionsgitter, den LEM, die zweidimensionale Anode, aber auch die Verteilung von Hochspannungs- und Signalleitungen beinhaltet, wurde benutzt, um Ereignisse von kosmischer Strahlung in einem Volumen von 200 L flüssigem Argon auszulesen. Rekonstruierte Spuren minimal ionisierender Teilchen mit $\delta$-rays wurden benutzt um die Leistung des Detektors zu beurteilen. Wir berichten über die gemessene Reinheit des flüssigen Argons, der Homogenität des elektrischen Feldes und der maximal gemessenen Signalverstärkung von $\sim 14$, die erstmals mit grossen Ausleseflächen erreicht werden konnte.
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Chapter 1

Introduction

Next generation long baseline neutrino experiments will be able to determine the neutrino mass hierarchy and to have a chance to directly measure the leptonic CP violating phase $\delta_{CP}$ by studying neutrino flavor oscillations over a very long baseline for a broad energy spectrum. As claimed by the proposed LBNO [1] and LBNE [2] experiments, the required physics sensitivity can be reached with a powerful neutrino beam coupled to a giant liquid argon (LAr) Time Projection Chamber (TPC), placed deep underground at a baseline of 2300 km and 1300 km, respectively. The fact that the LAr TPC detector digitally records the electronic image of ionizing events with mm-size resolution – therefore it is often called electronic Bubble chamber – allows to obtain unique tracking and calorimetric capabilities. Due to the large mass of the detector and the low background with a high sensitivity, the detector will also be able to set new limits on nucleon decay lifetimes and to detect neutrinos from astrophysical sources, such as core-collapse explosions, relic supernovas and Dark Matter annihilations.

In Section 1.1 we first briefly overview the main physics goals. The basic detector principle of a LAr TPC, including the motivation for the double phase technology, which is the major topic of this work, is described in Section 1.2 and finally, in Section 1.3 the organization of the thesis is presented.

1.1 Physics motivation

Future underground observatories for the detection of neutrinos and nucleon decays have very broad physics programs with compelling sensitivities in different channels. In the following, we briefly summarize the physics motivation for future neutrino experiments, including the measurement of elementary neutrino properties, the detection of neutrinos from the atmosphere and astrophysical sources as well as searches for nucleon decays. More details and in particular sensitivity studies of the proposed detectors can be found in [1, 2].

In the present picture of neutrino physics [3], neutrinos appear in three flavor states
Each of these flavor eigenstates is a different superposition (i.e., mixing) of the mass eigenstates $\nu_1$, $\nu_2$ and $\nu_3$. The observed oscillation phenomenon is described by three mixing angles $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$, the CP violating angle $\delta_{CP}$, the two squared-mass differences $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{31}^2 = m_3^2 - m_1^2$ and matter effects. Initially triggered by the first atmospheric results from SuperKamiokande (SK) [4], neutrino oscillations observed by solar, accelerator and reactor neutrino experiments have been used to precisely measure all oscillation parameters except $\delta_{CP}$ and the neutrino mass hierarchy sign($\Delta m_{31}^2$) with an accuracy of 20% or better. Due to the fact that the three mixing angles are now determined and large, CP violation in the leptonic sector becomes directly observable.

Atmospheric neutrinos are produced in the earth’s atmosphere by impinging cosmic rays. The various baselines from a few 10 km to 12000 km, as well as matter effects that occur when the neutrinos travel through the earth, determine the flavor oscillation probabilities. If the detector has a good energy- and angular resolution as well as flavor tagging capabilities for a wide energy range, precision neutrino physics beyond SK can be done. Moreover the matter effects can be used to probe the density structure of the Earth.

There are several known and unknown astrophysical neutrino sources: a core-collapse supernova explosion (e.g. SN1987a) occurs when a massive star with at least 8 times the mass of the sun collapses. In the subsequent explosion 99% of the energy is carried away in different phases by neutrinos. Therefore, a precise measurement of the neutrino flux during the first 10 seconds of a supernova of type II allows to test supernova models. Another astrophysical neutrino source are all supernova explosions since the beginning of the universe. Depending on the flux and the background, such Supernova Relic Neutrinos (SRN) can potentially be detected in the near future. A third, also not yet identified source of neutrinos might be due to the annihilation of Weakly Interacting Massive Particles (WIMPs) in massive objects. The basic idea is that WIMPS scatter off the nuclei in the sun where they eventually get trapped by gravity. Pairs of WIMPS can annihilate into leptons, quarks or bosons, which finally produce neutrinos that can be detected on the earth.

Grand Unification Theories (GUTs) attempt to unify the electroweak and the strong interactions by incorporating their symmetry groups $SU(2) \times U(1)$ and $SU(3)$, respectively, into a larger symmetry group. An experimental hint for the existence of such an internal symmetry of nature is e.g. the fact that the charges of the electron and the proton compensate with an enormous accuracy. Moreover, an extrapolation to a very high energy scale shows that the three coupling constants apparently merge. As a consequence of a new symmetry, GUTs predict that leptons and quarks transform into each other by exchanging a new heavy gauge boson. This finally allows protons and bound neutrons to decay, violating the conservation of the baryon number. Depending on the model, nucleons can decay into different channels with lifetimes that are accessible if the detector masses are sufficiently large. Currently the highest measured lifetimes for various decay modes into charged anti-leptons and mesons range from $3.6 \times 10^{34}$ to $8.2 \times 10^{33}$ years (90% CL), as reported in [5]. Depending on the decay channel,
next generation detectors are expected to increase current lifetimes significantly and hence to exclude or confirm proposed models.

1.2 Next generation LAr TPCs

As seen in the previous section, future neutrino observatories have a physics program that is very similar to the physics of the SK experiment. The giant underground Water Cherenkov (WC) detector searches for rare events, such as neutrino interactions and proton decays. Besides the best limits on diverse partial proton lifetimes, SK is acting as far detector of the T2K long baseline neutrino oscillation experiment, which delivered in 2011 the first hint that the mixing angle $\theta_{13}$ is non zero [6]. As previously mentioned, the next step in terms of long baseline neutrino oscillation physics is to address the CP violating phase $\delta_{CP}$ and the neutrino mass hierarchy by studying neutrino flavor oscillations in dependence of $L/E$.

Since the baseline $L$ for a given observatory is fixed, a neutrino beam with a broad energy spectrum will be used. Therefore, it is required that the detector is capable of reconstructing neutrino events over a broad energy range up to several GeV with a good energy resolution. Moreover, the detector needs to have a larger mass and better sensitivity compared to SK in order to provide sufficient statistics at very long baselines and also to set new standards in searches for astrophysical neutrino sources and nucleon decays.

1.2.1 Neutrino detection with LAr TPCs

The first idea of instrumenting large LAr masses with a TPC goes back to 1977, when C. Rubbia proposed the LAr TPC in an internal CERN report [7] as new detector concept for neutrino physics. Over three decades the ICARUS collaboration has been pioneering this new particle detector, culminating in the construction and operation of the ICARUS T600, the so far largest LAr TPC with a fiducial mass of 478 tons [8]. Besides the research of the ICARUS collaboration, credit has to be given to T. Doke and his collaborators [9] for performing important measurements of fundamental LAr properties, as well as to W. Willis and V. Radeka for pioneering LAr ionization chambers [10].

The basic idea of the detector is to record the ionization electrons produced by charged particles by means of the TPC technology: assuming that the applied electric field is aligned with the z-axis, the three-dimensional position $(x, y, z)$ of the electronic image is obtained by the drift time $t_d$ and the $(x, y)$ information from a two-dimensional electrode array. Due to ideal transport properties in LAr, the electronic image of an event is preserved and can be recorded with a very fine spacial resolution of $O(1 \text{ mm}^3)$. The two-dimensional readout of a single phase LAr TPC typically consists of two or three wire planes in the liquid (no amplification) on which currents are induced by moving drift electrons (ions have a very low mobility and can safely be neglected). In a typical layout, the electrons are first drifted through one or two induction planes, inducing bi-polar signals, and finally collected on the
Figure 1.1: A charged current (CC) quasi elastic (QE) muon neutrino interaction recorded with the ICARUS 50 L LAr TPC that was exposed to the West Area Neutrino Facility (WANF) neutrino beam. Both the highly ionizing stopping proton and the outgoing muon tracks can be seen in both views (collection on the left and induction on the right) [11].

collection plane, inducing mono-polar signals. To demonstrate the response of the LAr TPC, Figures 1.1 and 1.2 show $\nu_\mu$ interactions in the ICARUS 50 L and the ICARUS T600 detectors. The ICARUS 50 L was the first LAr TPC that has been exposed to a neutrino beam [11]. The event in Figure 1.1 shows the collection (left) and induction view (right) of a quasi elastic charged current interaction $n \nu_\mu \rightarrow p \mu$. Both the highly ionizing proton and the horizontally exiting muon can be seen in both views. A higher energy and therefore more complicated neutrino interaction with several final state particles is presented in Figure 1.2. The top image shows the collection view of the full event and at the bottom is a close-up of the vertex for both the collection and the induction II view (the ICARUS T600 has two induction views). Due to the tracking capabilities of the detector it is possible to identify the long horizontal muon (1), a neutral pion (2) that produces two photon showers ($\pi^0 \rightarrow \gamma\gamma$) and an interacting pion (3) with several secondary particles (4-8).

As summarized in [12], the LAr TPC allows to determine the particle type via a study of the topology and the deposited energy along a track for muons/pions, kaons and protons. Electrons are, due to the characteristic shower production, fully identified, which is of importance for electron neutrino appearance studies. For these searches, the neutral current background with the production of neutral pions can be rejected by the factor $10^{-3}$. NC background can be problematic, because of the $\pi^0$ decay into two photons, imitating electron showers. The rejection in LAr-TPCs is based on the conversion
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Figure 1.2: CC muon neutrino interaction in the ICARUS T600 LAr TPC with a muon (1), a neutral (2) and a charged pion (3) in the final state. Top: collection view of the full event. Bottom: close up around of the neutrino vertex for the collection (left) and the induction II view (right) [12]. [See text for more details.]

length of the photon as well as the fact that a converting photon produces in the initial part of the shower an electron-positron pair, rather than a single electron (the $dE/dx$ measurement with the LAr TPC allows to distinguish between single and double electron tracks). Concerning the performance of calorimetry, the reported energy resolution for electromagnetic showers are $\sigma(E)/E = 0.03/\sqrt{E(\text{GeV})} \oplus 0.01$ in the sub-GeV range and $\sigma(E)/E = 0.11/\sqrt{E(\text{MeV})} \oplus 0.02$ for energies below 30 MeV. The resolution studies in the two energy domains were carried out with neutral pion and stopping muon decays, respectively. The energy deposit of higher energy hadronic showers could be reconstructed with a resolution of $\sigma(E)/E = 0.30/\sqrt{E(\text{GeV})}$. However, the authors of [12] point out that the obtained resolution can be improved since the LAr TPC in principle allows to disentangle single tracks, studying their range and energy deposition independently.

1.2.2 The novel LAr LEM-TPC

Designing the charge readout for a giant LAr TPC with a mass between 10 and 100 kilotons, such as in the case of the proposed Giant Liquid Argon Charge Imaging experiment (GLACIER) [13], is very challenging: the necessary minimization of the number of readout channels leads to an increase of the maximum drift length as well as the readout size and thus
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Figure 1.3: Cosmic muon event, crossing the double phase LAr LEM-TPC prototype with an active area of $10 \times 10 \text{ cm}^2$. The event has been recorded with an effective signal gain of 30 w.r.t. to a single phase LAr TPC, leading to a signal to noise ratio > 100. Top: recorded waveforms of every readout strip for the two collection views (left: xView and right: yView). Bottom: event display showing the drift time vs. the strip number [19].

The double phase principle, applied to tracking detectors for neutrino physics has first been demonstrated with a 3 L LEM-TPC prototype with a $10 \times 10 \text{ cm}^2$ 2D anode readout [20, 21, 19]. Figure 1.3 from [19] shows a typical minimum ionizing particle (mip) event: the waveforms of all the readout channels from both views (left: xView and right: yView) are

the detector capacitance. Both the finite free electron lifetime that is given by the amount of electronegative impurities in LAr and diffusion effects reduce the amplitude of the induced signals. Besides a poorer signal quality, large detector capacitances imply an increase of the electronic noise. Due to the fact that charge multiplication could not stably be obtained in LAr [14], the double phase concept was introduced: electrons are drifted to the liquid-vapor interface, from where they are emitted into the vapor phase above the liquid. Once electrons are drifting in gaseous argon, secondary ionization occurs if the applied electric field is sufficiently high. In order to produce the necessary fields, so called gas multipliers, e.g. GEMs [15], THGEMs [16] or LEMs [17] are used. An overview of different detector layouts and results by different groups can be found in a recent review by A. Buzulutskov [18].
shown on the top and the typical event display, showing the drift time versus the readout channel number, is presented at the bottom. The event was recorded with an effective charge gain of about 30. Despite the presence of coherent noise, a signal to noise ratio $\gtrsim 100$ was achieved. Additionally, it can be seen that the induced signals on both views are symmetric and mono-polar. The basic motivation to use a double phase LEM readout with a 2D anode instead of the classical wire readout with one or more induction views and a collection view can be motivated with a few items:

- Scaling current LAr TPC detectors up to 100 kton devices comes along with an increase of noise and a reduction of the signals. The novel double phase readout that provides an adjustable gain, allows to increase the signal to noise ratio in order to obtain the maximal reconstruction efficiency.

- The use of the 2D anode has in terms of reconstruction efficiency the advantage to produce mono-polar and symmetric signals on both views. However, since in this case only half of the charge is collected on each view a gain of at least 2 is required in order to obtain a signal to noise of 10 for mips, which is the typical performance of the collection wire plane in a single phase LAr TPC.

- The energy threshold of the detector depends on the eventually reached amplification. We consider three cases: in the first case of a relatively low gain $\gtrsim 2$, mips are thanks to a S/N-ratio $\gtrsim 10$ and the use of the 2D anode reconstructed in all directions. With a gain $\gtrsim 10$, the energy threshold goes below 100 keV, allowing to reconstruct photons due to Bremsstrahlung, which are produced in electromagnetic showers. This has an impact on the energy resolution for the reconstruction of low energy $\nu_e/\bar{\nu}_e$ interactions (e.g. SN burst neutrinos). The last case of gains $\gtrsim 100$ reduces the energy threshold down to 10 keV. This energy domain is in particular interesting for the detection of nuclear recoils produced by WIMPs.

In continuation of the design, construction, successful operation, leading to the proof of principle of the double phase LAr LEM-TPC with a small scale prototype that is exhaustively discussed in [17], the goal of this thesis is to study the response of larger detectors, using particles from charged particle beams and cosmic rays. Therefore, work was done on the readout electronics as well as on event simulation and reconstruction. Besides performance studies it was very important to prove the scalability of the double phase readout concept to larger area devices ($10 \times 10 \text{ cm}^2 \rightarrow 40 \times 76 \text{ cm}^2$). A more detailed description of the content of the thesis is presented in the following.

1.3 Organization of the thesis

Chapter 2 describes the basic principles of the detector and is therefore the foundation to the performed detector response studies that are presented in later chapters. Due to the
relevance for the thesis we first describe the energy loss of heavy charged particles with moderate velocities. Then, the fundamental ionization and scintillation processes are discussed. In order to understand the response of the double phase LEM-TPC, the charge transport including electron drifts in LAr, the extraction into the vapor phase and the multiplication in the LEM are detailed. Finally, the signal induction on the 2D anode is explained.

In Chapter 3 we describe then the complete readout electronics that has been used for all the operated prototypes being described in this thesis. Besides the description of the data acquisition system and the corresponding software, the main focus of this chapter is on the design and the performance of the low noise charge sensitive preamplifiers.

After having defined the detector and the electronics response, Chapter 4 discusses the Monte Carlo event simulation and reconstruction. The Qscan software was implemented to display, simulate and reconstruct events from the prototypes that are described in the last two chapters.

Chapter 5 describes the test of a 120 L single phase LAr TPC exposed to a low momentum charged particle beam at the J-PARC slow extraction facility. The test was carried out as preparation for further beam tests with the final double phase LAr LEM-TPC. In this chapter we first explain the experimental setup, including the TPC with the LAr cryostat and the beamline instrumentation with the main focus on its particle tagging capability. After describing the run conditions and pointing out some specific event reconstruction algorithms for stopping and decaying particles, the calibration and studies on the stopping power for kaons and protons are presented. Moreover, it is shown that the MC simulation is in good agreement with the data.

The last Chapter 6 describes the design, construction, operation and performance of the so far largest double phase LAr LEM-TPC with a $40 \times 76$ cm$^2$ charge readout. First, the design, that is a direct extrapolation from the $10 \times 10$ cm$^2$ prototype, is introduced. Then, after overviewing the run period of about 4 weeks, it is shown how the detector was calibrated. In the final section, the main results, including studies of the electric field uniformity, the efficiency to reconstruct $\delta$-rays, the evolution of the free electron lifetime that is related to the LAr purity and the performance of the LEM are presented.
Chapter 2

The double phase argon LEM-TPC

When a charged particle passes through liquid argon, the deposited energy can be detected in form of produced ionization charge and scintillation light. Due to the facts that LAr is transparent to its own scintillation light and that the transport of ionization electrons is allowed over larger distances, if an electric field is applied, the TPC technology can be used for the detection of ionizing events. In order to understand the response and performance of the LAr (LEM-) TPC in general and in particular of the prototypes that are described in Chapters 5 and 6, this chapter details the working principle of the detector: after discussing the basic properties of LAr as detector medium in Section 2.1, the energy loss of heavy charged particles is described in Section 2.2. Section 2.3 and Section 2.4 explain then the ionization and excitation processes, respectively. In Section 2.5, particular attention is given to the electron transport, involving drift, emission into the gaseous phase and the multiplication in a Large Electron Multiplier (LEM) device. Finally, the charge readout plane is described in Section 2.6.

2.1 Basic LAr properties

The choice of liquid argon as detector medium has been well motivated in the literature [7]. As already mentioned, LAr allows to drift ionization electrons with a high drift speed (2 mm/µs at 1 kV/cm) and small diffusion (< 1 mm for 1 m) over large distances up to several meters without significant degradation of the imaging quality. Since the scintillation in LAr is detectable and orders of magnitudes faster ($\tau_s \approx 6$ ns and $\tau_t \approx 1.6$ µs) than typical electron drift times (up to several ms), it provides a precise event trigger. Liquid argon is due to its relatively high density of 1.4 g/cm$^3$ a good target that is suitable for rare event searches, such as the detection of neutrino interactions or nucleon decays. It is important to mention that argon is the most abundant rare gas in air (0.93%) and a byproduct of the liquid air industry. Therefore, LAr is relatively cheap and available in large quantities. Since the contamination of electronegative impurities in commercial LAr is about 2 ppm, further purification by more
than 3 orders of magnitude is required (see Section 2.5.1). The only drawback of the use of liquid argon is the necessity of a careful handling, as it is a cryogenic liquid with a boiling point of 87 K at atmospheric pressure. A summary of the most relevant parameters of LAr as detector medium is presented in Table 2.1.

Table 2.1: Physical, chemical and thermodynamical properties of argon [8, 22] and references therein.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number Z, standard atomic weight</td>
<td>18, 39.948 g/mol</td>
</tr>
<tr>
<td>Boiling point at 1 atm</td>
<td>87.3 K</td>
</tr>
<tr>
<td>Triple point</td>
<td>83.81 K, 0.689 bar</td>
</tr>
<tr>
<td>Liquid density at boiling point</td>
<td>1.389 g/cm³</td>
</tr>
<tr>
<td>Mean excitation energy I</td>
<td>188 eV</td>
</tr>
<tr>
<td>Average ionization energy W_{ion} (1 MeV e⁻)</td>
<td>23.6 eV</td>
</tr>
<tr>
<td>Average energy for photon emission W_{ph} (1 MeV e⁻)</td>
<td>24.4 eV</td>
</tr>
<tr>
<td>Average energy loss for mips ⟨dE/dx⟩_{mip}</td>
<td>1.519 MeV cm²/g</td>
</tr>
<tr>
<td>Radiation length X₀</td>
<td>19.55 g/cm²</td>
</tr>
<tr>
<td>Nuclear interaction length X₀</td>
<td>119.7 g/cm²</td>
</tr>
<tr>
<td>Molière radius R_M</td>
<td>12.62 g/cm²</td>
</tr>
<tr>
<td>Critical energy for electrons E_c</td>
<td>32.84 MeV</td>
</tr>
<tr>
<td>Scintillation wavelength</td>
<td>127 nm</td>
</tr>
<tr>
<td>Dielectric constant ϵ_r</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.2 Energy loss by heavy charged particles

When a moderately relativistic charged particle travels through the detector medium it loses its energy via single collisions with the electrons of the atoms. The mean rate of energy loss per unit length −⟨dE/dx⟩ for particles with charge ze in the region 0.1 ≲ βγ ≲ 1000 is described with an accuracy of a few % by the Bethe equation [22]

\[
- \langle \frac{dE}{dx} \rangle = K \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right].
\]

(2.1)

Here the unit of the energy loss is MeV g⁻¹ cm², K = 0.307 MeV g⁻¹ cm², Z/A can be taken from Table 2.1, m_e is the electron mass and T_{max} is the maximum energy that can be transferred from the traversing particle with mass M to a single electron with mass m_e:

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

(2.2)
2.2. ENERGY LOSS BY HEAVY CHARGED PARTICLES

The term \( \delta(\beta\gamma) \) in Equation (2.1) is the density effect correction: due to the transversal enhancement of the electric field of relativistic particles, more distant collisions become more important. However, the increase of energy loss is suppressed by the polarization of the medium. Using Sternheimer’s parametrization [22] the density term \( \delta \) is given by

\[
\delta(\beta\gamma) = \begin{cases} 
0 & \text{if } x < x_0 \\
2(\ln 10)x - \bar{C} + a(x_1 - x) & \text{if } x_0 < x < x_1 \\
2(\ln 10)x - \bar{C} & \text{if } x > x_1
\end{cases}
\] (2.3)

where in the case of LAr \( x = \log_{10} \beta\gamma \), \( x_0 = 0.201 \), \( x_1 = 3 \), \( a = 0.196 \), \( m = 3 \) and \( \bar{C} = 5.217 \).

As discussed below, the transferred energy to a shell electron can have large fluctuations. In case the energy of the emitted electron is high enough to further ionize the detector medium and thus producing a secondary track, it is called \( \delta \)-ray or knock-on electron [22].

The number \( dN \) of knock-on electrons with a kinetic energy between \( T \) and \( T + dT \) that is produced per track segment \( dx \) is given by

\[
\frac{d^2N}{dTdx} = \frac{1}{2} K z^2 Z \frac{1}{A} \frac{\beta^2}{T - T_{\text{max}}}.
\] (2.4)

It can be seen that the number of produced \( \delta \)-electrons decreases for moderate energy transfers \( T < T_{\text{max}} \) like \( T^{-2} \). Since the LAr TPC is a tracking device with high granularity, it allows to measure the deposited energy \( dE/dx \) along the main track as well as the identification of \( \delta \)-rays down to a cut-off between 2 and 4 MeV. Since the standard reconstruction of through-going charged particles, such as cosmic muons, discards resolved \( \delta \)-rays and accounts only for the deposited energy along the main track, the Bethe formula has to be modified. The so called restricted energy loss rate for relativistic ionizing particles imposes an energy transfer restriction \( T < T_{\text{cut}} \):

\[
- \frac{dE}{dx} \bigg|_{T<T_{\text{cut}}} = K z^2 Z \frac{1}{A} \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{cut}}}{I^2} \right) - \frac{\beta^2}{2} \left( 1 + \frac{T_{\text{cut}}}{T_{\text{max}}} \right) - \frac{\delta(\beta\gamma)}{2} \right].
\] (2.5)

It can easily be shown that the original form of the Bethe formulation from Equation (2.1) is approached as \( T_{\text{cut}} \rightarrow T_{\text{max}} \). The effect of such a \( \delta \)-ray energy cut-off for muons through LAr within a typical energy range between 100 MeV/c and 100 GeV/c is shown in Figure 2.1: the three solid lines in green, blue and red show the mean restricted energy loss rate as a function of the kinetic energy for the different values \( T_{\text{cut}} = 2 \) MeV, \( T_{\text{cut}} = 10 \) MeV and \( T_{\text{cut}} = T_{\text{max}} \), respectively. It can be seen that the relativistic rise is further suppressed by the energy cutoff. Since the momentum of single cosmic muons crossing the small detector prototypes is not known, we usually assume that the energy deposit is similar to the mean
 stopping power of minimum ionizing particles with $-\langle dE/dx \rangle = 2.12$ MeV/cm.

So far only the mean energy loss of heavy particles has been described. The energy loss probability distribution, measured with detectors of moderate thickness $\Delta x$, is well described by the Landau-Vavilov distribution \cite{23,24}. As shown in Chapter 6, this is also true for LAr TPCs, since the energy deposit $\Delta$ along charged particle tracks is sampled down to a few millimeters. The Landau-Vavilov distribution $f_L(\Delta) = \xi^{-1} \phi(\lambda)$, with $\lambda := (\Delta - \Delta_{MP})/\xi$ and

$$\phi(\lambda) = \frac{1}{\pi} \int_{0}^{\infty} e^{-u} \ln u - \lambda u \sin \pi u du$$

(2.6)

is described by a width parameter $\xi = (K/2)\langle Z/A \rangle(\Delta x/\beta^2)$ and the most probable value

$$\Delta_{MP} = \xi \left[ \ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right].$$

(2.7)

Unlike in the case of the mean value $\langle dE/dx \rangle \approx \langle \Delta E/\Delta x \rangle$, the most probable value for the energy loss per unit length $\Delta_{MP}/\Delta x$ depends on the detector thickness $\Delta x$. This can be seen in Figure 2.1, which shows $\Delta_{MP}/\Delta x$ for $\Delta x = 0.3$, 1.0 and 3.0 cm as dashed red, blue and green line, respectively.

---

**Figure 2.1:** Energy loss in LAr (unit: MeV/cm) of a muon as a function of the kinetic energy: the solid lines correspond to the mean energy loss for different cut-off energies $T_{cut}$ and are computed with Equation (2.5). The dashed lines show the most probable values $\Delta_{MP}/\Delta x$ for three different detector widths $\Delta x$. 
2.3 Ionization

Besides the excitation of atoms, traversing charged particles produce tracks of ionization charges in form of electron-ion pairs. In case of the LAr TPC a uniform electric field is applied in order to reduce the recombination of those pairs and to drift the negative charge carriers to the readout plane, allowing to record the electronic image of the event. Both the electron-ion pair production and their recombination in dependence of the applied electric field have been studied in detail and are described in this section.

2.3.1 The production of electron ion pairs

The \( W \) value is defined as the average energy that has to be expended to produce an electron-ion pair. The most precise measurement of the value \( W = 23.6^{+0.5}_{-0.3} \) eV was done by Miyajiama et al. [25], using the well defined energy peak produced by 0.976 MeV conversion electrons from \(^{207}\text{Bi}\). In order to make sure that all the produced electrons are detected and there is no recombination with ions (see Section 2.3.2), the electric field was increased until the measured value for the charge saturated. An interesting fact is that the \( W \) value in liquid argon is significantly smaller than in gaseous argon (26.4 eV). A possible explanation for this effect could be the existence of a conduction band with a band gap energy below the ionization potential \( E_{\text{gap}} < I \), like in the case of solid argon.

In order to understand the electron ion pair production theoretically let’s assume an interaction of a 1 MeV electron in LAr. At the end of the global process, when the energies of primary and secondary particles are below the minimal energy to excite further atoms, the deposited energy \( E \) can be written as

\[
E = N_iE_i + N_{ex}E_{ex} + N_i\epsilon,
\]

where \( N_i \) is the number of electron-ion pairs produced at an average energy expenditure of \( E_i \), \( N_{ex} \) is the number of excited atoms produced at an energy expenditure of \( E_{ex} \) and \( N_i\epsilon \) is the total kinetic energy of the \( N_i \) produced free sub-excitation electrons. The \( W \) value can then simply be calculated as \( E/N_i = E_i + N_{ex}/N_iE_{ex} + \epsilon \). As demonstrated in [25], there is good agreement between the experimental and the computed \( W \) values, assuming that the ionization potential \( I = 15.7 \) eV, which is used in the case of gaseous argon, is replaced by the band gap energy \( E_{\text{gap}} = 14.3 \) eV.

2.3.2 Electron ion recombination

Due to the presence of an external electric field that acts against the Coulomb attraction of electrons and ions, a fraction \( R \) of the produced ionization charge does not recombine and is consequently detectable. Besides the dependence on the applied electric field, the recombination factor \( R \) also depends on the local ionization density. This dependence is
explained by the fact that free electrons recombine not only with the parent ions (initial or geminate recombination), but also with other ions produced along the charged particle track (columnar recombination). Although all the developed recombination models are based on the Coulomb attraction, the external electric field and the diffusion of drifting charges, they depend on assumptions on the electric field and the ionization density. The Onsager model [26] that is based on geminate recombination was experimentally disproven [27]. A better description of the measured data is given by the columnar recombination models, such as the work of Jaffé [28] and the box model [29]. However, as concluded in [30] the semi-empirical Birks' approximation, which is typically used to describe the quenching of scintillation light, provides the best fit to LAr TPC data. In order to give an accurate description of the observed quenching at low fields, the Birks' equation \( R_{Birks} = 1/(1 + k(dE/dx)) \) is slightly modified to

\[
R_{Birks} = \frac{A}{1 + k \frac{dE}{dx}}. \tag{2.9}
\]

with \( A = 0.800 \pm 0.003 \) and \( k = 0.0486 \pm 0.0006 \) \((\text{kV/cm})(g/cm^2)/\text{MeV}\) [30]. It shall explicitly be mentioned that this approximation aims to provide a description of the recombination for modest electric fields \( (E < 1 \text{ kV/cm}) \), hence \( R \to 1 \) for \( E \to \infty \) is not a requirement. The given parametrization was obtained from the \( dE/dx \) measurement along stopping cosmic \( \mu^- \) tracks, which have been recorded with the ICARUS 3T LAr TPC. The approximation is valid in the range \( 0.1 < E < 1.0 \text{ kV/cm} \) and \( 1.5 < dE/dx < 30 \text{ MeV/(g/cm}^2) \). As a result, about 30% of the ionization electron-ion pairs produced by a minimum ionizing particle in LAr recombine with a drift field of 0.5 kV/cm \( (R_{mip} \sim 0.7) \).

### 2.4 Scintillation in LAr

It was previously explained that any energy deposit in LAr leads to the production of excited atoms \( \text{Ar}^+ \) as well as ions \( \text{Ar}^+ \). Equivalent to other rare gases, argon forms excited diatomic molecular states (dimers) that de-excite under emission of photons in the Vacuum Ultra Violet (VUV) region [9] via the process:

\[
\text{Ar}_2^* \to 2\text{Ar} + h\nu.
\]

Two independent mechanisms are responsible for the creation of the dimers \( \text{Ar}_2^* \): in case of self trapped excitation luminescence the dimers are simply formed by the collisions of an argon atom with an excited argon atom

\[
\text{Ar}^* + \text{Ar} \to \text{Ar}_2^*.
\]
Recombination luminescence is based on the recombination of an ionized argon dimer $\text{Ar}_2^+$ with an electron. Under emission of heat, the highly excited state $\text{Ar}^{**}$ decays non-radiatively to the excited state $\text{Ar}^*$, which finally leads to the formation of a dimer:

\[
\begin{align*}
\text{Ar}^+ + \text{Ar} & \rightarrow \text{Ar}_2^+ \\
\text{Ar}_2^+ + e & \rightarrow \text{Ar}^{**} + \text{Ar} \\
\text{Ar}^{**} & \rightarrow \text{Ar}^* + \text{heat} \\
\text{Ar}^* + \text{Ar} & \rightarrow \text{Ar}_2^*.
\end{align*}
\]

Due to the fact that both singlet and triplet states of the $\text{Ar}_2^*$ dimer are populated, the relaxation of the excited dimer has two characteristic time constants of $\tau_s \approx 6\ \text{ns}$ and $\tau_l \approx 1.6\ \mu\text{s}$. The emission spectrum is sharply peaked at 128 nm with a width of $\sim 10\ \text{nm}$. Under the assumption that each dimer emits one photons and that the number of produced excited states per electron-ion pair $N_{ex}/N_i \approx 0.21$, the $W$-value in LAr (see Section 2.3.1) can be used to give an estimate of the energy needed to produce one photon:

\[
W_{ph} = \frac{W}{1 + N_{ex}/N_i} \approx 19.5\ \text{eV}.
\] (2.10)

In order to detect the scintillation with standard photomultiplier tube (PMT) technology, the wavelength needs to be shifted to the visible range. As described in [31], a typical light readout for LAr TPCs consists of cryogenic PMTs with a window, which is coated with the wavelength shifter Tetraphenyl-Butadiene (TPB), shifting from 128 nm to $\sim 400\ \text{nm}$. To summarize, LAr has a very high scintillation yield of $5.1 \times 10^4\ \gamma/\text{MeV}$, it is transparent to its own scintillation and the scintillation light is moreover detectable. Due to the fact that the decay time constants are several orders of magnitude faster than typical electron drift times in LAr, the prompt scintillation is perfectly suitable to identify the $T_0$ of the event, making the LAr TPC a self-triggering device.

## 2.5 Electron transport

After discussing the basic interaction of heavy particles in LAr and the subsequent production of scintillation light as well as ionization charges that partially recombine, this section gives a brief description of the complete electron transport, starting with the drift in liquid argon, the emission into the gas phase and the electron multiplication process in the LEM.

### 2.5.1 Drift in liquid argon

Since the drift coordinate in a LAr TPC is directly given by the product of the measured drift time $t_d$ and the drift velocity $v_d$ for free electrons in LAr, prior knowledge of $v_d$ is important. Being mainly dependent on the applied electric field $\mathcal{E}$, the drift speed is also affected by
the LAr temperature. Moreover it was observed that contaminations with certain molecules, such as carbon hydroxides can enhance the drift speed. The most precise measurement of the drift speed as a function of the electric field $E$ and the temperature $T$ was done by W. Walkowiak [32]. After measuring the drift speed $v_d(E, T)$ for different electric fields and temperatures in the ranges from $0.5 \, \text{kV/cm} \leq |E| \leq 12.6 \, \text{kV/cm}$ and $87 \, \text{K} \leq T \leq 94 \, \text{K}$, the polynomial function

$$v_d(E, T) = (P_1(T - T_0) + 1) \left( P_3 E \ln \left( 1 + \frac{P_4}{E} \right) + P_5 E^{P_6} \right) + P_2(T - T_0) \quad (2.11)$$

could be globally fitted to the data. The obtained parametrization is given in Table 2.2.

**Table 2.2:** Resulting parametrization of the global drift velocity fit as a function of the electric field $E$ and the temperature $T$, as defined in Equation (2.11). The values are taken from [32].

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>$-0.01481 \pm 0.00095 , \text{K}^{-1}$</td>
</tr>
<tr>
<td>$P_2$</td>
<td>$-0.0075 \pm 0.0028 , \text{K}^{-1}$</td>
</tr>
<tr>
<td>$P_3$</td>
<td>$0.141 \pm 0.023 , \text{(kV/cm)}^{-1}$</td>
</tr>
<tr>
<td>$P_4$</td>
<td>$12.4 \pm 2.7 , \text{(kV/cm)}$</td>
</tr>
<tr>
<td>$P_5$</td>
<td>$1.627 \pm 0.078 , \text{(kV/cm)}^{-P_6}$</td>
</tr>
<tr>
<td>$P_6$</td>
<td>$0.317 \pm 0.021$</td>
</tr>
</tbody>
</table>

For weaker electric fields in the range $0.1 \, \text{kV/cm} \leq E \leq 0.5 \, \text{kV/cm}$, Equation (2.11) has to be extended with a polynomial fit to drift speed measurements from the ICARUS collaboration [33]. These data, obtained at a fixed LAr temperature of 89 K, are in the transition region around 0.5 kV/cm in very good agreement with the Walkowiak measurements.

Despite the fact that free electron drift is allowed, small contaminants of electronegative impurities can capture electrons. Due to their abundance in air, O$_2$, H$_2$O, N$_2$ and CO$_2$ are the main sources of electronegative impurities in a LAr TPC. The effect of impurities on the number of surviving drift electrons $N_e(t)$ after the drift time $t$ is described by the differential equation

$$\frac{dN_e(t)}{dt} = -\sum_i k_i [N_i] \cdot N_e(t) \quad (2.12)$$

with the simple solution

$$N_e(t) = N_e(0) \cdot e^{-t\sum_i k_i [N_i]} \quad (2.13)$$

where $k_i$ and $[N_i]$ are the attachment rate constants and molar concentrations for the different contaminants, respectively. Detailed measurements of the attachment rate constants for different electric fields and molecular contaminants are described in [34]. However, since the LAr TPC allows to measure the charge attenuation at the operating electric field via the expression

$$Q(t_d) = Q_0 \cdot e^{-t_d/\tau_e} \quad (2.14)$$

the free electron lifetime $\tau_e$ is directly obtained without prior knowledge of the present concen-
2.5. ELECTRON TRANSPORT

2.5.1 Emission from liquid to vapor argon

As sketched in the introduction, the extension of the LAr LEM-TPC with respect to a standard LAr TPC is to transfer the drift electrons from the liquid into the vapor phase, where they are then further multiplied by means of a Townsend avalanche that is triggered in the high field regions generated by the LEM. The double phase detector concept was triggered, after B. A. Dolgoshein and others discovered in 1970 that previously liberated electrons by an ionizing interaction in LAr can be emitted from the surface into the vapor phase with an efficiency close to 100% [36]. More sophisticated measurements of the emission of hot electrons from liquid and solid argon and xenon were carried out by Gushchin and others [37]. Varying the electric field across the interface of liquid and vapor argon, they have observed a threshold effect: as shown in Figure 2.2 the extraction efficiency increases with the applied electric field across the interface. An efficiency close to 100% is reached for fields $E > 2.5$ kV/cm. The second observation was the time dependence of the extraction: a fraction of the electrons is instantaneously emitted within 0.1 $\mu$s, whereas a part stays for $> 0.1$ ms at the interface.

Figure 2.2: Measurement of electron emission efficiency from LAr at 90 K into GAr as a function of the applied electric field in liquid [37].

tration of electronegative contaminants. In order to estimate the overall amount of impurities the term $\sum_i k_i \cdot [N_i]$ is typically replaced with the oxygen equivalent quantity $k \cdot [O_2]_{eq}$. According to [35], the relation between the free electron lifetime $\tau_e$ and the molar concentration of oxygen equivalent contaminants $[O_2]_{eq}$ measured in ppb (parts per billion) is then given by

$$[O_2]_{eq} \text{ [ppb]} \approx \frac{300 \ \mu s}{\tau_e}.$$  \hfill (2.15)

2.5.2 Emission of hot electrons

As sketched in the introduction, the extension of the LAr LEM-TPC with respect to a standard LAr TPC is to transfer the drift electrons from the liquid into the vapor phase, where they are then further multiplied by means of a Townsend avalanche that is triggered in the high field regions generated by the LEM. The double phase detector concept was triggered, after B. A. Dolgoshein and others discovered in 1970 that previously liberated electrons by an ionizing interaction in LAr can be emitted from the surface into the vapor phase with an efficiency close to 100% [36]. More sophisticated measurements of the emission of hot electrons from liquid and solid argon and xenon were carried out by Gushchin and others [37]. Varying the electric field across the interface of liquid and vapor argon, they have observed a threshold effect: as shown in Figure 2.2 the extraction efficiency increases with the applied electric field across the interface. An efficiency close to 100% is reached for fields $E > 2.5$ kV/cm. The second observation was the time dependence of the extraction: a fraction of the electrons is instantaneously emitted within 0.1 $\mu$s, whereas a part stays for $> 0.1$ ms at the interface.
This effect is enhanced at lower temperatures, close to the triple point at 83 K. As shown by Borghesani and others [38], both the temperature and the electric field dependence of the extraction is in good agreement with the electric field enhanced Schottky model. Based on the hypothesis of a negative potential $V_0$ for the conduction band in LAr, the drift electrons in the liquid phase have to surpass a potential energy barrier. Caused by an external electric field, the potential barrier is reduced (Schottky effect), leading to an enhancement of the thermionic current density. As concluded in [38], the measured trapping times as a function of the applied extraction field is in very good agreement with the theoretical values.

In the case of the double phase LAr LEM TPC, two aligned grids or meshes across the liquid-vapor interface allow to apply extraction fields independently from the relatively low drift fields $E_{\text{drift}} \leq 1 \text{ kV/cm}$. At the typically applied extraction fields of $E_{\text{extr.}} \geq 2 \text{ kV/cm}$, close to 100% of the charges that arrive at the liquid-vapor interface are emitted into the gas phase. Obviously a perfect alignment of the two grids is needed (see discussion in Chapter 6).

### 2.5.3 Townsend avalanche in a LEM

The extracted drift electrons in the vapor phase are finally drifted towards a collection plane where they are detected. Due to the applied electric field, electrons are accelerated in between two collisions with argon atoms. If the kinetic energy of an electron exceeds the ionization energy of the neutral argon atoms, secondary ionization occurs. Since liberated secondary electrons can produce further ionization, a cascade known as Townsend avalanche is formed. Introducing the first Townsend coefficient $\alpha$ as the number of produced electron-ion pairs $n$ per electron and unit path length, one can write the infinitesimal number of produced electrons per unit path length as

$$\frac{dn}{dx} = \alpha n.$$  \hspace{1cm} (2.16)

In the general case, where the electric field is not constant and thus $\alpha \equiv \alpha(x)$, the solution is given by

$$n = n_0 \exp\left[\int \alpha(x) dx\right],$$  \hspace{1cm} (2.17)

where the line integral is evaluated along the electric field lines. In case of a constant electric amplification field, the solution simplifies to $n = n_0 e^{\alpha x}$. A very useful empirical parametrization of the first Townsend coefficient, which depends on the electric field and the gas, is defined by

$$\alpha = A \rho e^{-\frac{B \rho}{E}},$$  \hspace{1cm} (2.18)

with the gas density $\rho$, the electric field $E$ and two gas specific constants $A$ and $B$. Under the assumption that the gas amplification device is operated in proportional mode, meaning that the detected charge is proportional to the initial charge, it makes sense to define the gain $G := n/n_0$.

Like in the LAr case, ionization always comes along with excitation, which means that
VUV photons are produced as well as electrons and ions. While the gain is mainly due to the described Townsend mechanism, also secondary effects, caused by the simultaneously produced ions and photons have to be taken into account: although the energy of the produced scintillation light is not sufficient to ionize directly argon atoms, photons can extract electrons from electrodes by photoelectric effect. A similar feedback, though much slower, is due to back drifting ions, which can eject further electrons when they impinge on the collection electrode. Obviously any of the described feedback mechanisms can turn into a continuous current, that may lead to the formation of an electron-ion plasma or a streamer. Due to the fact that such a streamer persists until the amplification device is completely discharged, the detector is paralyzed until the fields are back at the working point. As a consequence of the heat production, heavy discharges may damage the amplification device. In order to decrease the rate of discharges or to increase the maximum achievable stable gain, typical gas detectors work with a gas mixture, including a so-called quench gas that absorbs scintillation light and thus reduces the feedback. However, since the LAr TPC requires extremely low levels of contaminations of less than 1 ppb in order to drift electrons over large distances in LAr, chemical quenchers cannot be used.

Being positioned on top of the LAr TPC in the vapor phase, the Large Electron Multiplier (LEM) is responsible for the multiplication of the ionization charges. Similar to the more established Gaseous Electron Multipliers (GEMs) [15], the basic idea of the LEM is to create electron avalanches in the gap of two holed metal planes, which are spaced by an electrical
insulator. While the GEMs are made of 50 $\mu$m thick Kapton foils that are likely not applicable to cryogenic double phase detectors, the LEM or THGEM (for THick GEM) is a macroscopic, sturdy structure, made with standard PCB techniques. It consists of a 1 mm thick FR4 substrate with thin copper sheets laminated on both sides. The electrode-insulator-electrode sandwich is perforated with 800 $\mu$m spaced cylindric holes with a diameter of 500 $\mu$m. The view from top is shown in the scheme on the left and the picture on the right of Figure 2.3. The scheme shows that the hole diameter of the electrode (red) exceeds the diameter of the hole through the insulator (yellow). As demonstrated in [16] these so-called dielectric rims, typically about 50 $\mu$m thick, significantly reduce the occurrence of discharges and therefore increase the maximum achievable gain. The precise design parameters as well as the production of the LEMs, including the creation of dielectric rims, are detailed in Chapter 6. Besides the dielectric rims, we believe that the discharge probability is further reduced by the hole geometry of the LEM. Since the avalanche is happening inside the 1 mm long and 0.5 mm wide holes that are only surrounded by insulating material and no metal surfaces, secondary effects due to emitted scintillation light are suppressed. This is sometimes called mechanical quenching. A very detailed discussion of the discharge mechanisms, including finite element simulations, can be found in [17].

2.6 Charge collection on a 2D anode readout

The multiplied charges coming from the ionization in LAr are finally collected on a charge readout plane. The 2D anode basically consists of two perpendicular sets of electrode strips (or: views), which are separated by a very thin insulating layer. Due to the semi-transparent design of the device, arriving charges produce a similar response on both sets of strips, finally delivering the two coordinates of the detected charges. Although the concept was adapted from the readout for GEM detectors [39], the design parameters had to be optimized for the application in a LAr TPC. In order to define an optimal electrode geometry, we have considered the response of a point-like energy deposition in LAr. As a consequence of the electric field focussing and defocussing by the extraction grids and the LEM but also the diffusion in gaseous argon, a $\delta$-function like charge distribution in LAr arrives at the anode as a 1 mm extended charge cloud. Given this assumption, the induced signals on both views of the anode have to be mono-polar, fast and with similar amplitudes. Mono-polarity is guaranteed, since all the electrodes act in charge collection mode. As can be shown using the method of W. Shockley and S. Ramo [40, 41], electrons always drift against the weighting field of the corresponding collection electrode, inducing an entirely negative replacement current. Since the current is proportional to the electron drift speed in gas, the expected signal rise times are $< 0.5 \mu$s.

As sketched on top of Figure 2.4, the readout consists of a FR4 substrate with 500 $\mu$m wide copper strips (covered strips), spaced by 600 $\mu$m. On top of them, thin Kapton strips
provide the electrical separation from the second set of 120 µm wide readout strips (exposed strips). The intrinsic readout pitch of 600 µs for each view ensures that even point-like charge deposits in the detector induce signals on both views, guaranteeing a correct reconstruction of the \((x, y)\) coordinates. In order to collect in average equal amounts of charges on both views (exposed and covered strips), the local electric field was simulated with finite element methods\(^1\). It can be seen in the cut through the anode shown on the bottom left plot of Figure 2.4 that the exposed electrodes have a focusing effect on the electric field lines. Simulating different geometries, we have found that roughly half of the field lines end up on each of the two views if the width of the exposed strip equals 120 µm, as shown in the figure. The picture on the bottom right of Figure 2.4 shows the anode of the 3L prototype. It can be seen that the desired readout pitch of 3 mm is obtained by connecting five consecutive strips with the intrinsic pitch of 600 µm together. In a first test with a 3 L prototype, exposed to cosmic muons, we have demonstrated that the anode is working as expected [19].

\(^1\)COMSOL Multiphysics software, http://www.comsol.com
Chapter 3

Readout electronics and data acquisition

To acquire charge and light produced by ionizing events in a double phase argon LEM-TPC, a sophisticated detector readout system is required. Since one of the main goals of this work was to develop a new LAr-TPC charge readout, providing an improved image quality of the events, the readout electronics had to be optimized as well. Besides the development of a low noise charge sensitive preamplifier, we have developed in collaboration with CAEN\(^1\) a new data acquisition system, which was used to readout the three detector prototypes described in this work.

In this chapter, the design and the performance of this new readout electronics and data acquisition system are presented. A detailed knowledge of the electronics response is necessary in order to characterize the detector performance. Moreover, it is an important input to Monte Carlo simulation studies.

After an introduction to the readout electronics and data acquisition in Section 3.1, the design requirements are defined in Section 3.2. Then, in Section 3.3, we describe the readout electronics. Section 3.4 gives a detailed description of the custom made charge sensitive preamplifiers, including design and performance measurements and finally, in Section 3.5, the charge and light data acquisition is described.

### 3.1 General overview

The data acquisition system of a LAr-TPC in general has to be capable of recording for each event both ionization charge and scintillation light simultaneously, without any dead time. It is designed as continuous waveform digitizer for all channels, storing the digitized data in a circular buffer on a first in, first out basis. When a trigger occurs the data in the circular buffers are transferred to the readout computers (see Section 3.5). Obviously

\(^{1}\)CAEN S.p.A., http://www.caen.it
the ionization charge and the prompt scintillation light have very different demands to an acquisition system:

- As motivated in Section 3.2, the ionization charge produced in an event must be acquired with a time sampling of less than 1 µs during the maximum drift time of $O$(ms). Moreover, the system has to be able to simultaneously acquire thousands of readout channels. Due to the small signal charges of $O$(fC) to be readout from large detector capacitances of $O$(100 pF), signals need to be amplified and shaped before the digitization, hence low noise charge sensitive amplifiers have to be used.

- Since the scintillation light is detected with PMTs, single photoelectrons produce measurable signals, thus additional amplification is not needed. The time structure reaches from a few nanoseconds (fast decay component) up to the microsecond range (slow decay component).

A schematic overview of the light and charge acquisition system is shown in Figure 3.1. In this proposed system the data acquisition of charge and light data can be started by a global trigger coming from the prompt scintillation light. Since PMT signals do not need any additional amplification, a commercially available digitizer, such as the 250 MHz CAEN V1720, can be used. In order to acquire the charge data, we developed, in collaboration with CAEN, a new charge acquisition system. The design of the SY2791 is scalable and compact, thus it can be used for detectors up to the ton scale with $O$(1000) readout channels. As shown
in Figure 3.1, charge sensitive preamplifiers, ADCs and acquisition logic are placed on a single board. The purpose of the system is to continuously acquire simultaneously the waveform of each readout channel, maintaining a precise time synchronization between different channels. In addition, we implemented programmable triggers, based on the digitized ionization charge signals. We also chose to have preamplifiers directly pluggable (and thus exchangeable) on the acquisition boards, to be optimized to the needs of specific detectors. In our case we have developed custom made preamplifiers for unipolar charge collection signals, with sensitivities down to few thousands of electrons (see Section 3.4).

### 3.2 Design criteria

The final goal of a LAr TPC detector is to allow the 3D reconstruction of an ionizing particle trajectory in the LAr volume and the determination of the produced ionization charge along its path. Starting from the basic interaction of a charged particle with LAr, ionization charge is produced as well as scintillation light (128 nm), which can be detected with cryogenic PMTs coated with TPB wavelength shifter [31]. The ionization electrons, under the action of electric fields, typically between 500 V/cm and 1000 V/cm, are drifted with a speed between 1.6 mm/µs and 2 mm/µs towards the liquid surface [32]. Finally, in a LEM-TPC, after extraction into the gas phase and amplification inside the LEM holes, the electrons are collected on the electrode strips of a 2D anode, which are readout using low-noise charge preamplifiers. As introduced in Chapter 1 the effective gain is adjustable and a maximum of a few tens can be achieved. The drift coordinate z can be directly obtained by measuring the time difference between the prompt scintillation light used as a trigger of the event and the collection time of the charge.

Given a readout pitch of 3 mm, the mean charge per readout strip, deposited by a minimum ionizing particle parallel to the readout plane and perpendicular to the readout strips, is $\sim 1.5$ fC. For the design of our charge sensitive preamplifier we conservatively assumed no gain due to the LEM amplification. Our requirements were a signal to noise ratio of about 10 for 1 fC input charge and a combined detector and cable capacitance of about 200 pF. With a preamplifier sensitivity of about 10 mV/fC and a 12 bit ADC with a full range of 3.3 V, the RMS noise should be comparable with the least significant bit of the ADC. In order to achieve the low noise requirements, a first charge integrating stage is followed by a signal shaper, consisting of an integrator and a differentiator. In order to obtain a position reconstruction precision of about 1 mm for the z-coordinate, a fast signal rise time of about 0.5 µs combined with a sampling rate of about 2 MHz are required. For the falling time constant, a few microseconds is an acceptable compromise between the signal to noise requirement and the double track resolution.

In addition to the preamplifier requirements, it is very important to reduce the source capacitance of the preamplifiers. While the detector capacitance is given by the readout
Figure 3.2: Overall electronics layout of the setup with the detector readout on the left and the CAEN A2792 readout boards on the right.

strip geometry, the cable capacitance can be reduced by placing the preamplifiers close to the detector. Even with very short signal cables, the capacitance can easily be of the order of a few hundred pF, thus it is very important to have a compact readout and acquisition system which can be placed as close as possible to the detector.

3.3 The readout electronics

In this section we briefly discuss the electronic scheme of the detector and the design of the CAEN SY2791 readout system. The electrical layout of both is sketched in Figure 3.2. The drawing shows on the left the scheme of a single charge readout channel inside the cryostat. The readout channel is then connected via flat cable, which has to be fed through a flange of the cryostat, to the CAEN acquisition board.

As motivated in [17], the anode of the detector had to be supplied with a positive HV (~ 1 kV) in order to increase the transfer fields and thus increase the charge collection efficiency. In addition, the LEM is operated in pure argon gas and it may occur that occasionally electron avalanches inside the LEM holes turn into streamers which short the two LEM electrodes, finally inducing a discharge on the anode. As shown in Figure 3.2, each readout channel is connected via a 500 MΩ resistor to the guard ring of the anode at a HV of about 1 kV. To readout the small currents induced on the readout strips, the signals are decoupled from this bias voltage with 270 pF capacitors. In order to prevent the sensitive readout electronics from occasional overvoltages, a three stage discharge protection is implemented. As a first stage, surge arresters are mounted directly after the decoupling capacitors inside the cryostat. In normal operation they have a very small capacitance of about 1 pF. In case the voltages exceed ~90 V they open to ground, absorbing the main energy involved.

---

2ceramic NP0 10 kV capacitors
3EC 90,EPCOS AG, Munich, Germany
3.3. THE READOUT ELECTRONICS

Figure 3.3: Picture of a CAEN A2792 readout board. The window on the right is a cut through the screen, surrounding 16 plugged preamplifier prints.

...in a discharge. The additional two stages, low leakage double diodes\(^4\), followed by a 10 \(\Omega\) resistor and a JFET, are directly implemented on the preamplifier print which is detailed in Section 3.4.

The readout system consists of several CAEN SY2791 crates, each hosting a linear power supply and 8 CAEN A2792 readout boards, containing 32 channels each. Detector and readout system are interconnected with a shielded 32 signal flat cable. The preamplifiers (see Figure 3.6) are directly plugged on the A2792 boards, as shown in Figure 3.3.

In order to reduce pickup noise from the environment, the analog part, consisting of connectors, cables and the preamplifiers, must be well shielded. The copper shields of the flat signal cables, interconnecting the detector and the A2792 boards, must be connected to the cryostat (connected to the ground of the building) on one side and to the ground of the preamplifier circuit (analog ground) on the other side. To avoid noise directly induced on the preamplifiers, they are fully surrounded by a screen which is connected to the analog ground as well. Both, the screen and the preamplifier prints below, are shown in Figure 3.3. The idea behind the described scheme is that the ground has to be distributed in a star configuration. Any other connection to ground, such as the 230V power line ground, could create ground loops, being typically the dominant source of noise.

A relevant feature of the A2792 design is that the readout boards embody both, the analog and the digital sections, as illustrated on the right part of Figure 3.2. Signals are first amplified, shaped and then digitized by individual 12 bit 2.5 MS/s ADCs with serial readout interface. The 32 digitized signals are further processed by an FPGA, that continually stores

\(^{4}\text{BAV199 from NPX} \)
the data in 1 MB circular memory buffers for each channel independently, it provides the
trigger logic and controls the transfer of the data to a computer via an optical link. The
time synchronization between different boards and different crates is done with a single wire
connection (TT-link) in a daisy-chain configuration. In addition to the clock signal, which is
provided by the master board of a crate, also commands like start, stop and trigger alert are
propagated through the TT-link. The system provides a sophisticated channel by channel
trigger with two programmable thresholds: in case the signal exceeds a threshold value on any
channel, a trigger alert signal is forwarded via the TT-link to all the other channels, causing
them to lower the threshold to a second predefined value. Alternatively, the acquisition can
be triggered globally with an external signal. Such a trigger can for example be generated
by the prompt scintillation light detection.

3.4 The charge sensitive preamplifier

Avalanche electrons, produced in the holes of the LEM, are drifted towards the anode, where
they induce signals on the readout strips of the anode (see Chapter 2). In order to design
an appropriate charge sensitive preamplifier, one can consider the detector as a capacitor to
ground. The induction of currents by moving charge carriers can simply be replaced with a
current source connected to the capacitor. As motivated in Section 3.2 the goal is to measure
$O$(fC) charges injected into a few hundred pF capacitor. In order to convert such small
charges to measurable voltages, a small 1 pF sensing capacitor has to be used. A charge
sensitive amplifier is essentially a low noise amplifier with a capacitive feedback. Assuming
an ideal operational amplifier with infinite input impedance and an open loop gain $g$, the
fraction of charge that goes into the feedback capacitor ($C_f$) is given by

$$\frac{Q_f}{Q_{tot}} = \frac{1}{1 + \frac{C_{det}}{g C_f}}.$$  \hspace{1cm} (3.1)

Equation (3.1) shows, that in order not to depend on the detector capacitance $C_{det}$, the so
called Miller capacity $g \cdot C_f$ has to be much larger than the detector capacitance $C_{det}$. In this
case, the output voltage of the charge sensitive preamplifier is independent of the detector
capacitance and equals $Q_{tot}/C_f$.

A very important goal of such a charge sensitive preamplifier is to have a high signal to
noise ratio. In order to fulfill this criterium, a very low noise amplifier must be used. In
addition, shaping can be used to remove noise with frequencies outside the signal range.

3.4.1 Preamplifier circuit design

We have designed a custom made charge sensitive preamplifier (ETHZ preamplifier v0) which
was used for every detector described in this thesis. However, the existing design was then
3.4. THE CHARGE SENSITIVE PREAMPLIFIER

Figure 3.4: Schematic diagram of the charge sensitive ETHZ preamplifier v1. Version v0 is identical, except that R5=360 Ω and R7=∞.

Further improved (ETHZ preamplifier v1) in terms of open loop gain and a reduction of the undershoot observed after large charge injections. In this section design, simulation, measurements and finally the performance of both versions are discussed. The layout of the final preamplifier version v1, shown in Figure 3.4, consists of an overvoltage protection at the input, an amplifier with an RC feedback and a shaper, followed by a non-inverting linear amplifier. The layout of the custom made charge integrator is based on a preamplifier design for a high capacitance silicon detector (see Boiano et al., [42]). The amplifier has four low noise JFETs\(^5\) connected in parallel at the input. This has two advantages: first, at a given current, the overall transconductance of four JFETs is larger than in the case of a single JFET. In the described configuration a transconductance of about 80 mA/V is achieved. Second, since the input noise voltages of the four JFETs are incoherent and hence add in quadrature, the total resulting signal to noise ratio is increased, compared to a single JFET. The JFETs are then followed by a bipolar transistor Q6 in a folded-cascode configuration, keeping the drain voltage at a nearly constant level. This avoids a feedback to the input via the capacitance between gate and drain of the JFETs. The next stage, consisting of a npn-type bipolar transistor Q7 and the two resistors R5 and R6, converts the current back to a voltage. In the initial preamplifier scheme v0, R5 equals 360 Ω. In order to enhance the open loop gain, we enhanced the current flowing to the base of Q7 by increasing R5 up to 2.2 kΩ. After an additional emitter follower circuit, the voltage is fed back via RC to the input of the amplifier. We have chosen a 1 pF capacitor C\(_0\) which is discharged through a resistor R\(_0\) with a time constant \(\tau_F = 470 \mu s\).

\(^5\)NPX BF862 (former Philips)
CHAPTER 3. READOUT ELECTRONICS AND DATA ACQUISITION

After the charge integrator, the signals need to be shaped in order to match the bandwidth of the ADCs and to improve the signal to noise ratio. The shaping of the signal is done with a simple RC-CR configuration. In the case of preamplifier v1 we have included a mechanism to suppress the undershoot caused by the feedback RC: the resistor R7 is chosen such, that the product with the parallel capacitance C12 approaches $\tau_F$. If they are well matched, the zero pole caused by the feedback time constant is suppressed. Finally, after the shaping, the required voltage sensitivity of about 10 mV/fC is reached by means of an operational amplifier\(^6\) in a non-inverting configuration with gain 30.

Initial studies of the complete circuit were done with SPICE simulations\(^7\) and then first prototypes were realized and tested. Figure 3.5 shows on the left the simulated output voltage of a fast (0.1 µs) 1 fC charge injection and on the right a noise simulation for the complete circuit with a 200 pF source capacitance, including noise contributions from all the components. The maximum amplitude of a 1 fC signal (see left plot) equals 15.4 mV, thus the simulated preamplifier sensitivity equals 15.4 mV/fC. From the obtained spectral noise density, shown in the right plot of Figure 3.5, an output noise voltage of 1.28 mV RMS was computed. To conclude, the simulated signal to noise ratio for a 1 fC signal with 200 pF source capacitance equals 12.

For a further understanding of the preamplifier response we have derived an analytical function to approximate the output pulse shapes of infinitesimally short charge injections. In order to do this, we first approximated the transfer functions of the charge integrator with the RC feedback, the RC-CR shaper with zero pole cancellation and the additional operational amplifier in a non-inverting configuration. The product of the three transfer functions is

\(^6\)AD8656 operational amplifier, Analog devices, http://www.analog.com

\(^7\)SPICE 3f5, www.macspice.com
3.4. THE CHARGE SENSITIVE PREAMPLIFIER

The charge sensitive preamplifier is a critical component in the initial stages of signal processing for detectors. Its design is crucial for the accurate measurement of charge, which is fundamental in many scientific applications. The transfer function of such a preamplifier is given in Equation (3.2).

\[
H(\omega) \propto \frac{\omega}{i\omega \tau_f + 1} \cdot \frac{i\omega \tau_{corr} + 1}{(i\omega \tau_D + 1)(i\omega \tau_I + 1)} \cdot \frac{1}{i\omega \tau_{amp} + 1}. \tag{3.2}
\]

The first term, representing the transfer function of the charge integrator with a feedback constant \(\tau_f = 470 \mu s\), is followed by the RC-CR transfer function. For the integrator and differentiator time constants, which depend on all components of the RC-CR shaper, one gets \(\tau_I = 0.48 \mu s\) and \(\tau_D = 2.75 \mu s\). The nominator \(i\omega \tau_{corr} + 1\) is responsible for the zero pole suppression since it cancels the denominator \(i\omega \tau_f + 1\), in case \(\tau_{corr} \approx \tau_f\). The last term, coming from the additional amplifier, has the form of a low pass filter with time constant \(\tau_{amp}\) which turned out to be approximately equal to \(\tau_I\). A fast signal in the frequency domain is then equal to the product of the \(\delta\)-Function \((\delta \propto \omega^{-1}\) in the Fourier space\) and the simplified transfer function

\[
H(\omega) \propto \frac{\omega}{(i\omega \tau_D + 1)(i\omega \tau_I + 1)^2}. \tag{3.3}
\]

Finally, after applying the inverse Fourier transform, the time dependence of a fast input charge injection is obtained:

\[
V_{\text{response}}(t) = I \cdot \frac{\tau_D \cdot e^{t/\tau_D} - (\tau_D + t \frac{\tau_D - \tau_I}{\tau_I}) \cdot e^{t/\tau_I}}{(\tau_D - \tau_I)^2}. \tag{3.4}
\]

Equation (3.4) is already properly normalized, where \(I\) is the time integral of the output voltage \(I = \int dt V(t)\). It has the unit \([I] = \text{Vs}\). So far we have always assumed that signals are very fast but in practice it often happens that a signal can last for few \(\mu s\). A good approximation, which can be used to fit signals coming from tracks along the drift direction, is the convolution of the fast preamplifier response given in Equation (3.4) with a constant current with a duration \(\Delta t\). This is further discussed in the following section.

The last step of the designing phase was the realization of the circuit on a printed circuit board (PCB), as shown in Figure 3.6. The photograph illustrates two preamplifier circuits realized with discrete components on a four layer PCB. The top side with all the components is shown on the left. The bottom side with the analog ground and the power lines is shown on the right.
3.4.2 Performance measurements

After a successful test of first prototypes we have produced 1000 preamplifiers of version v0. As previously mentioned, the final version v1 has, by design, a higher open loop gain and a zero pole suppression mechanism is implemented. In order to do first tests of both versions and to compare them, we have upgraded 32 preamplifiers from version v0 to v1. The performance tests presented in this section were always done with 32 preamplifiers (v0 or v1) plugged on a CAEN A2792 acquisition board. The signals were then acquired and offline analyzed with the Qscan software described in Chapter 4. This means that the results presented here were measured in realistic run condition, as would be in case a detector were connected. Instead of a detector, the charges were injected by means of a small test box, schematically shown in Figure 3.7. The screening box can be directly plugged to the CAEN A2792 board. It allows then to simultaneously feed the 32 preamplifiers with a well defined test charge. As shown in the scheme, a voltage step $\Delta V$, generated with an arbitrary waveform generator, is injected to the test box. The input is connected to 32 voltage dividers, providing a 50 $\Omega$ termination and an attenuation of 1/100 for each channel. The charge pulse enters then via a (10 $\pm$ 0.25) pF test capacitor to the preamplifier input. The optional capacitance C to ground allows to simulate different detector and cable capacitances. The circuit is realized inside a screened box which is well connected to the analog ground of the preamplifiers. The trapezoidal voltage pulse shown in Figure 3.7 allows to input a constant current with different durations $\Delta t$ to each preamplifier. The voltage step $\Delta V$ was measured with a Keithley 2000
3.4. THE CHARGE SENSITIVE PREAMPLIFIER

Multimeter\(^8\) with a precision of about 0.5 mV.

The signals shown in the left plot in Figure 3.8 were obtained by pulsing the test capacitor with a constant voltage step $\Delta V$, but with different duration $\Delta t$, thus keeping the injected charge constant. The fitted preamplifier response, convoluted with a constant current over a time $\Delta t$, is superimposed to the digitized waveforms. The resulting time constants, summarized in Table 3.1 at the end of this section, agree well with the computed values $\tau_I = 0.48 \mu s$ and $\tau_D = 2.75 \mu s$ (see Section 3.4). In addition, the plot shows that the signal amplitude decreases with increasing time width of the signal. The charge and thus signal integral $I$ remain constant. The right plot in Figure 3.8 visualizes the effect of the zero pole subtraction implemented in version v1. To visualize the undershoot, a very long lasting current pulse with a time width of $\Delta t = 100 \mu s$ was injected to the input. The curve in red, showing the response of version v0, is decreasing due to the time constant of the RC feedback. As a consequence, for $t > 150 \mu s$, the output voltage falls below the initial pedestal, i.e. the baseline undershoots. It can be seen that in case of preamplifier version v1 the output voltage, shown in black, remains constant and the baseline is not distorted.

Besides the signal shape we have also investigated the voltage sensitivity and the preamplifier linearity. To do so, very short current pulses with a with of $\Delta t = 0.1 \mu s$ for different input charges from 10 fC to 160 fC were injected. For each configuration 1000 events were acquired and analyzed offline with the Qscan software (see Chapter 4). After subtracting the baseline, which was computed by averaging the initial samples, the fast preamplifier response function from Equation (3.4) was fitted to each waveform in order to determine the maximum amplitude. The left plot of Figure 3.9 shows the maximum amplitude, averaged over

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\(^8\)Keithley Instruments Inc., www.keithley.com
1000 events, as a function of the input charge on the left for preamplifier v0 in red and v1 in black. The data is well described by a first order polynomial. Under the condition that the function has to go through the origin, the only free parameter is the sensitivity, defined as the slope. The plot on the right shows the corresponding residual value for each data point. The dominant source of errors is the calibration of the input pulse.

**Figure 3.9:** Left: signal amplitude for different test charges between 10 fC and 160 fC ($\Delta t = 0.1 \mu s$) without a source capacitance. The slope of the linear fit corresponds to the preamplifier sensitivity. Right: residual values (data-fit).
preamplifier version v0 was used for all the measurements presented in this thesis. Since in this case the measured charge depends on the capacitance of the detector and the cable, the proper correction, given in Equation (3.1), has to be applied.

Finally, a summary of the performance measurements of 32 different preamplifiers is given in Table 3.1. The given errors equal the observed spread (RMS) among the different preamplifiers coming from the production tolerances of the components.

Table 3.1: Average parameters measured with 32 different preamplifiers of version v0 and v1. The given error of each value equals the observed spread (RMS value).

<table>
<thead>
<tr>
<th>preamplifier type</th>
<th>v0</th>
<th>v1</th>
</tr>
</thead>
<tbody>
<tr>
<td>shaping time $\tau_D$</td>
<td>$2.7 \pm 0.1 \mu s$</td>
<td>$2.8 \pm 0.1 \mu s$</td>
</tr>
<tr>
<td>shaping time $\tau_I$</td>
<td>$0.46 \pm 0.02 \mu s$</td>
<td>$0.46 \pm 0.02 \mu s$</td>
</tr>
<tr>
<td>sensitivity (no source capacitance)</td>
<td>$10.7 \pm 0.3 \text{mV/fC}$</td>
<td>$13.8 \pm 0.4 \text{mV/fC}$</td>
</tr>
<tr>
<td>open loop gain</td>
<td>$440 \pm 20$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>linearity (0-180 fC)</td>
<td>$\pm 1%$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>ENC at $C_{source} \approx 200 \text{pF}$</td>
<td>$780 \pm 30 \text{e}^-$ RMS</td>
<td>$770 \pm 30 \text{e}^-$ RMS</td>
</tr>
<tr>
<td>S/N (1 fC, $C_{source} \approx 200 \text{pF}$)</td>
<td>$8.0 \pm 0.3$</td>
<td>$8.1 \pm 0.3$</td>
</tr>
</tbody>
</table>

3.5 Charge and light data acquisition

After amplification, shaping and digitization, the acquired data need to be written to a storage system. We have implemented a general data acquisition software framework, which allows to write charge and light data, coming from different CAEN readout boards, to a data storage system. Figure 3.11 shows the layout of our data acquisition system. The CAEN A2818 (PCI)
or A3818 (PCIE) card, installed on a computer, can connect up to eight CAEN acquisition boards to the readout computer. Due to the use of an optical link the readout computers do not need to be positioned next to the detector. Another advantage is, that CAEN provides several different digitizers with the same standard, thus it was possible to design a general acquisition software which can be used for different readout systems. The layout is designed to allow a high acquisition rate even for large detectors. In case several acquisition boards are acquiring simultaneously, they can be connected to separate computers, working in parallel. As shown in Figure 3.11 the DAQ software, running on different computers, which are reading the data from various acquisition boards, is controlled by the user interface. Finally, the data are written into binary files on a common storage system.

The data acquisition software is subdivided into three programs: the manager is a user interface that controls the producer and the collector via the TCP/IP protocol. The task of the producer software is to send the configuration to the readout boards and to start and stop the acquisition. During a run it loops over all the acquisition boards, connected to the A2818/A3818 card, and writes the data into the flash memory of the computer. The so called shared memory is organized as circular memory buffer. In parallel the collector reads from the shared memory and writes the events into a file on an external storage disk.

Due to the parallelization of the process, a single event can be distributed to different binary files, thus we decided to generate a global index file. The offline viewer and analysis software Qscan (see Chapter 4) finally reads from this index the locations of all the channels and merges them to the full event.
Chapter 4

Event reconstruction and simulation

LAr TPCs record the complete electronic image of an ionizing event. Due to the optimal electron transport properties of the LAr medium (high electron mobility and small diffusion), large volumes can be instrumented with a spacial resolution down to the millimeter-scale. As explained in Chapter 2, ionization electrons drift over the distance $z = v \cdot t_{\text{drift}}$ towards the charge readout, where they induce signals on different sets of readout electrodes, hereafter referred to as views. Independently on the implemented technology (single or double phase), the readout provides at each sampling time two or more projections of the $(x, y)$ image of the event. In addition to the event topology, the size of the recorded signals give a direct measure of the produced ionization charge along each track, which in addition allows to do calorimetry.

Generally speaking, the event reconstruction is the task in between the data taking and the final physics analysis: it aims at the extraction of the relevant information, such as the types and the momenta of the detected particles. In the simplest case, where particles stop inside the detector, the stopping power along the produced track allows to identify the particle [43, 11]. In case the particle does not stop inside the fiducial volume, a good estimation of the momentum is obtained by measuring the multiple scattering of the traversing particle [44]. Besides the reconstruction of tracks, which is in the focus of this work, it is also possible to reconstruct showers: due to ambiguities coming from the high ionization density, it is neither possible nor needed to reconstruct each single track in three dimensions. The appropriate strategy is to reconstruct global event parameters like the total charge, the shower direction, the charge profile and the vertex as well as the initial part of the shower in order to discriminate $e^-/e^+$ from $\gamma/\pi^0$ showers [45].

Since several different detectors have been tested in the context of this work, it was important to use a single simulation and reconstruction software framework. The Qscan software package was originally implemented for the ICARUS experiment and was then adapted to
other detectors. Equivalent to the LArSoft\(^1\) package that is being used by ArgoNeuT [46] and the future experiments \(\mu\)BooNE\(^2\) and LBNE\(^3\), Qscan allows to simulate, reconstruct and visualize events for various detectors.

In Section 4.1 we first give a brief introduction to Qscan. Then the event simulation, including the complete digitization, is explained in Section 4.2. Since a general procedure to reconstruct arbitrary events with sufficient efficiency does not exist, Section 4.3 mainly describes fundamental reconstruction tools. In order to give an example for a complete three-dimensional track reconstruction, we specifically discuss the reconstruction of straight tracks with \(\delta\)-ray attachments, as they were recorded with the 200 L double phase LAr LEM-TPC detector under cosmic ray exposure (see Chapter 6). Examples for other complex event topologies like \(K^+\) decays are described in Chapter 5.

### 4.1 The Qscan software

Qscan is a multipurpose software framework to simulate, reconstruct and visualize events from LAr TPC detectors. The software was initially implemented and used by the ICARUS collaboration to produce results from the reconstruction of stopping muons in the ICARUS T600 detector [47, 48] and to measure the free electron lifetime [33] as well as the electron recombination in LAr [30]. In a second phase, the software has been used to reconstruct quasi-elastic neutrino events in the 50 L ICARUS TPC that was exposed to the CERN West Area Neutrino Facility WANF [11, 49]. This experiment led to the first measurement of the cross section for quasi-elastic neutrino interactions in LAr. Due to the development of several new double phase LAr TPC prototypes, including the 3 L [19], the 120 L (see Chapter 5 and references therein) and the 200 L detector (see Chapter 6 and references therein), a set of new algorithms and a new ROOT\(^4\) [50] based graphical user interface have been implemented. The Qscan software framework comes along with three main functionalities:

- It provides a set of tools to store and reconstruct data from different LAr TPC detectors.
- Being interfaced to MC generators (currently GEANT3 and GEANT4) to propagate particles through any detector geometry, it allows to produce fully digitized MC events that can be post-processed similar to real data from a detector.
- A graphical user interface allows to scan raw data online. Moreover, Qscan has a 3D event display to visualize MC truth events as well as the reconstructed event for both real and MC generated data inside the detector geometry.

\(^1\)https://cdcvs.fnal.gov/redmine/projects/larsoftsvn
\(^2\)http://www-microboone.fnal.gov
\(^3\)Long Baseline Neutrino experiment, http://lbne.fnal.gov
\(^4\)http://root.cern.ch
4.2 Event simulation

Despite the fact that LAr TPCs ideally provide a high resolution image of any ionizing event, MC simulations are an important tool to validate reconstruction algorithms and to study the detector performance. Moreover, a working MC simulation of a detector allows to study different effects like non-uniform drift fields, different noise levels, impurities, etc. This is in particular important for physics performance studies of giant LAr detectors for future long baseline neutrino oscillation experiments [1]. All the MC simulation code and in particular the digitization procedures that are presented hereafter, have been validated with both testbeam and cosmic ray data, as reported in Chapters 5 and 6.

This section is subdivided into two parts: Section 4.2.1 first describes the propagation of particles through the geometry of the experimental setup. The final generation of signal waveforms by conversion of the deposited energies to signals is described in Section 4.2.2.
Figure 4.2: Three dimensional event display of Qscan, showing the ROOT geometry of the 200 L detector and $\mu^-$, tracked through the geometry by GEANT4. The figure shows an overview of the geometry (1), the extracted fiducial volume together with its local coordinate system (2) and a closeup of the $\mu^-$ track with several $\delta$-electrons (3).

4.2.1 Particle propagation in detector geometries

Qscan uses the Virtual Monte Carlo package VMC\(^5\) (see [52] and references therein) to interface with GEANT4\(^6\), a toolkit for the passage of particles through matter [53]. Since the VMC interface loads the MC libraries at runtime, Qscan is completely independent from the MC simulation code, allowing for instance to use GEANT3 instead of GEANT4. The second advantage is that the ROOT geometry package TGeo can be used to define the geometry of the experimental setup. This feature is important since the same geometry definition can be used to track particles in GEANT3 and GEANT4. Moreover, TGeo is also the preferred geometry format to display the detector together with its reconstructed event objects in the three dimensional, ROOT based, event display. An example of a MC simulated muon event in the 200 L detector (see Chapter 6) is displayed in Figure 4.2. (1) shows the overview of the geometry, consisting of the cylindric cryostat and the cuboidal detector. The isolated TPC volume with the MC truth tracks are shown in (2) and (3) shows a closeup of the $\mu^-$ track in blue with some $\delta$-ray electrons in green.

GEANT4 provides a large set of different physics processes. Depending on the required

\(^5\)http://root.cern.ch/drupal/content/vmc
\(^6\)http://geant4.cern.ch
level of details and physics models, it is possible to enable or disable different electromagnetic and hadronic processes via physics lists. Typically we are using the QGSP BERT physics list that uses the Quark Gluon String model for simulating high energy hadronic interactions. To provide accuracy at energies below 10 GeV, the list is extended with the Bertini cascade model [54]. Concerning the tracking configuration, depending on the readout pitch of the simulated detector, one usually has to define an upper limit for the stepping size in order not to see any discrete effects. Typically the maximum step length is fixed to about 10% of the readout pitch. Unlike in the case of typical Geant4 simulations, particle propagation cut-offs are defined as kinetic energies, rather than ranges. In order to properly implement charge quenching effects, one wants to track secondary electrons, being produced along ionizing tracks, down to very low energies. As discussed elsewhere [30], an electron tracking cut-off of 10 keV is a good compromise between microscopic accuracy and computing speed.

4.2.2 Waveform generation

The goal of the waveform generation is to convert the MC truth information to LAr TPC data, as it would be recorded in a real experiment. Based on the energy deposit $\Delta E_{\text{dep}}$ and the length $\Delta x$, given at each step of every tracked particle in the MC simulation, the readout signals are produced as explained in the following:

1. The deposited energy $\Delta E_{\text{dep}}$ is converted into the amount of produced ionization charge $\Delta Q_0 = e (\Delta E_{\text{dep}}/W_{\text{ion}})$ with the elementary charge $e$ and the ionization work $W_{\text{ion}} = 23.6$ eV, as given in Table 2.1. Due to electron ion recombination, which depends on the ionization density as well as on the applied electric field, a fraction of the produced electrons recombine. Since Birks’ approximation gives the best fit to the reconstructed data [30], it is reasonable to implement quenching at MC level by multiplying the charge with $R_{\text{Birks}}(\Delta E_{\text{dep}}/\Delta x, E)$. In Section 5.7.2 it is shown that the two parameters of the model $A_{MC} = 0.8$ and $k_{MC} = 0.05$ (kV/cm) $\left(\frac{\text{MeV}}{\text{g/cm}^2}\right)$ provide good agreement with the data.

2. The remaining charge is then transported up to the collection plane. After choosing the coordinate system such that the anode plane is parallel to the $(x, y)$ plane, the charge, being initially produced at $(x, y, z)$, is drifted along the electric field lines until it leaves the fiducial volume or it reaches the readout plane. In case of a constant field $(0, 0, E)$, the final charge position equals $(x' = x, y' = y, z' = z_{\text{anode}})$ and the corresponding drift time is $t_{\text{drift}} = (z_{\text{anode}} - z)/v_{\text{drift}}(E)$. Otherwise, in case of an inhomogeneous electric field, an external look-up table, providing the final coordinates as well as the drift time for any point within the fiducial volume, is used. After including also charge attenuation effects due to an imposed finite free electron lifetime $\tau_{MC}$, the charge is
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given by

\[ \Delta Q = \frac{\Delta E_{\text{dep}}}{W_{\text{ion}}} \cdot e \cdot \frac{A_{\text{MC}}}{1 + k_{\text{MC}}/\mathcal{E} \cdot \Delta E_{\text{dep}}/\Delta x} \cdot e^{-t_{\text{drift}}/\tau_{\text{MC}}}. \]  

(4.1)

Diffusion effects – since negligible over drift distances up to several meters – have so far not been considered in the MC simulation.

3. Depending on the arrival position \((x' = x, y' = y, z' = z_{\text{anode}})\) of the drift charge \(\Delta Q\), currents are induced on the corresponding readout electrodes of the different views. These currents are then further processed by a charge sensitive preamplifier. The finally recorded signal \(V_{\text{out}}(t)\) is a convolution of the induced current \(I(t)\) and the response of the preamplifier \(h(t)\):

\[ V_{\text{out}}(t) = I \ast h(t) = \int_{t_0}^{t} I(t') \cdot h(t - t') dt'. \]  

(4.2)

Obviously both the preamplifier response and the induced currents depend on the readout type and the used electronics. The simplest case is the LEM readout with a 2D anode, both being described in Chapter 2: due to the fast electron drift in gas and the short induction gap between LEM and 2D anode, the induced current \(I(t)\) approaches a \(\delta\)-function and the signal is directly given by the fast response of the preamplifier.

In the case of the 120 L single phase LAr TPC, being described in Chapter 5, the induction gap is large and the electrons move much slower, which leads to very slow signals. Instead of the fast preamplifier response, Gaussian waveforms gave a better description of the observed signals. The third case is the signal induction on wire plane readouts: besides the collection plane that records unipolar signals, usually one or more induction planes with bipolar induction currents are used. A detailed description of the used response is given in [48].

After finishing this procedure for each step, noise of a given amplitude can be added on top of the signal waveforms. Besides the generation of white noise, it is also possible to use a specific frequency spectrum that has e.g. been extracted from real data. The final step is the digitization of the generated waveforms. Figure 4.3 shows on top the generated waveforms of the MC \(\mu^-\) from Figure 4.2 and on the bottom the corresponding event display.

4.3 Event Reconstruction

After recording data from a LAr TPC or LAr LEM-TPC detector, the data is processed by several reconstruction algorithms. Starting from the local, channel-by-channel signal discrimination, the final goal is to reconstruct physical objects like tracks, showers and event vertices. As there can be large differences among detectors and event types, Qscan provides various methods to reconstruct events. In this section we mainly overview the algorithms that were
4.3. EVENT RECONSTRUCTION

Figure 4.3: Example of a fully MC generated $\mu^-$ event in the 200 L detector. The MC steps of the same event are shown in Figure 4.2. The waveforms for the two views (left and right) have been generated, using the known ETHZ preamplifier response, given by Equation (3.4), and Gaussian noise with a RMS value of 3 ADC counts. Top: waveforms $V_{out}(t)$ of all the readout channels are shown with different colors. Bottom: typical event display, showing the drift time versus the strip number. The greyscale is proportional to the signal amplitude.

commonly used to analyse straight tracks seen in the 120 L LAr TPC from Chapter 5 and the 200 L double phase LAr LEM-TPC from Chapter 6. More specific procedures, as e.g. the decay vertex finding, needed to analyze beam events in the case of the 120 L LAr TPC, are described in the corresponding section.

Despite the fact that detectors can be different from each other, any reconstruction basically goes through the following steps:

1. The raw waveforms are processed: this involves noise reduction as well as the subtraction of the baseline (see Section 4.3.1).

2. Hits, defined as signals that are discriminated from the noise, are identified and reconstructed (see Section 4.3.2).

3. Clusters are formed by grouping close hits together (see Section 4.3.3).

4. Tracks are identified for each view (see Section 4.3.4).
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5. Finally, the three dimensional track reconstruction is done by matching coincident tracks from different views (see Section 4.3.5).

In the following sections, the items 1. to 5. are explained and demonstrated with examples from different detectors, using real data as well as MC generated data. As already mentioned, other possible objects like event vertices and showers are discarded in the description given here.

4.3.1 Signal processing

The data acquisition system records the amplified, shaped and digitized output voltage $V_{out}(t)$ for each electrode with a discrete time sampling. In order to extract physical signals efficiently and accurately, a minimal signal to noise ratio of about 10 is required. Although the electronics is in principle designed to fulfill this requirement, experimental data can be distorted by external noise sources and an imperfect shielding of the detector and the signal lines. In order to suppress noise without affecting the signal component too much, hence improving the signal to noise ratio, two different algorithms are used: the Fast Fourier Transform (FFT) filter, and the coherent noise subtraction algorithm.

The FFT filter makes use of the fact that induced noise, being produced by external sources like switching power supplies, computers, etc, is often dominated by a few specific frequencies. After transforming the waveforms $V_{out}(t)$ to the frequency space, the Fourier transformed waveforms $\hat{V}_{out}(\omega)$ are processed in order to reduce the noise components. The final, noise suppressed waveforms $\hat{V}_{out,filt}(t)$ are then obtained by applying an inverse FFT to $\hat{V}_{out,filt}(\omega)$. Due to the fact that the waveforms are discrete and the total number of samples is an integer power of two, the computing time is minimized by using the FFT implementation.
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A concrete example of the FFT algorithm is presented in Figures 4.4 and 4.5: the K$^+$ beam event, recorded with the 120 L LAr TPC (see Chapter 5), demonstrates the effect of the filter. The high frequency noise, seen in the raw event on the left of Figure 4.4, is efficiently removed in the filtered event on the right. In this case the best way to improve the signal to noise ratio was to suppress frequencies above 80 kHz. The left plot of Figure 4.5 shows the amplitude for each channel and frequency. In this plot it can be seen that a continuous background is superimposed with discrete frequency lines. While the continuous component is due to the signals and the intrinsic preamplifier noise, the sharp lines correspond to discrete noise frequencies that are induced by external sources. Due to the fact that most of the noise frequencies are above 100 kHz, a smooth cut-off, implemented with a Fermi potential of width 3 kHz, efficiently suppresses the noise, while keeping the signals, besides a reduction of the bandwidth, unaffected. Unlike a smooth cut-off, a sharp cut in the frequency spectrum introduces artefacts in the time domain. Figure 4.5 shows the effect on a single waveform before (dashed black line) and after filtering (solid red line).

The coherent noise filter is implemented to remove identical noise patterns that are seen on larger sets of readout channels. Unlike in the case of the FFT filter, which directly suppresses the frequencies of single channels and thus reducing the signal bandwidth, the coherent noise filter ideally subtracts only the noise while keeping the signals unchanged. During the operation of detectors it is often observed that all the readout channels, being hosted on the same readout board, have exactly the same noise in terms of frequency, phase and amplitude. An example of such an event, recorded with the 200 L double phase LAr LEM-TPC (see Chapter 6), is given in Figure 4.6. Since the noise of every channel that belongs to the same acquisition board is almost identical, it can be considered as disturbance of the
baseline. This time-dependent baseline first has to be computed for each single time sample, including all the channels on a physical readout board. Finally, similar to the subtraction of a constant pedestal, the baseline is subtracted from each sample. The difficulty of the calculation of the time-varying baseline is to select only the channels without a signal. Since signals are amplitude fluctuations with respect to the baseline, a good way to compute the baseline value for a given time sample is to use only the $N$ channels with the smallest voltage values. Depending on the needs, $N$ can be chosen between 1 and 32: in the case of $N = 1$, the baseline is defined at each time sample $t$ by the minimum Voltage $V_{\text{out}}(t)$ of all the 32 readout channels per acquisition board. On the other hand, in the case of $N = 32$, signals are discarded and all the channels are used to calculate the baseline. The choice $N \approx 16$ allows that signals are not affected, even in case they are present in half of the readout channels. Although this algorithm ideally has no effect on the signals, there are two limitations: tracks that are perfectly horizontal, like in the case of beam particles, cannot be distinguished from noise and are therefore subtracted. As a consequence, the coherent noise filter could e.g. not be used to improve the data from the beam test experiment (see Chapter 5). Figure 4.7 shows a single readout channel, taken from the same event that is presented in Figure 4.6. The noise fluctuations that are present in the unfiltered event (dashed black line) are significantly suppressed after applying the filter (solid red line). It can also be seen that the algorithm does not affect the signals, despite its significant effect on the noise.

After suppressing the noise, the (constant) pedestal of each waveform has to be computed and subtracted from each sample. In order to avoid any bias due to physical signals, only pre-trigger samples are used to compute the mean value. Another possibility is to use the most probable value since it does not depend on tails, which are due to signals.

Figure 4.6: Cosmic ray event from the 200 L LAr LEM-TPC that is described in Chapter 6. Left: raw event that shows a characteristic coherent noise pattern. Right: final event, after applying the coherent noise filter.
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4.3.2 Hit identification and reconstruction

The smallest sub-unit of the reconstructed event is the hit. Physically, a hit corresponds to a track segment below a readout strip. The charge of this segment is then drifted towards the strip, where it induces a signal. The information that is attributed to a hit is the deposited charge $\Delta Q$, the three-dimensional length $\Delta x$ of the track segment, the drift time, which is equivalent to the drift coordinate $z$, the readout view and the electrode strip number.

More technically speaking, hits have to be extracted from the signal waveforms by means of a standard threshold discrimination. Due to changing noise conditions, the threshold is defined in relation to the measured RMS noise value $\sigma$, which is measured for each event and readout strip, using the pre-trigger samples. A typical value for the threshold is $V_{\text{thresh}} = 3\sigma$.

In the general case there can be several close, or overlapping tracks per event, producing a superposition of several signals/hits on a single readout strip. As discussed in Chapter 3 the shaping time constants of the preamplifiers are chosen such, that double tracks being separated by a few $\mu$s can be resolved. In order to explain the working principle of the hit-finding algorithm, Figure 4.8 shows an example of two subsequent hits in a single readout channel. The waveform was recorded with the $10 \times 10$ cm$^2$ prototype and shows a single waveform from a cosmic ray track with an emitted knock on electron.

Moving from the left to the right, a hit candidate $hit_i$ is initiated in case the signal waveform (blue) exceeds a pre-defined threshold $V_{\text{thresh},1}$ (dashed line) and terminated, when
it either goes again below the same threshold or in case a new, subsequent hit candidate hit_{i+1} is triggered. The imposed trigger condition for subsequent hits is that the minimum voltage between the two hit candidates goes below the value \( \min(V_{\text{max},i}, V_{\text{max},i+1}) - V_{\text{thresh},2} \). \( V_{\text{thresh},2} \) (dotted line) is a secondary pre-defined threshold, responsible for the re-triggering of subsequent hits. Besides increasing the threshold, the number of fake hits due to noise can be reduced by imposing a minimum time over threshold \( t_{\text{fin}} - t_{\text{ini}} > \Delta T \). Initial and final drift times (\( t_{\text{ini}} \) and \( t_{\text{fin}} \)), as well as the hit amplitudes \( V_{\text{max}} \) are defined as indicated in Figure 4.8. In order to calculate the integral of each hit, the waveform is integrated from the initial to the final time sample. To reduce any bias, coming from the height of the threshold, the window, in which the integral is computed, can be extended in case there is no other hit attached.

The main parameters of the hits that need to be reconstructed are the hit time and the hit integral: together with the location of the corresponding readout channel, the hit time directly provides the information of the hit location in the considered view (projection), whereas the hit integral is related to the produced ionization charge and therefore provides the calorimetric information. In order to improve the accuracy of these two evaluated parameters, the signal waveforms can be fitted with a pre-defined function. Two examples of waveform fits are shown in Figure 4.9: the left plot shows the waveforms of a double hit from a cosmic ray event, recorded with the 3L double phase LAr LEM-TPC, whereas the right plot is a beam event, recorded with the 120 L single phase LAr TPC. As the LEM-TPC has a faster
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signal induction, the used fitting function is a convolution of a constant current

\[ I(t) := I_0 \cdot \theta(t - t_0) \cdot \theta(t_0 + \Delta t - t)/\Delta t \]  (4.3)

of duration \( \Delta t \) and integral \( I_0 \) and the normalized response of the preamplifier \( h(t) \) from Equation (3.4):

\[ V(t) = I * h(t) = \int_{t_0}^{\infty} I(t')h(t - t')dt'. \]  (4.4)

The function is analytically computed and since the response with the integration and differential time constants is already known, the only three fitting parameters are the integral \( I_0 \), the time \( t_0 \) and the signal width \( \Delta t \). In the case of the slowly induced signals from the 120 L TPC, a Gaussian with integral \( I_0 \), mean time \( t_0 \) and the width \( \sigma \) fits well to the data. As shown on the left plot of Figure 4.9, the fitter automatically adds additional functions in case of subsequent hits.

4.3.3 Cluster finding

After a successful hit-finding, adjacent hits of different readout channels are grouped together. Since physical objects like tracks or showers are extended, the hit clustering is the first step towards a more global reconstruction of the event. The second advantage of clustering is that single hits, which are often due to arbitrary noise, can easily be removed by applying a cut on the cluster size. Besides the improvement of the purity, also the hit finding efficiency can be increased, since it is possible to search for more hits around the borders of clusters with a lowered threshold.

The clustering algorithm, used to analyze the data that is presented in this work, is based

Figure 4.9: Waveforms (dashed black line) from two different detectors, superimposed with the fitted functions (solid red line). Left: the cosmic ray event from the 3 L double phase LAr LEM-TPC is, due to the fast response, fitted with a function that is based on the preamplifier response function. Right: beam event from the 120 L single phase LAr TPC, due to its slow signals fitted with a Gaussian.
on the search of directly adjacent hits: starting from a single hit, the nearest neighbor (NN) algorithm iteratively expands the cluster by adding close hits. Looping over all hits in the cluster, it searches for unclustered hits within a pre-defined time and readout channel range around the current hit. Once a new hit is found, it is added to the cluster. The algorithm continues looping, until no more hits are found in the vicinity of the cluster. Like in the case of the hit-finding algorithm, the parameters of the algorithm depend on the detector as well as on the event type. Since the NN clustering is optimized to reconstruct connected objects, like tracks, it was perfectly suitable for the reconstruction of the 3 L, 120 L and 200 L TPC data. A more detailed description of the implementation of the NN clustering algorithm is presented in [48].

### 4.3.4 Track reconstruction

Starting from general clusters that can assume any topology, the tracking algorithm, which was used for the reconstruction of the 200 L LAr LEM-TPC data, aims at the identification of straight tracks. The straight track assumption is justified, since the multiple scattering is negligible for the maximally 60 cm long cosmic ray tracks. The method being described here can be easily generalized to the case of bent tracks. In this section we first describe a Hough-transform based tracking algorithm for the identification of the main, through-going cosmic rays and then a second algorithm to reconstruct knock-on electrons, appearing as secondary tracks.

The basic idea of the track identification, being described here, is to convert the problem of finding aligned hits into the trivial problem of finding a maximum. The Hough Transform (HT) [56] transforms hits with coordinates \((x, z)\), where \(x\) is given by the readout strip number and \(z\) by the drift time, into the parameter space of straight lines, also called Hough space. The basic procedure of the HT is to evaluate the parameters of all the straight lines, going through each hit in the \((x, z)\) plane. If a subset of points are aligned, there is a single line going through all of them and its parameter pair (angle \(\theta\) and offset \(r(\theta)\)) will appear as a maximum in the two dimensional, binned Hough space. Looping over each cluster, the HT based track identification algorithm goes through the following steps:

1. Each hit coordinate pair \((x, z)\) is transformed via HT to the parameter space. As shown in Figure 4.10, straight lines are parametrized by an angle \(\theta\) and the minimal distance to the origin of the coordinate system \(r\). The transformation to the Hough space is then given by

\[
r(\theta) = x \cdot \cos \theta + z \cdot \sin \theta.
\]  

(4.5)

After defining the binning of the Hough space with the variables \((r, \theta)\), the algorithm computes \(r(\theta)\) for each angle \(\theta\) and adds the point with weight 1 to the two dimensional histogram. This step is then repeated for each hit of the cluster.
2. The bin with the largest number of entries \((r_{\text{max}}, \theta_{\text{max}})\) gives then directly the parameters of the straight line that crosses most of the hits. In order to avoid fake tracks, a minimum threshold of typically \(N_{\text{min}} = 4\) hits is required. The two dimensional track is then defined by all the hits that are close to the found straight line.

3. In case it is needed to find other straight tracks, step number 2. can be repeated for the residual hits that belong to the cluster but not to a track, until the number of hits in a track candidate goes below the user-defined threshold \(N_{\text{min}}\). Finally, the main track is again fitted with a straight line.

4. After finding the main track, all residual hits that belong to the cluster but not to the track, are tagged as \(\delta\)-ray hit candidates. Then, the algorithm groups and tags close \(\delta\)-ray hit candidates as \(\delta\)-rays. Since single hits can easily be produced by noise, \(\delta\)-rays require at least two consecutive hits. Figure 4.11 shows the MC generated \(\mu^-\) with a \(\delta\)-ray. The event display for both views 0 (left) and 1 (right) show in red the hits that belong to the main track and in green the hits that belong to \(\delta\)-rays.
4.3.5 Three dimensional track reconstruction

The most important information, obtained from the hits, is the charge $\Delta Q$ that is related to the signal integral and the three dimensional track length $\Delta x$. The information of the two dimensional tracks from complementary views have to be combined in order to reconstruct $\Delta x$ as well as the complete three dimensional image of the event. Due to intrinsic ambiguities coming from the projection technique, this task is in general very difficult. However, the fact that only straight tracks are considered, simplifies the three dimensional reconstruction a lot, since the problem is reduced to the simple matching of two-dimensional tracks: comparing the drift times of the first hits of tracks, an algorithm loops over all two dimensional track candidates until a unique pair of tracks from both views is found. In case of the event shown in Figure 4.11, the algorithm links the two red tracks, since the first hits from view 0 and 1 both have a similar drift time $t_{\text{drift}} \approx 0$ (the $\mu$ is entering from the top of the chamber through the anode). To reconstruct the three dimensional hit coordinates $(x_0, y_0, z_0)$ and $(x_1, y_1, z_1)$ for the views 0 and 1, the straight line approximation is used: first, the tracks of both views (view 0 and view 1) are fitted with the linear equation

$$ z_0 = a_0 \cdot x_0 + b_0 \quad \text{and} \quad z_1 = a_1 \cdot y_1 + b_1 \quad (4.6) $$

with the slopes $a_{0,1}$, the offsets $b_{0,1}$ and the common drift coordinate $z = t_{\text{drift}} \cdot v_{\text{drift}}$. Equation (4.6) makes use of the fact that the strips of the two readout views are perpendicular and the coordinate system is chosen such that view 0 (1) directly provides the $x_0$ ($y_1$) coordinate. Besides the naturally provided readout coordinate $z_0$ ($z_1$) and $x_0$ ($y_1$) for view 0 (view 1), using Equation (4.6), the missing coordinates $y_0$ ($x_1$) are given by

$$ y_0 = \frac{z_0 - b_1}{a_1} \quad \text{and} \quad x_1 = \frac{z_1 - b_0}{a_0}. \quad (4.7) $$

Besides the absolute position of the hits of view 0 and view 1, the three dimensional track length

$$ \Delta r_{0,1} = \sqrt{\Delta x_{0,1}^2 + \Delta y_{0,1}^2 + \Delta z_{0,1}^2} \quad (4.8) $$

has to be computed for both views independently. In the case of view 0 (view 1), $\Delta x_0$ ($\Delta y_1$) is equal to the readout pitch that is typically for both views equal to 3 mm. Further, $\Delta y_0$ and $\Delta x_1$ can be computed according to Equation (4.7) and $\Delta z_{0,1}$ is given by Equation (4.6). As final result for the three dimensional track pitch we get

$$ \Delta r_0 = \Delta x_0 \sqrt{1 + \frac{a_0^2}{a_1^2} + \frac{a_0^2}{a_1^2}} \quad \text{and} \quad \Delta r_1 = \Delta y_1 \sqrt{1 + \frac{a_1^2}{a_0^2} + \frac{a_1^2}{a_0^2}}. \quad (4.9) $$

Finally, using the proper charge calibration of the readout and $\Delta r_{0,1}$ from Equation (4.9), the expression $\Delta Q_{0,1}/\Delta r_{0,1}$ can be computed for both views. For reasons of simplicity, hereafter the same expression is often renamed to $\Delta Q/\Delta x_{0,1}$ or $dQ/dx_{0,1}$. 
4.3. EVENT RECONSTRUCTION

The hits that have been tagged as δ-ray hits (see Section 4.3.4), do not necessarily form straight tracks. Therefore, the best way to reconstruct those hits is to find for each δ-ray hit of view 0 a coincident δ-ray hit of view 1. This means, that the resulting coordinates of each hit on view 0 are defined as \((x_0, y_1, z_0)\), where \(y_1\) is taken from a hit on view 1 with a similar drift time, i.e. \(|t_{\text{drift,1}} - t_{\text{drift,0}}| < \epsilon\). In case no coincident δ-ray hit is found on the other view, it is matched with the main track, since in such a case it can be assumed that δ-ray and \(\mu^-\) are superimposed. An example for the final, three dimensionally reconstructed MC generated event from Figures 4.2 and 4.11 is shown in Figure 4.12: the coordinates of all reconstructed hits of view 0 are shown in the 3D display, superimposed with the MC tracks. It can be seen that the through-going \(\mu^-\), as well as the δ-ray in green match with the reconstructed hits in red.
Chapter 5

A 120 L LAr TPC exposed to a charged particle beam

In this chapter we describe the performance of a single phase 120 L LAr TPC, exposed to a tagged low momentum charged particle beam at the J-PARC slow extraction facility. This experiment, being part of a common R&D program towards a proposal to search for CP violation in the leptonic sector and for proton decay using a 100 kt scale GLACIER type detector [57], was carried out by the T32 collaboration (ETHZ, KEK, Iwate University and Waseda University). Although LAr TPCs have been built and operated since more than 30 years, the performance was mainly studied with cosmic rays, neutrino beams or MC simulations. However, we believe that exposures to charged particle beams, providing particles of known mass, momentum and direction, are essential to assess the performance of this detector in a quantitative way and thus providing the necessary inputs to physics sensitivity studies. This includes for instance the charged particle identification performance, $e/\pi^0$ separation and the detector response to electromagnetic and hadronic showers in the 0.1-20 GeV energy domain.

The K1.1BR beamline of the J-PARC slow extraction facility provides a composition of $K^+, \pi^+, e^+$ and protons with a momentum of 0.8 GeV/c. Due to delays in the production of the double phase charge readout that is finally to be tested, the beamtest was done with a single phase LAr TPC. The produced chamber has been equipped with a single readout plane that, moreover, had a coarser readout pitch compared to state-of-the-art LAr TPCs or the novel LAr LEM-TPCs. Despite the fact that the readout geometry did not allow to do any three-dimensional reconstruction, the collected sample of stopping protons and kaons could be used to develop new reconstruction algorithms, to give a preliminary measurement of the charge quenching and to validate the existing MC simulation code that is described in Chapter 4.

In Section 5.1 we first give an overview of the experimental setup, including the beamline instrumentation and the 120 L LAr TPC. After a characterization of the particle beam...
in Section 5.2, Section 5.3 summarizes the collected data samples. The event reconstruction of different particle interactions is then elaborated in Section 5.4. Further, Section 5.5 describes the detector calibration including the charge attenuation during the drift and the response of the readout electronics. Based on these calibration measurements the Monte Carlo simulation was implemented and tuned as described in Section 5.6. Finally, the recombination factor measurement as well as a data-MC comparison are presented in Section 5.7.

5.1 The experimental setup

The beamtest took place in the Hadron Experimental Hall at J-PARC [58]. This newly built and commissioned facility provides beams of secondary particles which are produced by irradiation of a production target T1 with 30 GeV protons that are slowly extracted from the Main Ring. The K1.1BR beamline, in which we had tested the 120 L LAr detector, has been designed and constructed for the TREK experiment [59]. Since this experiment aims at $K^+$ decay studies, the beamline was optimized to obtain a high purity $K^+$ beam with a momentum of $\sim 0.8$ GeV/c. The required momentum and mass separation was achieved by bending magnets and an electro-static separator (ESS), respectively. In the optimal configuration with 3.6 kW of protons on target, a $K/\pi$ ratio of $\sim 1$ with a $K^+$ rate of $\sim 1$ kHz was achieved. However, since for this work particle tagging is more important than the purity of the beam, Section 5.1.1 describes only the beamline instrumentation. More details on the beamline optics and its performance can be found elsewhere [60]. The 120 L LAr TPC together with the cryostat are separately presented in Section 5.1.2.

5.1.1 The beamline instrumentation

Although the charged particle beam was enriched with kaons, it contained fractions of pions, protons and positrons. In order to characterize the beam and to be able to trigger efficiently on specific particle types, the beamline was equipped with different detector elements. Figure 5.1 shows a picture of the last five meters of the K1.1BR beamline. As indicated, the beam enters from the left, going first through a Fitch-type differential Cherenkov counter (1) and the first time of flight detector TOF1 (2). The second counter TOF2 (4) is located about 3.5 m downstream TOF1. In addition to the Cherenkov and the TOF detectors, a threshold gas Cherenkov counter (3) that allows to separate positrons from pions is installed in between the two TOF counters. For certain run configurations a momentum degrader (5) is placed downstream the TOF2 counter. Since the 120 L LAr TPC (6) acts as a stopping calorimeter it is placed at the end of the beamline. To trigger only on particles that enter the LAr TPC, a $5 \times 5$ cm$^2$ scintillation counter, hereafter called beam defining counter (BDC), is placed in front of the beam window of the LAr cryostat. Besides the mentioned beamline instrumentation a beam hodoscope and two multi-wire proportional counters (MWPC) were
5.1. THE EXPERIMENTAL SETUP

Figure 5.1: Picture of the beamline instrumentation: the secondary particles enter from the left, passing a Cherenkov counter (1) that discriminates K$^+$ from $\pi^+$, the first time of flight (TOF) counter (2), a gas Cherenkov counter to identify positrons (3), the second TOF counters (4), an optional momentum degrader (5) and finally the LAr cryostat (6).

used to measure the beam profile. It can be seen in Figure 5.1 that the whole experimental area was enclosed with concrete blocks. Due to the high radiation level during beam-time, access was prohibited and consequently all the beamline instrumentation, including the LAr detector, had to be operated remotely. In the following paragraphs we give a brief description of the three main elements of the beamline instrumentation.

The *Fitch-type differential Cherenkov counter* is dedicated to separate kaons from pions with a momentum from 740 to 800 MeV/c. The detector, shown on the left of Figure 5.2, makes use of the fact that kaons and pions propagating through matter with the same momentum, emit Cherenkov light with different characteristic polar angles. As originally proposed by V. Fitch [61], the refractive index of the radiator material can be chosen such, that the larger angle Cherenkov radiation from pions is totally reflected, whereas the radiation produced by kaons penetrates the radiator. The Cherenkov counter that is used in the K1.1BR beamline has a 40 mm thick acrylic radiator with a critical angle for total reflection of 42.2°. The Cherenkov light produced by crossing kaons is emitted with an angle of 38°. A parabolic mirror, located behind the radiator, focuses the penetrating Cherenkov light into the Winston cones of an outer ring of 14 PMTs (K-ring). In the case of pions, which emit Cherenkov light with an angle of 47°, the light is totally reflected. Due to a second mirror that is installed around the radiator the light is detected by a second, inner ring of PMTs (\(\pi\)-ring). The velocity of protons with the same momentum is below the Cherenkov light production threshold and thus they do not produce signals in both PMT rings. It is reported in [59] that
with the described configuration a $K^+$ trigger efficiency $> 99\%$ with $< 1\%$ misidentified $\pi^+$ can be reached within a momentum range of $740 - 800$ MeV/c.

The *Time Of Flight (TOF) detector* consists of two scintillation counters that are spaced with a distance of $\sim 3.5$ m. The achieved timing resolution of $\sim 200$ ps allows an excellent separation between $K^+$, $\pi^+$ and protons (see also Section 5.2).

The *lead-glass counter* is placed in front of the 120 L LAr TPC, as shown in the right picture of Figure 5.2. These detectors were originally used in the electromagnetic calorimeter for the TOPAZ electron-positron collision experiment at TRISTAN, KEK [62]. The lead-glass block has a density of 5.2 g/cm$^3$ and the thickness in the middle, where the beam goes through, equals 12.4 cm. Although it is in fact equipped with a PMT in order to detect the produced Cherenkov light, the main purpose for our experiment was to reduce the beam momentum.

### 5.1.2 The 120 L LAr TPC

The LAr TPC - since acting as stopping calorimeter - is located downstream the beamline instrumentation, which was introduced in Section 5.1.1. The experiment was carried out in an access restricted area, hence the chamber, the data acquisition and the cryogenic system had to be operated and monitored remotely. The *cryostat* that hosts the LAr TPC was borrowed from the MEG experiment [63]. Due to the fact that it was constructed to test a liquid xenon (LXe) calorimeter prototype exposed to $e/\pi^0$ beams, it was perfectly suitable for the experiment being described here. As shown in both pictures of Figure 5.3, the cryostat consists of two cylindric vessels, aligned with respect to the beam axis. The evacuable volume
5.1. THE EXPERIMENTAL SETUP

in between the two cylinders is filled with super-insulating material, consisting of several layers of reflective foils with spacers in between to avoid thermal conductivity. Consequently, the heat load during normal operation, when the inner vessel is filled with 87 K LAr, is reduced to about 30 W. The front flange has in the center, where the beam enters, a 0.13 mm thick beam window. There are two access flanges on the top: one is devoted to feed through signal, high voltage and different sensor cables for the slow control and monitoring of the system; the second houses the cold head of the cryocooler as well as the LAr and LN$_2$ inlets.

The cryogenic system has to keep the contained LAr safely at a constant temperature and pressure. In addition, it also has to provide the necessary LAr purity to drift electrons over the full drift distance of 40 cm without significant losses. Commercial LAr typically has impurity concentrations of $O(1 \text{ ppm})$. In order to reach the necessary purity to drift, the initial molar concentration of oxygen contaminants has to be reduced by three orders of magnitude (see Section 2.5.1). To achieve this purity the LAr is filled through a custom made purification cartridge that contains a stack of reduced CuO powder and 4A molecular sieve pellets for the removal of O$_2$ and H$_2$O, respectively. Since a similar cartridge was used for several tests, a detailed description can be found in [17]. In order to remove impurities coming from leaks or outgassing materials throughout the run, a gas phase purification system is implemented: a metal bellow pump pushes the LAr boil-off gas through a commercial purification filter\footnote{SAES type MC3000, \url{http://www.saesgetters.com}}, providing an output purity of $< 0.1 \text{ ppb}$ of O$_2$ and H$_2$O. The clean gas is then re-injected into the inner vessel, where it gets re-condensed on the cold surfaces. The cooling of the cryostat is done by two independent systems: a Gifford-McMahon (GM) cryocooler with a
cooling power of 160 W and a $\sim 4$ m long LN$_2$ coil which can provide a maximum cooling power of $> 600$ W at 87 K. Both the cold head of the GM cryocooler and the LN$_2$ coil, are mounted on the same flange on top of the cryostat. A Keyence$^2$ programmable logic control (PLC) is used to control the cooling power by keeping temperature and pressure in the inner vessel constant. In addition, safety is guaranteed by three independent systems: an electro valve that opens in case of a power loss, an overpressure valve that opens at 1.5 barg (bar gauge) and a rupture disk, opening at 2 barg.

The LAr TPC detector consists of a drift volume with the charge readout on top and a light detection system on the bottom. As already mentioned in the introduction to this chapter, the TPC is only equipped with a single readout plane, which is immersed in LAr. As

\[ \text{http://www.keyence.co.jp} \]
shown in the scheme on top of Figure 5.4, the ionization charges produced by beam particles are drifted perpendicularly towards the charge readout on top, where they induce signals on the readout strips that are vertically aligned with respect to the beam. To summarize the basic scheme, the two spatial coordinates that are recorded with this detector are the drift time and the longitudinal position (strip number) with respect to the beam axis.

Going more into the details of the chamber, the cuboid drift volume that is shown in the left picture of Figure 5.4, is on the sides delimited by four PCB plates with copper strips printed on the inside. These field shaping electrodes are equally spaced with a pitch of 2 cm and a gap of 1 mm in between. The charge readout is placed on top of the drift volume: it consists of a screening grid with a wire pitch of 5 mm and the anode on top with a distance of 1 cm. The presence of this grid has two effects: first, it screens the induced voltages on the readout electrodes from drifting charges below the grid and second, it allows to increase the field and thus the velocity of the drifting charges above the grid. As a consequence, the induced signals have a faster rise-time, compared to a setup without such a grid. The screening grid is shown in the background of the left picture in Figure 5.4. It is identical with a second grid that is used as cathode and has two cross beams needed to reinforce the frame of the grid. The electrode of the anode, as shown on the bottom right of Figure 5.4, is segmented in 76 times 1 cm wide strips. Apart from the ionization charge that is readout with the TPC, the simultaneously produced scintillation light is detected by two cryogenic PMTs from Hamamatsu (type R6041-02ASYM MOD). In order to be sensitive to the LAr scintillation that has a wavelength of 128 nm, the PMT windows are coated with a thin layer of a polymer matrix, embedding the wavelength shifter TPB. A summary of the TPC dimensions, including the readout geometry, is given in Table 5.1.

Table 5.1: Dimensions and readout layout of the LAr TPC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total LAr volume</td>
<td>200 L</td>
</tr>
<tr>
<td>fiducial volume</td>
<td>120 L</td>
</tr>
<tr>
<td>fiducial mass</td>
<td>170 kg</td>
</tr>
<tr>
<td>maximum drift length</td>
<td>40 cm</td>
</tr>
<tr>
<td>induction grid-anode distance</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>readout cross section</td>
<td>76 × 40 cm²</td>
</tr>
<tr>
<td>readout pitch</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>induction grid pitch</td>
<td>0.5 cm</td>
</tr>
<tr>
<td># readout channels</td>
<td>76</td>
</tr>
</tbody>
</table>

To acquire the charge signals, a CAEN SY2791 crate with three A2792 acquisition boards, equipped with 76 ETHZ preamplifiers of type v0, is used (see also Chapter 3). The charge DAQ is triggered externally, either by the internal PMTs or a global trigger coming from...
the beamline instrumentation. To match the events recorded with the LAr TPC and the completely different DAQ system of the TREK beamline instrumentation such as the TOF, BDC, Fitch type Cherenkov counter, each event had to be labeled with a unique event stamp. This was provided by a Master Trigger Module (MTM) that generates a unique run, spill and event number for each accepted trigger. After converting the three generated numbers to analog signals, they were fed to three unused channels of the third CAEN A2792 board. Finally, after encoding these three additional channels offline, all the data coming from the beamline instrumentation could be added to the event, providing the necessary information to tag particles of a specific type.

5.2 The charged particle beam

As mentioned in the previous section, the beamline delivered in the best configuration a K/π-ratio of ∼ 1 with a K⁺ rate of ∼ 1 kHz. However, since the optimization work of the beamline was ongoing during the data taking phase, the particle composition of the beam was varying with time and had to be evaluated for each run. Since in the case of LAr runs small event rates of \( O(10 \text{ Hz}) \) are preferable to avoid pile-up and to cope with the huge amount of collected data (∼MB/event), the beam intensity was reduced.

More important than reaching a high kaon yield was to precisely tag different particle types. This is demonstrated in Figure 5.5: the two plots describe the particle composition of the beam during run 48, using the signals of the Fitch-type differential Cherenkov counter (left) and the TOF counters (right). In the left plot, the sum of all the K-ring signals is

![Figure 5.5](image-url)
plotted against the signals induced in the $\pi$-ring. It can be seen that only three cases appear:

- By detector design, only 740-800 MeV/c kaons produce signals in the K-ring but not in the $\pi$-ring.

- Faster particles, such as $e^+$, $\pi^+$ or $\mu^+$, induce only signals in the $\pi$-ring, since the produced Cherenkov light is totally reflected.

- Protons around 800 MeV/c do not produce Cherenkov light, thus there is no signal seen by both PMT rings (amplitude values around 1000 ADC counts are due to a pedestal, which has not been subtracted).

Since the point sets of the three cases are distinct, the Fitch type Cherenkov detector allows an efficient particle selection. After tagging particles according to the cuts that are indicated as dashed lines in the left plot of Figure 5.5, the corresponding $e/\pi/\mu$, K and proton TOF distributions are shown on the right. It can be seen that due to the good timing resolution of $\sim 200$ ps also the TOF counters allow a very good particle discrimination. Moreover the plot shows that the number of particles that were initially misidentified by the Cherenkov counter is almost negligible. As summarized in Table 5.2, the final event selection uses the information from the Cherenkov as well as the TOF counters.

**Table 5.2:** Selection criteria for tagging $e^+/$π$^+$, $K^+$ and protons, using the information from the Fitch type Cherenkov and the TOF counters.

<table>
<thead>
<tr>
<th>particle type</th>
<th>K-ring cut (ADC counts)</th>
<th>$\pi$-ring cut (ADC counts)</th>
<th>TOF cut (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+/$π$^+$</td>
<td>&lt; 2000</td>
<td>&gt; 1450</td>
<td>&lt; 13.5</td>
</tr>
<tr>
<td>$K^+$</td>
<td>&gt; 2000</td>
<td>&lt; 1450</td>
<td>&gt; 13.5 AND &lt; 17</td>
</tr>
<tr>
<td>$p$</td>
<td>&lt; 2000</td>
<td>&lt; 1450</td>
<td>&gt; 17</td>
</tr>
</tbody>
</table>

Besides the knowledge of the beam composition and the particle tagging capability of the instrumentation, it is important to understand the momentum profile with respect to the beam axis for the different particles. Starting from a fixed beam momentum of 800 MeV/c, momentum loss and spread are introduced by the presence of different materials in the 20 m long beamline. All these effects have been included in the GEANT4 simulation, which is described in Section 5.6.

Figure 5.6 shows the simulation of a $\pi^+$ (black), p (red) and a $K^+$ (green), crossing the last 5 m of the beamline. It can be seen that for instance the proton momentum is already substantially reduced to about 700 MeV/c when it enters the last 5 m of the beamline. The layout of the beamline instrumentation, consisting of two TOF counters, a gas Cherenkov counter and the LAr cryostat with the TPC inside, is shown on top of Figure 5.6.
the geometry, the plot shows the momentum of the three different particles as function of the beam axis coordinate $z$. It can be seen that the $\pi^+$ crosses the TPC without significant momentum loss. The proton, being the heaviest particle, stops in the first third of the TPC, whereas the $K^+$ stop in the second half. Due to the presence of a momentum degrader, that was only present during the kaon run 52, the $K^+$ loses at $z \approx -50 \text{ cm}$ the right amount of kinetic energy in order to stop inside the TPC; the momentum degrader used for run 52 is a lead glass counter and a lead brick.

5.3 Run description

After installing the detector inside the cryostat in the experimental area, the detector was evacuated during one week by a 300 L/s turbo molecular pump from Edwards$^3$ and a 40 L/s SAES getter pump$^4$. The achieved vacuum level was $\sim 10^{-6} \text{ mbar}$ with a combined outgassing

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$^3$http://www.edwardsvacuum.com  
$^4$http://www.saesgetters.com
and leak-rate of $O(10^{-3}$ mbar l/s). The evacuation phase is not only needed to remove the air from the vessel before filling with LAr, it also allows to detect leaks and a good vacuum helps to remove water from materials. Since the used detector materials, like Epoxy, contain water, a good vacuum is needed to drive the degassing process. After the evacuation phase, the detector vessel was filled with argon gas (GAr) through the input purification cartridge. Finally, once the detector was filled with GAr, the cooling phase was initiated by operating the GM cryocooler as well as the LN$_2$ heat exchanger. While the contained GAr was cooling down we kept adding GAr in order to keep the pressure above 1 bar absolute. Throughout this process the gas recirculation was running at maximum speed, continuously purifying the GAr. Once the vessel was at LAr temperature, we started to add LAr through the same input purification cartridge until the detector was completely immersed. During the whole filling procedure and also during the data taking period of more than one week, the gas recirculation system was never turned off.

After adjusting the necessary cooling power that was needed to keep the cryostat at a constant temperature and pressure, we first turned on the PMTs to measure scintillation light produced by cosmic and beam particles. Then, after a successful commissioning of the light readout, we started to operate the TPC. The final field configuration is reported in Table 5.3. Due to the occurrence of discharges, most likely in the HV feedthrough for the cathode, the high voltage of the cathode had to be limited to $-8$ kV. With the resulting field of 200 V/cm, the electron drift speed is $\sim 0.8$ mm/$\mu$s (see Section 2.5.1). As designed, we kept the induction grid at ground and the anode at +1 kV, providing an induction field of 1 kV/cm.

Depending on the purpose of the run, the LAr TPC was either recording cosmic ray events with a trigger on the prompt scintillation light, or beam events, using an external trigger from the beamline instrumentation. Cosmic ray runs were mainly used to measure and monitor the free electron lifetime in LAr, while the beam data was essential to study the detector response to different particles. Table 5.4 summarizes the parameters of the three main runs that were used for the analysis. Run 48 was recorded without particle tagging and it mainly contains $\pi^+$ that cross the detector straight. Since the absolute charge calibration of the

### Table 5.3: Applied voltages and resulting electric fields during the data taking phase.

<table>
<thead>
<tr>
<th>voltage / field</th>
<th>anode</th>
<th>+1.0 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>induction grid</td>
<td>GND (0 V)</td>
<td></td>
</tr>
<tr>
<td>cathode grid</td>
<td>$-8.0$ kV</td>
<td></td>
</tr>
<tr>
<td>induction field</td>
<td>1.0 kV/cm</td>
<td></td>
</tr>
<tr>
<td>drift field</td>
<td>0.2 kV/cm</td>
<td></td>
</tr>
</tbody>
</table>
readout electronics was not measured, these minimum ionizing events are used to calibrate the detector (see Section 5.5). Run 49 was recorded with a different beam, providing a large fraction of protons. As explained in Section 5.2, the \( K^+ \) run 52 was recorded with a momentum degrader. To trigger on kaons online with high efficiency, the K-ring signals from the Fitch-type differential Cherenkov counter (FC) were required to exceed a threshold.

A set of different kind of beam particle interactions recorded with the 120 L LAr TPC are shown in Figure 5.7. The event displays show the drift time in the TPC in dependence of the readout strip. The signal amplitude in the two-dimensional plot is proportional to the signal amplitude. Since the maximum drift length equals 40 cm, the resulting maximum possible drift time with a field of 200 V/cm is about 500 \( \mu s \) which corresponds to the selected drift time range. Height, orientation of the TPC and the strip numbering is such that beam particles enter more or less in the middle of the TPC at \( \sim \) 250 \( \mu s \) from the left (readout strip number 0) and then they propagate horizontally to the right. Starting from the top row, Figure 5.7 shows a through-going \( \pi^+ \) event recorded in run 48. Field distortions due to the two cross-beams (see Section 5.1.2) can be seen around the readout channels 25 and 50. The second event (top right) is a stopping proton from run 49 that ionizes more towards the end of the track. The next four events are all \( K^+ \) events, taken from run 52: the two events are both leptonic \( K^+ \rightarrow \nu \mu \mu^+ \) decays with a branching ratio of 63.55 \( \pm 0.11\% \), the third one is a candidate for the hadronic \( K^+ \rightarrow \pi^+ \pi^0 \) decay, which has a branching ratio of 21.66 \( \pm 0.08\% \) [22]. Unlike in the case of these three decays, where the kaons ionize more towards the end until they stop, the fourth kaon event shows an incoming \( K^+ \) that undergoes a hadronic interaction before it stops and thus no increase of ionization density is visible towards the end of the track. In the last row one can see on the left a positron, producing an electromagnetic shower and on the right a cosmic muon. Cosmic muons have an average momentum of \( \sim 4 \) GeV/c and release, depending on the cutoff threshold for the \( \delta \)-ray identification, about the same energy like mips. In this particular event, the \( \mu \) enters the fiducial volume through the anode and leaves through one of the two sides.
5.3. RUN DESCRIPTION

Figure 5.7: Events recorded with the LAr TPC after noise subtraction. From top left to the bottom right: through-going $\pi^+$, a stopping proton, two stopping $K^+$ decaying at rest into $\mu^+\nu_\mu$, a stopping $K^+ \rightarrow \pi^+\pi^0$ candidate, an inelastic interaction of a $K^+$, an electromagnetic shower, produced by an $e^+$ and finally a cosmic $\mu$. [See text for more details]


### 5.4 Event reconstruction and selection

Before being able to measure the ionization produced by stopping particles or to compare the collected data samples with MC generated data, the events have to be reconstructed. Following the basic procedure that was introduced in Section 4.3, the first step is to reduce the noise and to subtract the pedestal value from the waveforms. Second, the hit finding algorithm discriminates signals from noise. The clustering algorithm groups then close hits together, allowing to finally reconstruct tracks and vertices. Due to the use of a single view, the coarse readout pitch of 1 cm, the readout geometry, but also the presence of a charged particle beam with kaon decays, etc., the generic reconstruction had to be adapted to the characteristics of this experiment. In the following we describe the specific reconstruction of the beamtest data.

A key point of the event reconstruction was the optimization of the noise subtraction. Due to the presence of noise, exceeding the intrinsic noise of the preamplifier, the data had first to be processed by a sophisticated noise suppression algorithm. Although the noise in all the events in Figure 5.7 has already been suppressed with the algorithm being described here, it can be seen that the noise strongly varies with the channel number and that there is a number of discrete noise frequencies, picked up from the environment. Due to the restricted access to the detector it was not possible to further improve the grounding during run time, hence the noise suppression had to be done offline. As detailed in Section 4.3.1, the used FFT-filter suppresses all the frequencies above a smoothened cutoff frequency of 80 kHz. This relatively low cutoff provides an optimal signal to noise ratio between 6 and 10 for mips, depending on the readout channel and the run number. Considering the fact that the noise of the unprocessed events exceeds the average mip signal amplitude, this is an improvement of more than one order of magnitude. The drawback of the FFT filtering is the bandwidth reduction, which significantly spoils the signal waveform and the timing resolution.

Following a common baseline subtraction, hits are identified by requiring that a signal is longer than $3 \mu s$ above threshold. Since the noise is fluctuating from channel to channel and from event to event, a $3 \sigma$ threshold was chosen, where $\sigma$ is defined as the RMS value that is independently computed for each readout channel in each event. To avoid contributions from real signals, only samples that were recorded before the actual event trigger are used. Once signals are discriminated from the noise with an acceptable efficiency and purity, neighboured hits are grouped together by the NN-cluster algorithm that is described in Section 4.3.3. Figure 5.8 shows a typical through-going mip and a stopping proton event after finding hits and building clusters. It can be seen in both events that the actual particle track produces in both events a large number of clustered hits (red rectangles), whereas noise hits (black rectangles) are not grouped.

After identifying the clusters, a track finding algorithm was used to reconstruct through-going mips, stopping protons and the $K^+ \rightarrow \mu^+ \nu_\mu$ events. The algorithm, being specifically
5.4. EVENT RECONSTRUCTION AND SELECTION

Figure 5.8: Event displays for a through-going $\pi^+$ (left) and a stopping proton (right). Found hits that belong to the main particle are marked in red, others, marked in black, are considered to come from noise. [See text for more details]

implemented for these beamtest data, aims at finding the stopping point of the main track as well as all the hits belonging to it. In case of stopping particles, the algorithm finally reconstructs the collected charge in dependence of the projected residual range. Looping over all the hits of a found cluster that contains more than 15 hits, the algorithm goes through the following steps:

1. The first hits on the left, where the beam particle enters the TPC, has to be within the time window of the beam. It is also required that the track is starting before the third readout strip.

2. After identifying a hit on the readout strip $i$, the algorithm moves to strip $i+1$, searching for the next hit. A hit belongs to the track when there is a time coincidence with the previous hit. In case of two overlapping candidates, the hit with the smallest signal integral is disregarded. Otherwise, in case of no overlapping hit on the strip $i+1$, the algorithm moves to the next strip $i+2$.

3. If more than two subsequent readout strips do not have overlapping hits, the algorithm terminates.

4. After the successful identification of a connected chain of hits, the algorithm finds kinks, which might be caused by multiple scattering, interactions or decays, as for instance shown in the case of a $K^+ \rightarrow \mu^+\nu$ in Figure 5.9. Moving again hit by hit from the left to the right, a straight line is fitted to the last four hits on the left and the next two hits on the right. The idea is that the computed angle reaches a maximum in case the anchor point corresponds to the decay or scattering point. If the maximum angle is less than 0.1 rad, no kink is found in the main track. Otherwise the decay kink is defined by the intersection point of the two straight line fits.
CHAPTER 5. A 120 L LAR TPC EXPOSED TO A CHARGED PARTICLE BEAM

Figure 5.9: Reconstruction of a stopping K$^+$, decaying into a $\mu^+$ and a $\nu_\mu$. Left: hits, identified as main track in red, the hits identified as secondary track in green and noise hits in black. Right: same event-display superimposed with linear fits of the main and secondary track. [See text for more details]

5. In case a decay kink was found, all the hits in the chain on the left, including the decay-hit, belong to the main track, the others to the secondary track.

6. Finally, all the residual hits of the cluster that have not been tagged as main or secondary track are identified as noise hits.

Figure 5.8 shows on the left a fully reconstructed through-going mip that does not interact or scatter and on the right a stopping proton. Both, protons and through-going mips are then basically just selected by requiring that they are straight and that there are no secondary tracks attached to the main track. In case of the mips, the track has to cross the chamber completely, whereas the stopping point of the proton is given by the most right hit. Figure 5.9 shows a stopping and decaying K$^+$: red hits belong to the main track, green hits belong to the secondary track and noise hits are blue or black. The right plot shows the fitted straight lines in red and green for the main and secondary track. In the case of the kaon decays, the described algorithm is only able to reconstruct the $K^+ \rightarrow \mu^+\nu$ decays in which the $\mu^+$ is forward emitted. Since the goal of this analysis is the reconstruction of the stopping power for the primary track, backward emitted $\mu^+$ would only add charge to the primary track, which is not desired.

In order to study the vertex reconstruction precision, the algorithm was tested with MC generated events with known decay vertex position. As expected, we found that the resulting error on the obtained vertex for protons equals $\sim 3$ mm: since the strip below which the proton stops is known with high certainty, the intrinsic error equals $1/\sqrt{12}$ cm, given a flat distribution of the real stopping point within the 1 cm wide strip. In the case of stopping K$^+$ events, where the decay vertex is defined as the intersection of the two straight lines (initial K+ and outgoing $\mu^+$), the error is larger and equals 5 mm.

Figure 5.10 shows the reconstructed vertex positions for protons and kaons. Besides the
reconstructed real data (solid lines) we also show the reconstructed vertex of MC simulated events. The MC simulation, being described in Section 5.6, uses realistic particle momentum distributions that were obtained from beamline simulations, detector materials as well as an accurate description of the electronics response. It can be seen in Figure 5.10 that the histograms obtained with real data agree well with the MC simulation. Since the reconstruction errors are smaller than 1 cm, the spread of about 10 cm is due to the different momenta of the particles, introduced by the significant amount of material in the beamline. It is important to say that the data-MC agreement of the residual particle ranges provides a good validation of the implemented beamline and detector geometries. In the case of the kaon reconstruction (green) both distributions (data and MC) show a tail on the left which is due to decays in flight or hadronic interactions of the primary kaon. These events were obviously not used for the final stopping power analysis. The reason for the absence of a tail on the left of the stopping point distribution for protons is introduced by the reconstruction, since clusters with less than 15 hits are discarded.

5.5 Detector calibration

To obtain the real ionization charge after electron-ion recombination, one has to take into account the drift losses due to the presence of impurities and the calibration of the readout electronics. Other losses are due to the presence of a framed grid in front of the charge collection anode. In the following we first use cosmic muon data to measure the free electron lifetime, then we use through-going mips to obtain the calibration of the charge readout.
Figure 5.11: Measured free electron lifetime in LAr during the beamtest. At the beginning of the test, the lifetime was $\sim 670 \ \mu$s, then it degraded with a slope of $\sim -45 \ \mu$s/day.

5.5.1 Free electron lifetime measurements with cosmic rays

To measure the free electron lifetime, a reference charge has to be measured at different drift times. Beam particles produce only horizontal tracks at equal drift time, hence they cannot be used for this analysis. In contrast, tracks produced by cosmic muons that cross the detector with various angles are well suited. Although the absolute angle cannot be reconstructed, it is known that they produce more or less straight tracks with a more or less constant mean energy deposit along their trajectory. Therefore, the mean free electron lifetime for each cosmic ray run can be extracted by studying the mean charge produced by crossing cosmic muons in dependence of the drift time.

As described in Section 5.4, after the noise suppression, hits were found, fitted and clustered together. Instead of using the beam-specific track reconstruction it was only needed to verify that the tracks cross the full drift volume. This step is needed to avoid any bias due to the trigger efficiency and the missing angular information of each track. The measured charge of identified cosmic ray hits, plotted against the corresponding drift time, shows an exponential dependence with a characteristic time constant $\tau_e$ that can finally be extracted. A very detailed analysis on cosmic rays and the evaluation of the LAr purity is presented in Section 6.5.1. Since the aim of this test was to address the performance of a LAr TPC, here we only present the obtained results. Figure 5.11 shows the measured free electron lifetime as function of the time after filling the LAr detector. The first $\sim 60$ hours were reserved for
5.5. DETECTOR CALIBRATION

Figure 5.12: Charge response of the readout: the two plots show the raw (left) and calibrated (right) charge response. The measurement was done with through-going and almost minimum ionizing $\pi^+$ from run 48. The black circles mark the mean value for each readout strip (the statistical errors are smaller than the dimension of the circles). The colors, going from blue via green to red are proportional to the number of entries per bin.

the commissioning of the beam and the detector, thus there are no data points available. The measured data points in a time window between $\sim 60$ and $\sim 160$ hours are consistent with a straight line fit with an initial lifetime of $\sim 670 \, \mu s$ and a degradation of about $45 \, \mu s$ per day. All results presented in the following have been corrected with the measured lifetime by multiplying each hit charge with the factor $e^{t_{\text{drift}}/\tau}$, where $\tau$ is taken from Figure 5.11. It shall be mentioned that, despite the continuously running gas recirculation, the purity degradation could not be stopped but it was sufficiently slowed down to operate the chamber throughout the beamtest period.

5.5.2 Charge response of the detector

After the correction for the free electron lifetime, through-going mips have been used to study the response of the charge readout. Due to the relatively small momentum loss of $\pi^+$ and $\mu^+$ when they traverse the fiducial volume, the deposited energy per readout strip is constant and approximately equal to the energy deposit of mips. After reconstructing and selecting through-going mip events from run 48, as explained in Section 5.4, the resulting signal integrals of the selected hits can be used to study the channel-by-channel response of the charge readout. Figure 5.12 shows on the left the signal integrals of hits from selected though-going particles versus the strip number. The black circles on top of the scatter plot indicate the average signal integral and the error of the mean for each readout strip. Besides the known field distortions around channel 0, 25, 50 and 75, caused by the induction grid frame with the two cross-beams (see Section 5.1.2), large signal fluctuations up to a factor of two are observed. This is mainly coming from variations of the preamplifier response: besides intrinsic sensitivity fluctuations given by limits in the production precision of the preamplifier...
components, the used ETHZ preamplifier of type \( v0 \) (see Section 3.4) is due to its low open loop gain sensitive to the cable capacitances. Since all the signal lines, including the cables, had a different length and thus a different capacitance, large fluctuations are expected. Due to the fact that the detector was not equipped with a charge injection mechanism with test capacitors, an absolute calibration of the charge readout was not possible. Therefore, the only way to calibrate the charge readout is to use the average signals induced by mips as reference. After applying the mip calibration to the data, the measured quantity is the charge relative to the mip charge \( \Delta Q/\langle \Delta Q_{\text{mip}} \rangle \). The right plot in Figure 5.12 shows the through-going mip charge profile after calibration. The signals of readout strip number 32 are disregarded because of noise.

Besides the used calibration run 48 also the proton run 49 contained a large fraction of pions. In order to study the error of the calibration, the two runs were compared. Figure 5.13 shows on the left the mean values together with the statistical errors of the mip signal integrals of the two runs for each channel. It can be seen that the average signals of the two runs are similar. Only the first two active channels (number 2 and 3) are very different and they have not been used for the further analysis (see also the right plot of Figure 5.12). Since both channels are close to the epoxy frame, charging up effects causing time dependent distortions of the induction field, might be responsible for this anomaly. The overall calibration error is finally described by the standard deviation of \( ((Q_{\text{mip},48}) - (Q_{\text{mip},49}))/\langle \Delta Q_{\text{mip},48} \rangle \). The resulting calibration error of \( \sim 5\% \) is in the following taken into account as systematic error.

**Figure 5.13:** Left: charge response for the reference calibration run 48 and another \( \pi^+ \)-run 49. Right: histogram of the calibration error \( \langle (Q_{\text{mip},48}) - (Q_{\text{mip},49}) \rangle/\langle \Delta Q_{\text{mip},48} \rangle \). An overall systematic error on the calibration of \( \sim 5\% \) has to be taken into account.
5.6 The Monte Carlo simulation

As mentioned at the beginning of this chapter, one of the main goals of the beamtest was to measure the charge losses due to electron-ion recombination. In order to compare the measured charge with the initially deposited energy that leads to a measurement of the quenching factor $R = Q/Q_0$, it is essential to properly reconstruct the residual range of a particle defined as the distance from the readout strip below which the particle stops. The residual range allows then to obtain the theoretical $\Delta E/\Delta x$ value and thus $\Delta Q_0/\Delta x$ for the track segments, using the Bethe formula, defined in Equation (2.1). Due to the missing second readout plane, providing the coordinate that is transverse to the beam axis, only a projection of the residual range can be obtained. Moreover, it is also impossible to reconstruct for each event and readout strip the precise value of $\Delta x$, although it is due to the well known beam close to 1 cm. Only with a good MC simulation that simulates the propagation of particles in the materials used in the experiment, it is possible to compare the measured mean charge $\langle \Delta Q \rangle$ with the average deposited kinetic energy $\langle \Delta E \rangle_{mc,truth}$ as a function of the projected residual range. The second goal of a precise MC simulation for this beamtest experiment is to validate the existing MC code, being described in Chapter 4. In this section we first give an overview of the complete simulation, then we briefly describe the implemented beamline geometry. In order to take non-uniformities of the electric drift field into account, an electric field map is used. Going then to the digitization, we first explain the implementation of the random and the coherent noise, the signal shape and finally the fine-tuning of the simulation.

Most of the material in the beamline comes from the instrumentation used to tag the particles, thus only the last five meters of the T32 beamline has been implemented in the event-by-event simulation. The first 15 m of the beamline, containing a lot less material, was simulated in a standalone GEANT4 simulation in order to obtain the proper momentum distributions for all the types of particles in the beam. As explained more generally in Section 4.2.1, the used VMC\textsuperscript{5} [52] interface allows to use the ROOT\textsuperscript{6} [50] geometry package TGeo\textsuperscript{7}. Trying to introduce all the materials that are significant for energy loss and scattering, we have implemented all the scintillation counters (TOF and BDCs), a simplified gas tube (GC), the lead bricks (LB), the lead glass counters (LG) and the cryostat with the 120 L LAr TPC. The layout of the implemented instrumentation is shown on top of Figure 5.6. The geometry of the LAr detector is shown in more detail on the left of Figure 5.14. As described in Section 5.1.2, there are two cylindric vessels with two front flanges that are equipped with thin beam windows. The rectangular blue box, shown inside the inner vessel, represents the fiducial LAr volume with the dimensions $76 \times 40 \times 40$ cm$^3$. Via the VMC package, GEANT4 is used to propagate beam particles through the ROOT geometry. Table 5.5 summarizes

\textsuperscript{5}http://root.cern.ch/drupal/content/vmc
\textsuperscript{6}http://root.cern.ch/drupal/
\textsuperscript{7}root.cern.ch/download/doc/18Geometry.pdf
Chapter 5. A 120 L LAr TPC Exposed to a Charged Particle Beam

Figure 5.14: Example of a K⁺ GEANT4 event simulation. Left: openGL based 3D event display of Qscan showing the detector geometry with a MC K⁺ (red) that decays into a νµ and a µ⁺. Right: full digitization with realistic noise, the finite element computed field map and the measured electronics response of the detector.

The main input parameters and physics list of the MC simulation. As shown in the table, similar to GEANT3, the VMC interface allows to convert the defined cutoff energies for various particles into range cutoffs, used by GEANT4. According to the particle composition of the

Table 5.5: Parametrization and physics list of the MC simulation.

<table>
<thead>
<tr>
<th>physics list</th>
<th>QGSP_BERT</th>
</tr>
</thead>
<tbody>
<tr>
<td>e, δ-ray, γ, µ cut-off energies</td>
<td>10 keV</td>
</tr>
<tr>
<td>maximum step length</td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>

run that is simulated, the MC particles are shot from a single point that is located about 5 m upstream the LAr TPC. After tracking the particle through the geometry, similar to the real run trigger condition, it is first verified that the particle crosses the beam defining counter (BDC) in front of the LAr TPC. As previously explained, also the geometry of the beamline is run-dependent: in case of the kaon run 52 a momentum degrader, consisting of a lead glass counter (LG) and a lead brick (LB), are added. The MC event in Figure 5.14 shows a K⁺, entering from the left, stopping and decaying into a µ⁺ and a νµ. Like in the case of events from Figure 5.7, the decay point of the K⁺ inside the fiducial volume is around strip number 55. The µ⁺ is not contained. On the right side of Figure 5.14 one can see the same event, but fully digitized. Since the baseline digitization of MC events is discussed in detail in Section 4.2.2, here we only emphasize the implementation of the electric field, the coherent noise and the signal shape and scale.

Although the drift box with printed field shaping electrodes on the inside provides a uniform drift field, distortions are introduced by the induction grid that is placed 1 cm below the anode. The massive epoxy frame with two cross-beams covers several strips and introduces also field distortions on neighboring strips that are not directly affected. In some events of
5.6. THE MONTE CARLO SIMULATION

Figure 5.7 it can for instance be seen that some signals around the strips 0, 25, 50 and 75 arrive later due to field distortions. In order to properly take into account these effects in the MC simulation, the field was evaluated with a two-dimensional finite element computation. In absence of diffusion after a drift time of 200 µs, that is negligible compared to the 1 cm readout pitch, the coordinate of charges after drifting is calculated for each starting point in the fiducial volume. The so created look-up table allows then to include a realistic charge drift in an inhomogeneous electric field without significant increase of computation time. As a consequence, the simulated event shows the same electric field features like real events. This can for instance be seen in the digitized MC event that is shown on the right of Figure 5.14.

Coherent noise is usually picked up from the environment, which means that its specific frequency spectrum depends strongly on the experimental area and can moreover be time dependent. In order to obtain a realistic simulation of the detector performance, the generic white noise with a flat frequency spectrum as described in Section 4.2.2, is not sufficient. Taking events without physical signals, noise amplitude histograms were filled for each channel and each frequency of the full spectrum (real and imaginary part). The noise waveform is then built, using random numbers from these frequency distributions. Since the resulting noise does not include the correlation which is seen among channels that are housed on the same DAQ board, common noise has to be added separately. The events in Figure 5.7 show common noise on channel 0 to 31 (board 0), 32 to 63 (board 1) and 64 to 75 (board 2). To imitate the observed correlation, we added the noise of channels 0, 32 and 64 to the already generated uncorrelated noise of the other channels on the same board. It turned out that a 1:1 ratio of random and coherent noise gives the best description of the data. The pattern of the coherent noise can be seen in the MC event display on the right of Figure 5.14. After the implementation of the correct power spectrum and the correlation of the noise among the readout strips, the absolute scale had to be fixed. First, the RMS noise amplitude of the relevant runs was evaluated, then, after measuring the obtained noise in the MC runs, the MC noise of each channel was rescaled in order to approach the real data. Figure 5.15 shows on the left the RMS noise values for each readout channel after filtering for both MC (histogram lines) and real data (circles with errors). The graph shows that the real and the artificial MC noise are identical for all the channels. It can also be seen that the noise in run 52 (green) is higher than in the two preceding runs 48 (black) and 49 (green), which means that the coherent noise was increasing with time, making it necessary to treat each run separately.

The signals are generated as described in Section 4.2.2. Unlike in a double phase LAr LEM-TPC that produces very fast signals Section 2.6 and thus allows to use the preamplifier response function for the digitization, a Gaussian is better suited for the 120 L TPC being described here. Since the channel-by-channel charge response of the detector readout was not calibrated before the run, the MC simulation has to be matched to the data, using mip signals.

This means that MC generated signals from through-going $\pi^+$ were first reconstructed and then rescaled in order to approach the average mip signals obtained in the calibration run 48, similar to the rescaling of the MC generated noise. After rescaling, the obtained charge profile that is shown on the right of Figure 5.15, is equal to the real data profile shown in Figure 5.12.

To summarize the work done for the MC simulation, first we have implemented an accurate description of the geometry with the proper particle tracking characteristics of all the materials. Concerning the digitization of the signals we have taken into account of the most important effects like electric field distortions, random and coherent noise and the response of the charge readout of the detector. The latter was done by comparing the response of through-going mips.

5.7 Results

The main goal of this beamtest from the physics point of view was to study the ionization charge of stopping particles, such as protons and kaons, in LAr and to use these data to validate existing MC simulation code. After the description of the event reconstruction, the detector calibration and the MC simulation, this section presents the main results that were obtained during the beamtest. In Section 5.7.1 the measurement of the stopping power and a study of the charge recombination for stopping protons and kaons is presented. Section 5.7.2 shows a comparison of the data and the MC simulation.
5.7. RESULTS

Figure 5.16: Reconstructed stopping power for protons (left) and kaons (right) as a function of the residual range. The charge of each strip is normalized to the charge induced by through-going mips from run 48.

5.7.1 Stopping power and charge recombination

As particles traverse the detector medium, they lose kinetic energy by exciting and ionizing argon atoms. Depending on the electric field strength $E$ and the ionization density ($\propto dE/dx$) only a fraction $R = R(E, dE/dx)$ of the produced charge does not recombine and can be measured. To measure the quenching factor $R := Q/Q_0$, the detected charge $Q$ has to be compared with the initially produced charge $Q_0$, that can be calculated if the residual range of the track is known. As mentioned above, the detector has, apart from the low electric field and the coarse readout pitch, two basic limitations: first, a missing second readout coordinate makes it impossible to reconstruct the residual range and second, the absolute charge calibration of the electronics is unknown.

The final stopping power results that were obtained from the proton run 49 and the kaon run 52 are shown in Figure 5.16 on the left and the right, respectively. As a consequence of the two limitations, the measured physics quantities are the mip-normalized charge $\Delta Q/\langle \Delta Q_{mip} \rangle$ and the projected residual range. It can be seen that in both cases more ionization is produced towards the stopping point of the track. In both plots the black dots show the average deposited charge $\langle \Delta Q \rangle/\langle \Delta Q_{mip} \rangle$ together with the statistical error of the mean. The spread of the single data points around the mean values is visualized with a rainbow color scale going from blue to red.

The next step is to extract the quenching factor, using both proton and kaon data. As previously explained the true unquenched ionization charge has to be obtained from the MC simulation. Following the description of the MC simulation in Section 5.6, beam particles are tracked in the beamline geometry, digitized and reconstructed. Similar to the real data, through-going MC $\pi^+$ events are used as reference. Therefore, the quantity $R_{mip}/R$, given
Figure 5.17: Measurement of the charge quenching with stopping protons (red) and kaons (green). A straight line with slope \( k = 0.040 \pm 0.001 \) (kV/cm)(g/cm\(^2\)) MeV is fitted to the data points. [See text for more information.]

by

\[
\frac{R_{\text{mip}}}{R} = \frac{\Delta Q_{\text{mip}}}{\Delta Q_{0,\text{mip}}} \left( \frac{\Delta Q}{\Delta Q_0} \right)^{-1} = \frac{\Delta Q_0}{\Delta Q_{0,\text{mip}}} \cdot \left( \frac{\Delta Q}{\Delta Q_{\text{mip}}} \right)^{-1},
\]

(5.1)
can easily be obtained: the term \( \Delta Q/\Delta Q_{\text{mip}} \) stands for the average normalized charge as it is shown in Figure 5.16 and \( \Delta Q_0/\Delta Q_{0,\text{mip}} \) is the same quantity, but from MC generated data. It shall be stressed here that the MC simulation for this analysis had no quenching included and therefore entirely depends on the deposited energies \( dE/dx \). Figure 5.17 shows the values \( R_{\text{mip}}/R \) as a function of the average deposited energy \( \langle dE/dX \rangle_{\text{MC}} \) that is obtained from the MC simulation. The fact that a linear dependence is seen for both the proton (red) and the kaon (green), nicely confirms Birks' approximation

\[
R_{\text{Birks}} = \frac{A}{1 + \frac{k}{E} \frac{dE}{dX}},
\]

(5.2)
saying that \( R^{-1} \) is proportional to \( dE/dx \), which is in our case replaced with the expression \( \langle dE/dX \rangle_{\text{MC}} \). Due to this expected linearity of the data points, the function

\[
f(x) = \left( 1 + \frac{k}{E} x \right) \cdot \left( 1 + \frac{k}{E} \left( \frac{dE}{dX} \right)_{\text{mip}} \right)^{-1}
\]

(5.3)

with

\[
x := \langle dE/dX \rangle_{\text{MC}}, \text{ and } \langle dE/dX \rangle_{\text{mip}} = 1.53 \text{ MeVcm}^2/\text{g}
\]
5.7. RESULTS

Figure 5.18: Stopping power of protons (left) and kaons (right) as function of the projected residual range. The plots show the beam measurements (triangles), MC simulations without quenching (solid red) as well as MC with different quenching input parameters \( k_{MC} \). [See text for more details]

can be fitted to the data. The function is properly normalized, which means that it equals unity for \( \langle dE/dX \rangle_{MC} \equiv \langle dE/dX \rangle_{mip} \). The only free fitting parameter \( k \) is proportional to the slope and equals \( k = 0.040 \pm 0.001 \) (kV/cm)(MeV g/cm\(^2\)). This value has to be compared to the value measured by ICARUS with a 3 T detector \( k = 0.0486 \pm 0.003 \) (kV/cm)(MeV g/cm\(^2\)) [30]. A possible reason for the discrepancy is the different readout structure of the ICARUS detector. Compared to the 120 L LAr TPC that has a readout pitch of 1 cm, the ICARUS 3 T detector had a much better spatial resolution of 2 mm. First of all this allows a better measurement of the recombination factor close to the stopping point and obviously large \( dE/dx \) points are dominating this measurement. A second reason is due to the \( dE/dx \) value: as already explained we use the average stopping power \( \langle dE/dx \rangle_{MC} \), integrated over the full strip width of 1 cm as best estimator for the \( dE/dx \) in the middle of the strip. Considering the fact that \( dE/dx \) is increasing faster than linearly towards the end of the track, the average leads to an overestimation of its true value, which is equivalent to an underestimation of \( k \).

5.7.2 Validation of the LAr MC simulation

Since the event reconstruction and selection were tuned to allow only non-interacting and stopping kaons and protons, or through-going pions, the dominant process of the energy loss is well described by the Bethe Bloch formula. On the other hand the measured quantity in this detector is the drifting charge and not the deposited energy. Despite different models for electron-ion recombination that are introduced in Section 2.3.2, the electric field \( E \) and the \( dE/dx \) dependence is well described by Birks’ Law. This was found in the previous section and other experiments using similar detectors with similar drift fields [30]. In order to include the quenching in the MC simulation, it therefore makes sense to use Birks’ approximation. As explained in Section 4.2.2 this means in practice that the generated deposited energy \( dE \)
of each MC step with length $dx$ is multiplied with the factor

$$R_{Birks}(dE/dx, \mathcal{E}) = \frac{A_{MC}}{1 + (k_{MC}/\mathcal{E}) \cdot (dE/dx)}.$$  \hfill (5.4)

Figure 5.18 shows the stopping power versus the projected residual range for protons on the left and kaons on the right. Both plots show again the real data, together with MC simulations without quenching ($R = 1$), and different values for $k_{MC}$. Since the real data as well as the MC generated data are normalized by the mip charge, the value of the overall scaling parameter $A_{MC}$ is not relevant. The plot shows that the simulation, using the input parameter $k = 0.05$ (kV/cm)(g/cm$^2$MeV), agrees very well with the data. It can be seen that the MC curves for both protons and kaons are within the errors of the measured data points.

As reported in [30], the parameters $A_{MC}$ as well as $k_{MC}$ do not necessarily have to be equal to the measured ones. That has mainly to do with the fact that in case of the MC simulation, the quenching is applied to all $\delta$-ray electrons that are tracked down to very low cutoff energies of 10 keV. In the case of the reconstructed values of the charges $\Delta Q$ that finally leads to $\Delta E$, only electrons above 2 MeV can be separated from the main track. $\delta$-rays of lower energy cannot be resolved, thus the ionization charge produced by them is just added to the overall $\Delta Q$. Sometimes the reconstructed track, being a composition of the main track and all the small unresolved $\delta$-rays is referred to as dressed track. To study the difference between the MC generated quenching with $k_{MC}$ and the reconstructed quenching with $k_{rec}$,
that are in fact related to each other by the formula

\[
\frac{A_{\text{rec}} \cdot Q_0}{1 + \left( \frac{k_{\text{rec}}}{E} \right) \cdot (dE/dx)} = \sum_i \frac{A_{\text{MC}} \cdot Q_{0,i}}{1 + \left( \frac{k_{\text{MC}}}{E} \right) \cdot (dE_{i}/dx_i)},
\]

(5.5)

(the summation index \(i\) runs over all the MC steps of length \(dx_i\) and deposited energy \(dE_i\) contributing to a single reconstructed hit) the analysis of Section 5.7.1 was repeated for the reconstructed MC data. The final result for the three different values of \(k_{\text{MC}}\) is shown in Figure 5.19. It can be seen that the measured slopes \(k_{\text{rec}}\) are in average 20% lower than the input values \(k_{\text{MC}}\).

Besides the good MC agreement for the stopping particles, also through-going mips are well described. Figure 5.20 shows the charge distribution of the normalized charges \(\Delta Q / \langle \Delta Q_{\text{mip}} \rangle\) for both real (black points with errors) and MC generated data (blue line). The observed distributions are shown twice in linear (left plot) and in log scale (right plot). While for the stopping particles only the mean values of the produced charges were studied and compared, the agreement of the two Landau distributions for through-going mips prove that also the simulated Landau fluctuations agree well with the measured data.

To conclude, the beamtest data of stopping protons, kaons and through-going pions have been compared with MC simulations, in particular addressing the proper implementation of quenching. The use of Birks’ law that takes the \(dE/dx\) and the electric field \(E\) into account, though latter was not tested here, provides an accurate reproduction of the collected data.
Chapter 6

The large area double phase
LEM-TPC

In [19] and references therein we have reported on the operation of a small prototype double phase argon LEM-TPC with a readout area of $10 \times 10 \text{ cm}^2$. In order to instrument an area of 4000 m$^2$, as in the case of the future 100 kt GLACIER detector [13], the proposed readout is subdivided into $0.5 \times 0.5 \text{ m}^2$ modules.

Although the production of both, LEM and 2D projective anode of this size is feasible, it is not apriori clear that the readout technology is scalable to large sizes. During the operation of the $10 \times 10 \text{ cm}^2$ prototype at higher gains, we have occasionally observed discharges between the two LEM electrodes. Since the area of a $0.5 \times 0.5 \text{ m}^2$ large LEM is 25 times larger, the rate of discharges might be too high for a stable operation. Additionally, also the capacitance, and thus the stored charge on the LEM, increases with the area. Without any segmentation of the electrodes, a discharge occurring at a single spot could damage the device locally. Since there is only one electrode with one HV connection on each side of the LEM, a short on a single spot would disable the full device. Regarding the signal to noise performance, an increase of the detector size is always coupled with an increase of electronic noise (see Section 3.4). The capacitance of a single one meter long readout channel (strips) of the 2D projective anode is about 600 pF, thus the overall detector and cable capacitance approaches 1 nF.

Besides these intrinsic problems of the LEM and the 2D projective anode, there are also mechanical issues related to the large area. The LEM, as well as the anode, are epoxy plates with a thickness of about 1 mm. In order to keep the two plates flat, with a precise 2 mm gap in between, a well designed supporting system with spacers is required. In addition to the support of the LEM and the anode, the whole charge readout module has to be precisely aligned with the LAr surface. It is very important to keep the LAr level with a precision of 1 mm in the middle of the two extraction grids; too large deviations would reduce the extraction efficiency. In conclusion, a very robust mechanical structure is needed for supporting the different stages of the charge readout.
In order to address possible problems related to the large area, we designed a first prototype of a large area double phase LEM-TPC with charge readout. Since the new device was originally designed as upgrade for the T32 testbeam experiment (see Chapter 5), an effective readout size of $40 \times 76 \text{ cm}^2$ was chosen to fit into the existing cryostat. The new readout is with an area of 0.3 m$^2$ significantly larger than the $10 \times 10 \text{ cm}^2$ prototype and in fact even bigger than the proposed $0.5 \times 0.5 \text{ m}^2$ readout modules for GLACIER. To solve the mechanical problems, mentioned above, the readout was designed as a compact and robust unit. The hereafter called charge readout sandwich fully embeds extraction grids, LEM, 2D projective anode, as well as the distribution of the signal and HV lines. In order to do a first test of this readout sandwich in double phase conditions, we have constructed a new drift chamber, equipped with a PMT light readout. Moreover, a Greinacher/Cockcroft-Walton voltage multiplier circuit was used to generate the drift field. After the successful operation of the detector, the results were published in [64] and [65].

In this chapter, design, construction, operation and first performance tests of the large area double phase argon LEM-TPC with a 2D projective anode readout are presented. Starting with the description of the experimental setup in Section 6.1, the first operation of the chamber in warm gas and double phase conditions is described in Section 6.2. After a short description of the specific track reconstruction in Section 6.3, the calibration of the readout electronics is described in Section 6.4. After these preparatory sections, we finally discuss the obtained detector performance in Section 6.5.

### 6.1 Experimental setup

The $40 \times 76 \text{ cm}^2$ large charge readout was designed, produced and assembled together with a new drift volume with a maximum drift length of 60 cm. The TPC was equipped with a Greinacher voltage multiplier and a PMT light readout. For a first test of the detector, it was placed inside the cryostat of the Argon Dark Matter (ArDM) experiment [66], located at CERN. In this section, we first give a brief overview of the detector, then design and construction of the charge readout sandwich and the High Voltage (HV) layout are detailed. After the description of the DAQ configuration and the trigger, the essential parts of the cryogenic setup are discussed.

#### 6.1.1 Overview of the LEM-TPC

Figure 6.1 shows a 3D drawing of a cut through the full detector on the left together with the detector scheme on the right. Starting from the readout sandwich (1), which is separately described in the next section, the drift volume (2) is located below. It is delimited by four PCB plates with 30 copper strips printed on the inner side. The so formed field shaping electrodes are 1.8 cm wide and have a pitch of 2 cm. Due to this rather closed geometry, field
6.1. EXPERIMENTAL SETUP

Figure 6.1: 3D CAD drawing showing a cut through the detector (left) together with the schematic detector layout (right): the charge readout sandwich (1), the drift volume (2) with the field shaping electrodes, the cathode mesh (3), and below the HV protection grid (4) the light readout (5).

...distortions, coming from the ground of the cryostat wall, are reduced. On top and bottom the potential is defined by means of the extraction (1) and the cathode grid (3), respectively. Due to the acceptable optical transparency of 75%, the same type of grid was used as cathode and extraction grid. Finally, as shown in Figure 6.1, the scintillation light is detected with two cryogenic PMTs\(^1\) (5), placed 10 cm below the cathode, at the bottom of the detector. To protect the sensitive photocathode of the PMTs, we decided to place an additional grid (4), again identical to the extraction grids, between the cathode and the PMTs. Similar to the light readout of the testbeam setup (see Chapter 5), the windows of both PMTs were coated with a wavelength shifter. A picture of the fully assembled detector, hanging from the flange of the ArDM cryostat, is shown on the left of Figure 6.2.

6.1.2 Design and construction of the charge readout sandwich

In a series of tests with the 10 × 10 cm\(^2\) prototype we have successfully optimized the LEM geometry as a charge gain of 30 could finally be reached [19]. In order to achieve a similar performance with the large area LEM it was essential to keep as much as possible from the existing layout. On the other hand certain changes, related to the increased area of the readout, had to be applied. Differently from the small prototype, where LEM and anode were

\(^1\)Hamamatsu R11065
just fixed at the corners, a solid frame was needed in order to support the large extraction grids and to keep anode and LEM flat. This triggered the design of a compact and robust charge readout sandwich. Positioned at the top of the drift volume across the LAr surface, it provides the extraction, amplification and detection of the ionization charges. The 2D computer-aided design (CAD) drawing in Figure 6.3 shows a cut along the short side of the 40 × 76 cm² large readout sandwich. From top to bottom, the drawing shows the signal distribution plane (1), connected via HV decoupling capacitors (2) to the HV distribution plane (3), the 2D projective anode (4) and, at a distance of 2 mm, the LEM (5). At the bottom are two extraction grids, one in gas (6) and one in liquid (7). Both grids are glued to massive, 1 cm thick epoxy frames (e), shown in green. In the following paragraphs the LEM, 2D anode, extraction grids and the PCB planes for the distribution of HV and signal lines, are detailed.

The LEM with its effective size of 40 × 76 cm² is shown on the left of Figure 6.4 together with a closeup. It was designed with the geometric parameters of the 10 × 10 cm² prototype: a thickness of 1 mm, a hole pitch of 800 µm and a hole diameter of 500 µm. The only difference in the design was the subdivision of the top and the bottom electrode into eight segments each, seen on the left of Figure 6.4. All the segments are supplied with HV through 500 MΩ surface mounted resistors. The advantage of such a layout is that in case of a discharge in a single LEM hole, only the energy stored in a single segment is released. As a consequence, the produced heat and thus the risk of a possible damage to the device is reduced. To ensure that such discharges do not propagate to the adjacent segments, the electrodes were separated by a distance of 1.6 mm. The dead area between the segments was used to place 1.6 mm wide
6.1. EXPERIMENTAL SETUP

Figure 6.3: 2D CAD drawing of the readout sandwich, providing charge extraction, amplification and detection. The main elements are listed on the left (numbers): the signal distribution PCB plane (1), the HV decoupling capacitors with $C_{dec} = 271$ pF (2), the HV distribution PCB plane (3), 2D anode (4), LEM (5), extraction grid in gas (6) and in liquid (7). Other components shown in the graphics (letters) are the connectors for the signal cables (a) behind the surge arresters (b), 33 Ω resistors (c), the multi pin connectors between the anode and the HV distribution plane (d), epoxy frames and spacers (e) and finally supporting angles to attach the sandwich to the drift volume (f).

and 2 mm high FR4 spacers below and above the LEM. In absence of such distance keepers the exposed LEM and anode were touching, making the operation of the device impossible. However, due to the waviness of both LEM and anode, the nominal distance of 2 mm in between them could, despite the use of spacers, only be kept with an error of about 1 mm. Since a PCB plate of this size could not be drilled at the CERN TS/DEM workshop, it was produced by an external company\(^2\). After the drilling, dielectric rims around the holes were etched: starting from a 50 $\mu$m thick layer of copper, 40 $\mu$m were slowly etched away, leading to a 10 $\mu$m layer of copper and 40 $\mu$m thick, perfectly centered dielectric rims around the holes. A closeup of the rims is shown in the LEM picture in Figure 6.4. Finally, the bare copper electrodes were passivated (controlled oxidation process) in order to prevent the copper electrodes of the LEM from corrosion. After soldering the resistors and the two HV connectors, HV tests in air were made in order to verify that there are no shorts or other damages. Since all the sparks were occurring randomly distributed in time and area, we concluded that the produced LEM had no production failures.

Similar to the LEM design, also the parameters for the \textit{2D projective anode} were taken from the small $10 \times 10$ cm\(^2\) prototype: two orthogonal sets of strips with a 400 $\mu$m pitch, insulated with a 50 $\mu$m thick Kapton (polyimide) layer in between. In order to reach an effective readout pitch of 3 mm, 5 strips were connected together. Differently from the $10 \times 10$ cm\(^2\) prototype, the readout strips are oriented at $\pm 45^\circ$ with respect to the detector axis (see Figure 6.4, right), making the readout suitable for a possible future test beam: since the beam direction would be along the detector axis, this readout configuration avoids parallel tracks to the readout strips of one view. The $40 \times 76$ cm\(^2\) large anode with $2 \times 256$ readout channels, shown in Figure 6.4, was produced by the CERN TS/DEM workshop. Since no

\(^2\)Eltos S.p.A., San Zeno (AR) Italy
shorts between adjacent strips were found, we concluded that the anode was fully functional.

The extraction grids, designed to enhance the field across the liquid-gas interface in order to allow an efficient and fast charge extraction into the gas phase, are placed below the LEM. In order to avoid transparency losses due to the collection on the top extraction grid (see discussion in [17]), the wires of the two extraction grids have to be perfectly aligned. Since it is very difficult to produce two identical wire frames with a pitch of 3 mm, identical grids were made etching a mesh structure from stainless steel foils. At the CERN TS/DEM workshop four 150 µm thick grids with a “wire” width of 150 µm and a pitch of 3 mm were produced. After the etching, the grids were glued on 1 cm thick and 5 cm wide epoxy frames (see Figure 6.5, left). In order to keep the grids flat, the frames had to be pre-tensioned before attaching the mesh to them. Two of these grids, eventually used for the extraction, were first optically aligned in the central region and then fixed together with precision pins. Due to the fact that the grids were slightly squeezed (consequence of the pre-tensioning), a perfect alignment was not possible. Deviations up to about 1.5 wire diameters were found at the edges. As explained above, the two remaining grids were used as cathode and protection grid.

The top part of the sandwich consists of a HV distribution plane and a signal routing plane, both connected via decoupling capacitors. Being connected to the anode below, this part has to provide a voltage of about +1 kV to all the strips and to decouple and route the signals to the connectors. Each strip of the 2D anode is connected to the HV distribution plane (Figure 6.3). This PCB board is designed to distribute the HV via surface mounted 500 MΩ HV resistors from a single point to all the readout strips of the 2D anode. The picture on the right of Figure 6.5 shows the HV distribution plane (bottom), half of it covered with the signal routing plane. On the uncovered part of the HV distribution plane, the surface mounted resistors and the decoupling capacitors are seen. The signal routing plane is at low
6.1. EXPERIMENTAL SETUP

![Image of one of the extraction grids (left) and the charge readout sandwich during the assembling: the half in the back is already covered with the signal plane, in the foreground the HV distribution plane with the decoupling capacitors and the 50 MΩ resistors is seen.]

Figure 6.5: Image of one of the extraction grids (left) and the charge readout sandwich during the assembling: the half in the back is already covered with the signal plane, in the foreground the HV distribution plane with the decoupling capacitors and the 50 MΩ resistors is seen.

Voltage and it hosts for each channel a surge arrester and the 33 Ω resistor, both being part of the first discharge protection stage (see Section 3.3). The 512 signal channels, as well as the ground, are distributed to 16 ERNI connectors with 68 pins each.

Finally, all the described components of the charge readout sandwich were screwed together, as shown in the sketch of Figure 6.3. After an additional HV test of all the electrodes, the sandwich was attached on top of the drift volume, which was already hanging from the top flange of the ArDM cryostat. Figure 6.6 shows the full chamber while being inserted into the cryostat. It can also be seen, that we have attached four identical capacitive level meters (only two are visible) close to the corners of the readout sandwich. They ensure that the LAr level is adjusted in the middle of the two extraction grids with a precision of less than 1 mm. The signal plugs on top of the sandwich are then connected to the feedthrough with 1.5 m long flat ribbon cables ($C = 40 \text{ pF/m}$), shown in green. The picture on the right shows how the cables, coming from the readout sandwich, are connected to the signal feedthrough. It is made of 16, 40 cm long, flexible Kapton prints, each having 32 signal lines and going through fine slits of a custom made CF100 UHV flange. After glueing the cables, the vacuum tightness of the flange was tested.

6.1.3 The HV layout

For the $10 \times 10 \text{ cm}^2$ prototype, as well as for the single phase LAr-TPC (Chapter 5), the high voltage of the cathode was generated by a commercial power supply providing maximally 35 kV. The construction of a HV feedthrough, needed to supply the electrodes inside the cryostat with HV, is very challenging: obviously it has to hold high voltages, a leak tightness of $10^{-9} \text{ mbar}\ell/\text{s}$ is required in order not to spoil the purity, and moreover, it must withstand cryogenic temperatures. A very appealing alternative is to put the HV supply directly inside the cryostat. This is feasible because all the electrodes at very high negative potentials
Figure 6.6: Left: final top view of the full assembly, including the readout sandwich with the signal cables on top and the capacitive level meters attached to the four hanging supports at the corners (only two are visible in the front). Right: connection of the 16 Kapton cables, being fed through a CF100 flange, to the ERNI plugs on top of the charge readout sandwich.

are immersed in liquid argon, which has a very high dielectric strength of $\approx 1 \text{ MV/cm}$. As demonstrated in [67], a Greinacher voltage multiplier circuit can be operated in LAr. Given an alternating voltage with the peak to peak value $V_{pp}^{in}$ and a frequency of 50 Hz, the Greinacher multiplier ideally generates at each stage $i$ the voltage $V_i = iV_{pp}^{in}$. The obtained linear voltage increase from the first to the last stage can directly be used to supply the voltages of the field shaping electrodes of the detector drift volume. Considering the fact that the natural discharging time of the circuit, coming from the reverse leakage current of the diodes, surface currents and the ionization charge produced in the detector, is of the order of a day, the multiplier does not need to be continuously recharged. In terms of noise, which is often produced by HV generators, this is a clear advantage compared to external power supplies. Since in case of an external HV supply the voltage is distributed to the field shaping electrodes by means of a resistive voltage divider, drawing a continuous current, the supply can never be switched off. On the other hand, external power supplies are easier to control than a Greinacher multiplier: the only way to ramp down its voltage is to ground the last stage. This means that besides an alternating current source for charging, also a sophisticated discharging device is required (see Figure 6.2, left).

Figure 6.7 shows the scheme of the used Greinacher multiplier. Each of the 31 stages from $i = 0$ to $i = 30$ is connected to a field shaper. Having the most negative potential, the cathode is connected to the stage $i = 30$, while the stage $i = 0$ with the lowest voltage is connected to the bottom extraction grid. In order to be able to freely choose the potential of the extraction grid, the first stage of the Greinacher circuit is, as shown in red in Figure 6.7, shifted with a DC voltage source. The realization of this circuit can be seen in the right
6.1. EXPERIMENTAL SETUP

Figure 6.7: Electric circuit [64] of the used greinacher/Cockcroft-Walton voltage multiplier (black, stage 3 is highlighted in blue) with additional components (red) to shift the voltage of the first stage that is connected to the bottom extraction grid.

picture of Figure 6.2. Due to the use of PCB techniques, the circuit is directly soldered on the outer side of a PCB, defining the drift volume. Each field shaping electrode, printed on the inside, is connected with a via through the PCB to a stage of the Greinacher voltage multiplier. The designed Greinacher circuit is nominally capable of delivering up to 60 kV, corresponding to a potential difference of 2 kV between each stage and a resulting maximal electric drift field of 1 kV/cm. In order to prevent the Greinacher circuit components (diodes\(^3\) and capacitors\(^4\)) from damage due to discharges between the HV electrodes (cathode and last field shapers) and the dewar wall (grounded), the last Greinacher stages are connected to the electrodes via 2 GΩ HV resistors. In case the cathode discharges to ground, the discharging current coming from the charge stored in the Greinacher circuit is reduced because of the presence of these resistors. Figure 6.2 (right) shows these cylindrical resistors at the bottom right in light blue. Since the only way to ramp down the voltage in such a system is to ground the cathode, a rotatable discharging mechanism, with a metallic ball at the same height as the cathode, was constructed as shown on the left of Figure 6.2. When the metallic ball is in contact with the cathode, a discharging current flows through a resistor chain with a total resistivity of 1.2 GΩ to ground. More details, related to the HV system can be found in [64].

A complete layout of all the high and low voltage connections is sketched in Figure 6.8. The positive and negative voltages of the 2D anode, both LEM electrodes and both extraction grids are externally generated by standard HV power supplies. In order not to introduce noise we have used external low pass filters. As explained in the description of the charge readout sandwich, the HV is distributed via 500 MΩ resistors to the anode strips and the electrode segments of the LEM. Figure 6.8 shows once more the HV decoupling of the anode strips and the over-voltage protection circuit for the charge sensitive preamplifiers, which are both discussed in Chapter 3.

\(^3\)BY505, NXP Semiconductors, http://www.nxp.com
6.1.4 Data acquisition and trigger

Each of the 16 Kapton cables, being fed through a CF100 flange, is finally connected via 1.5 m long shielded flat ribbon cable to a CAEN A2791 data acquisition board (see Section 3.3). Figure 6.9 shows the CAEN acquisition system, consisting of two CAEN SY2792 crates on the left and the detector with its signal feedthrough on the right. The eight acquisition boards of each crate are connected via optical link with a daisy-chain configuration to a dedicated readout computer (one computer per crate). During the data taking, the data files were independently written on a single storage disk, connected to the local LAN network. The fastest data rate acquired during the experiment was 40 MB/s, corresponding to a trigger rate of 20 Hz. The charge acquisition was externally triggered by the light readout: a NIM discriminator produced a trigger, whenever the signal amplitude of any of the two PMTs exceeded an adjustable threshold value.

6.1.5 Cryostat, slow control and LAr purification systems

For a first cryogenic test, the previously described detector was inserted into the cryostat of the ArDM experiment. The cryostat is designed to safely keep about 2 tons of highly pure LAr. Due to the large amount of LAr, the system has to be fully monitored and controlled by a programmable logic control system (PLC), fulfilling basic safety requirements. A detailed description of the PLC can be found in the PhD thesis of U. Degunda [68]. As shown in Figure 6.10, the cryostat consists of several parts: the detector (1) is hosted by the main vessel that contains highly purified LAr (2), an independent external bath with not purified LAr.
bath surrounding and thus cooling the detector vessel and the LAr purification cartridge (3), a gas purification circuit (4) and a condenser with two cold heads attached to two Gifford-McMahon cryocoolers (5). While the stability of the cryogenic system has been asserted prior to this run, one of the goals of the new test was the validation of the liquid and the recently added gas recirculation system. The gas purification is done in a similar way as for the $10 \times 10$ cm$^2$ setup: an all-metal membrane pump, which is connected to the top flange of the main detector vessel with a heated tube, pushes the warmed boil-off gas with a flow of 200 slpm through a commercial gas purification cartridge. In order to liquify it back and hence close the circuit, it is returned to the main detector vessel via a coil inside the bath of the purification column (3). In parallel to the gas purification the cryostat is equipped with a cryogenic LAr bellow pump. Due to this pump, located at the bottom of the purification column, a flux of LAr through the purification cartridge is generated. Here we have only discussed what is most relevant for the run being described in this work. A very detailed description of the cryogenic setup of the ArDM-Experiment can be found in the PhD thesis of L. Epprecht [69].

6.2 Operation of the detector

After closing and sealing the cryostat, it was evacuated during two months down to $10^{-5}$ mbar. To ensure the basic functionalities of the detector, interrupting the evacuation, the cryostat was filled with an argon-isobutane gas mixture at room temperature and an absolute pressure of Air-cooled Cryomech AL 30, Cryomech Inc., Syracuse, USA
6Typ N 0150.1.2 AN.12 E; KNF Neuberger AG, CH-8362 Balterswil, Switzerland
7MicroTorr MC4500; SAES Pure Gas, Inc., San Luis Obispo, California, USA
Figure 6.10: 3D CAD drawing of the setup: the $40 \times 76 \text{ cm}^2$ LEM TPC (1), the main detector vessel (2), the purification column (3), gas recirculation system (4) and the condenser with two cold heads (5).

of 1 bar. Following the successful verification of the detector operation in warm gas (pure argon and an argon-isobutane mixture), the cool-down procedure was initiated. Finally, after filling the cryostat with LAr, the LEM-TPC was operated during one month in double phase conditions. In this section we first discuss the argon-isobutane gas run, then the double phase operation of the detector is presented.

6.2.1 First operation with an Ar-isobutane gas mixture

The operation of this detector in gas at 1 bar and room temperature is fundamentally different from the operation in double phase conditions: since LAr is about 800 times denser than GAr at room temperature, minimum ionizing particles deposit less energy (2.1 MeV/cm in LAr, compared to 2.44 keV/cm in GAr [70]) and thus less charge per unit path length is produced. This loss of charge yield in GAr needs to be compensated with charge multiplication, performed by the LEM. While the maximum amplification factor in double phase mode was of $O(10)$, much higher gains can be reached with the three times less dense GAr at room temperature: as discussed in [71] and references therein, even small concentrations
of impurities from degassing quench ions and scintillation light enough to reduce secondary effects (photon and ion feedback) and thus increase the maximum achievable gain.

To test the functionality of the LEM and the 2D projective anode, starting from a vacuum of \(2 \cdot 10^{-5}\) mbar, we filled the detector with an Ar-isobutane (95%/5%) gas mixture. This is a standard gas mixture used for gaseous detectors. Since the light was fully quenched by isobutane, we had to use the internal channel by channel charge trigger of the CAEN acquisition board.

After first tests with very low voltages we increased all the fields, including the drift field, until we recorded first physical events. The final electric field configuration is summarized in Table 6.1:

### Table 6.1: Electric field configuration for the operation of the detector with an Ar-isobutane (95%/5%) gas mixture at 1 bar and 293 K.

<table>
<thead>
<tr>
<th>applied voltage</th>
<th>electric field</th>
</tr>
</thead>
<tbody>
<tr>
<td>anode</td>
<td>+1 kV</td>
</tr>
<tr>
<td>top LEM</td>
<td>+0.8 kV</td>
</tr>
<tr>
<td>bottom LEM</td>
<td>-0.46 kV</td>
</tr>
<tr>
<td>top grid</td>
<td>-0.7 kV</td>
</tr>
<tr>
<td>bottom grid</td>
<td>-0.8 kV</td>
</tr>
<tr>
<td>cathode</td>
<td>-3.8 kV</td>
</tr>
<tr>
<td>anode-LEM</td>
<td>1000 V/cm</td>
</tr>
<tr>
<td>LEM</td>
<td>12.6 kV/cm</td>
</tr>
<tr>
<td>grid-LEM</td>
<td>200 V/cm</td>
</tr>
<tr>
<td>extraction</td>
<td>100 V/cm</td>
</tr>
<tr>
<td>drift</td>
<td>50 V/cm</td>
</tr>
</tbody>
</table>

Table 6.1: electrons were drifted with a field of 50 V/cm towards the lower extraction grid, where the field was doubled in order to avoid the collection of charges on the grid. After another field increase at the level of the top extraction grid, the electrons were multiplied by the LEM and finally collected on the strips of the 2D projective anode. With the given fields we managed to record tracks, as shown in Figure 6.11. Since the LEM discharged with
a constant average rate of about 1/min, we decided not to increase the amplification further and stopped the run after a few hundred triggers. The event in Figure 6.11 shows a straight track, crossing the full 60 cm long drift volume \( v_d \approx 20 \, \text{mm/μs} \) at \( E = 50 \, \text{V/cm} \), simulated with Magboltz 8.4, [72] and references therein). Looking at all the collected events we could conclude, that the LEM segments as well as the anode readout strips were properly connected and functional. Moreover, a first test of the Greinacher circuit generating the drift field was performed.

6.2.2 Double phase operation

In order to reach impurity concentrations of \( O(1 \, \text{ppb}) \), needed to drift over 60 cm in LAr, the vessel was filled through the purification cartridge, which has already been used for the \( 10 \times 10 \, \text{cm}^2 \) setup (see description in [17]). After the adjustment of the LAr level by means of the four capacitive level meters, the detector was kept in these conditions for more than four weeks. Throughout this time, the system was in a thermodynamic equilibrium, with a stable detector gas pressure of \( \approx 1020 \, \text{mbar} \). In comparison with the \( 10 \times 10 \, \text{cm}^2 \) setup, this is about 50 mbar higher, hence higher amplification fields are required in order to achieve a comparable amplification.

After the commissioning of the cryogenics, the light readout and the Greinacher voltage multiplier (results published in [64]), the chamber was operated for the first time in double phase conditions. After commissioning the full LEM-TPC, we concluded that at fields above 32-33 kV/cm, sparks occurred regularly and a stable operation could not be sustained. Besides the performance tests of the double phase charge readout, we had to study the efficiency of the newly installed purification systems. Since the free electron lifetime could be precisely measured with the LEM-TPC, the chamber was operated during about three weeks for one hour per day. Minimizing the risk of a premature end of the run due to a damaged LEM, the amplification field was conservatively set to 31 kV/cm.

Table 6.2: Configuration of the best electric field configuration with the highest gain.

<table>
<thead>
<tr>
<th>applied voltage</th>
<th>electric field</th>
<th>field strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>anode</td>
<td>+1 kV induction</td>
<td>2 kV/cm</td>
</tr>
<tr>
<td>top LEM</td>
<td>+0.6 kV LEM</td>
<td>35 kV/cm</td>
</tr>
<tr>
<td>bottom LEM</td>
<td>-2.9 kV grid-LEM</td>
<td>0.6 kV/cm</td>
</tr>
<tr>
<td>grid (gas)</td>
<td>-3.62 kV extraction (liquid)</td>
<td>2 kV/cm</td>
</tr>
<tr>
<td>grid (liquid)</td>
<td>-6.12 kV drift</td>
<td>0.4 kV/cm</td>
</tr>
<tr>
<td>cathode</td>
<td>-30.12 kV</td>
<td></td>
</tr>
</tbody>
</table>

The other fields, summarized in Table 6.2, were optimized for transparency within the
allowed limits: the drift field, generated with the Greinacher voltage multiplier was set to 400 V/cm, corresponding to an input voltage of $V_{in} = 900 \text{ V}_{pp}$ and the extraction field was 2 kV/cm. The field between the top extraction grid and the LEM was 1.5 times higher than the drift field and the field between the LEM and the anode was maximized, keeping the absolute anode potential at $+1 \text{ kV}$. The virtual ground is in this configuration in between the top and bottom electrode of the LEM. We have decided not to exceed this limit in order to avoid too much stress on the decoupling capacitors, connecting the readout strips of the anode to the readout electronics (virtual ground).

As indicated in Table 6.2, towards the end of the operation, we managed to ramp the LEM field up to 35 kV/cm. Being the only run at such high fields, we recorded about 30'000 triggers before a breakdown occurred. Some of the best events from this run are shown in Figure 6.12: the first two are crossing cosmic muons, the third one is a hadronic interaction, releasing a large amount of energy inside the chamber and the last one is an electromagnetic shower candidate. Since the DAQ was triggered with the light readout, the known trigger time $T_0$ was subtracted in all the event displays. After another few days of operation at lower amplification fields, the run was stopped.
Figure 6.12: Cosmic ray events recorded in double phase conditions with a LEM field of 35 kV/cm. The four event displays show from top to bottom two muons, a hadronic interaction and an electromagnetic shower candidate. [See text for more details.]
6.3 Reconstruction of cosmic ray events

The reconstruction of crossing cosmic muon events, producing straight tracks, was described in Chapter 4. In this section we only give a brief overview of the basic steps in the reconstruction procedure, pointing out some detector specific nuances from the generic case. Due to the presence of coherent pick up noise, which could not be eliminated during the data taking, the events had to be first digitally filtered (see Section 4.3.1). This was done in two steps: first, the coherent noise filter, an algorithm to subtract common noise on all channels, second the FFT filter have been applied. Differently from the T32 beam test data from Chapter 5, only very dominant discrete frequencies were suppressed in the frequency space. Finally, the common subtraction of the pedestal value was performed. After the digital signal processing of the waveforms, straight muon tracks with δ-rays have been identified and reconstructed using the standard Hough-transform and δ-ray finding algorithms, which are both described.

Figure 6.13: Fully reconstructed cosmic ray event. Top: digitally filtered waveforms of all the readout channels for view 0 (left) and view 1 (right). Bottom: identified hits are shown in the drift time versus strip number plane. Identified through-going muon hits are shown in red; identified δ-ray hits, seen as attachments to the main track, are shown in green.
in Section 4.3.

An example of a single event is presented in Figures 6.13 and 6.14. Figure 6.13 shows on the top the filtered waveforms and at the bottom the identified through-going muon hits (red) as well as identified δ-ray hits (green). Finally, the three dimensionally reconstructed event can be seen in Figure 6.14. After reconstructing all the events from different runs we have required that the particle produces a straight track and that it crosses the anode. The resulting angular distribution of all accepted and reconstructed through-going tracks are presented in Figure 6.15. In the left histogram, which shows the polar angle \( \theta \) with respect to the \( z \)-axis (drift direction), it can be seen that almost vertical tracks along the drift field are not reconstructed (\( \theta \sim \pi \)). Obviously we have assumed that all particles travel downwards, i.e. \( \theta > \pi/2 \). The histogram on the right of Figure 6.15 shows the distribution of the azimuthal angle \( \phi \). The reconstruction efficiency drops when the \((x,y)\) projection of the track is parallel to one view, i.e. \( \phi \in \{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\} \).

The most relevant reconstructed variables that are used in the following sections are the hit integrals \( \Delta I \approx dI \) together with the three dimensional track length \( \Delta x \approx dx \). Finally, after applying the calibration of the readout electronics (see following section), the reconstructed charge per unit length \( dQ/dx \) of the through-going mips for both views (0 and 1) was used to study the performance of the readout.
6.4 Calibration of the readout electronics

As explained in Chapter 3, the integrals $dI$ of identified signals (hits) are proportional to the acquired charge, more precisely, the charge that is transferred from the detector into the feedback capacitor $C_f$ of the charge sensitive preamplifier. As a consequence, besides the preamplifier sensitivity also all the involved capacitances and the open loop gain of the preamplifier (version v0 was used for this test) have to be taken into account. Table 6.3 presents the values of all the capacitors: since the anode strip capacitances were not measured during the operation, a two dimensional finite element simulation\textsuperscript{8} was performed to compute the capacitances. The reason for the large strip capacitances of about 500 pF/m comes from the fact that the two views are only separated by a 50 $\mu$m thick insulation layer made of Kapton strips. View 1 has wider strips and thus the capacitance is larger. In addition, due to the $\pm 45^\circ$ orientation of the strips, the strip length and the capacitance varies. In Table 6.3 two problems can directly be seen: the anode strip capacitance $C_{strip,0}$ is of the order of the decoupling capacitance $C_{dec}$. Hence, only about half of the charge goes to the decoupling capacitor and to the readout electronics. The second problem is that due to the large cable capacitance and the small open loop gain of preamplifier version v0, the Miller capacitance

\begin{table}[h]
\centering
\begin{tabular}{ll}
\hline
wide anode strips, forming view 0: $C_{strip,0}$ & 26-272 pF (482 pF/m) \\
narrow anode strips, forming view 1: $C_{strip,1}$ & 34-351 pF (621 pF/m) \\
HV decoupling: $C_{dec}$ & 270 pF \\
cable: $C_{cable}$ & 353 pF \\
preamplifier v0: $(g + 1) \cdot C_f$ & 438 pF \\
\hline
\end{tabular}
\caption{List of detector and readout capacitances. The anode strip capacitances were calculated, all the others are measured.}
\end{table}

\textsuperscript{8}FEMM, www.femm.info/wiki/ HomePage
\[ \left( (g + 1) \cdot C_f \right) \text{ is of the order of the cable capacitance } C_{\text{cable}}, \text{ resulting in an additional charge loss of a factor two.} \]

\[ \frac{Q_f}{Q_{\text{strip}0,1}} = \frac{1}{1 + C_{\text{strip}0,1}/C'} \cdot \frac{1}{1 + C_{\text{cable}}/( (g + 1) \cdot C_f )}, \quad \text{where} \]

\[ \frac{1}{C'} = \frac{1}{C_{\text{dec}}} + \frac{1}{(g + 1)C_f + C_{\text{cable}}}. \]

Equation (6.1) shows the precise calculation of the measured charge \( Q_f \) with the only difference that the decoupling capacitance \( C_{\text{dec}} \) is replaced by the full readout capacitance \( C' \), consisting of the decoupling capacitance in series to the sum of the cable and the Miller capacitance of the preamplifier.

To illustrate the effect of the different strip lengths we have used the fact that charges, collected on a corner of the readout, produce different signals on the two views, since the strip lengths are maximally different. The left plot of Figure 6.16 shows the difference between the average signal integrals (not calibrated) of the two views at different positions \((x, y)\). While the charge readout in the central region, where the strips have the maximal length on both views, is symmetric, the expected asymmetries appear at the corners. The right plot of Figure 6.16 shows the measured charges after the calibration. To take the varying strip length into account, the capacitance was parametrized as a function of the view and the strip number. In addition to the capacitances listed in Table 6.3 we have used an average value for the preamplifier sensitivity of \( 10.7 \pm 0.3 \) mV/fC, as was measured with 32 preamplifiers of type v0 (see Chapter 3 and in particular Table 3.1). Due to the fact that we have not performed a calibration of each single charge sensitive preamplifier, sensitivity fluctuations of about 3% have to be taken into account (larger fluctuations could be possible if the preamplifiers were not produced in the same bunch).
6.5 Results

In this section a detailed response study of the $40 \times 76$ cm$^2$ large double phase Ar LEM-TPC is presented. We take the fair assumption that most of the cosmic rays are muons with an average momentum of about 4 GeV/c. Since $\delta$-rays of a few MeV are not taken into account in the $dE/dx$ reconstruction of the through-going muon tracks, we can further assume that the deposited energy loss per unit length approximates $dE/dx_{mip} = 2.1$ MeV/cm which is after electron-ion recombination equivalent to an ionization density of $dQ/dx \approx 10$ fC/cm.

After discussing the free electron lifetime and the readout efficiency of the charge readout sandwich, we report on the drift field uniformity, the free electron lifetime throughout the run and the achieved gain as well as the signal to noise ratio of the charge readout. Finally, a study of the reconstructed $\delta$-rays is presented.

6.5.1 Free electron lifetime measurements

As described in Section 6.1.5 the cryogenic system was equipped with two separate purification systems for liquid and gaseous argon. During the run period both systems have been operated, thus it was important to monitor the liquid argon purity. In order to measure the charge attenuation as a function of the drift time, we have used the reconstructed cosmic muon tracks. The data points in Figure 6.17 show the mean $dQ/dx$ values of all reconstructed muons for different drift times. Adding the average $\langle dQ(t_d)/dx \rangle$ for all 10 $\mu$s wide bins from both views together, the exponential function $e^{-t_d/\tau_e}$ with the free electron lifetime $\tau_e$ could
Figure 6.18: Evolution of the measured free electron lifetime during the data-taking period: in the first phase, the LAr-recirculation system has been commissioned, then the gas recirculation system was turned on, both without significant impact on the free electron lifetime. In the last phase, when the LAr recirculation was running at maximum speed, a steady increase was observed.

Since the electron lifetime was measured every day, the obtained data can be used to understand the efficiency of the purification systems. The plot in Figure 6.18 shows the lifetime evolution during the last three weeks of operation. Starting from a lifetime of about 170 $\mu$s we first did initial tests with the liquid recirculation. During this period the free electron lifetime remained constant. In a second phase, the gas recirculation was turned on. Due to changes in pressure and liquid argon level we did not acquire data with the double phase readout. However, after stopping the gas recirculation, the observed free electron lifetime was not significantly different. During the last phase we have finally operated the liquid argon recirculation system at its maximum speed. Since we saw a steady increase of the free electron lifetime until we stopped the run, we conclude that the liquid argon recirculation system was efficiently working. At the end of the data-taking, a free electron lifetime of 470 $\mu$s was reached. This corresponds to an oxygen equivalent impurity concentration of about 0.64 ppb.

6.5.2 Readout efficiency

In some runs, especially towards the end of the data-taking period when the purity was good and the LEM could be operated at high gains, most of the events contained tracks with missing segments. As a consequence of the $\pm 45^\circ$ orientation of the two views it was not a priori clear if this efficiency of the readout was persistent and confined to certain regions
6.5. RESULTS

Figure 6.19: Coordinates \((x,y)\) of reconstructed hits, belonging to a straight track. The left plot shows a fully efficient readout. On the right side the same plot is shown for the highest gain run. It can be seen that some regions have very low efficiency.

or whether it was changing with each event. Figure 6.19 shows the \((x,y)\) coordinates of all the hits from reconstructed tracks. While the left plot shows a fully efficient readout at the beginning of the run, in the right plot, representing the highest gain run at a LEM field of 35 kV/cm, large inefficient areas can be identified. Since these two runs were recorded at the beginning (left) and the end (right) of the data-taking period, all the runs in between had been analyzed as well in order to understand if something occurred in between the runs. After dedicated studies, presented in [73], we could conclude that the inefficient area was smoothly growing whenever the LAr purification was turned on. In fact it could be seen, that the readout recovered during the gas recirculation phase, in between the two LAr purification periods (see Figure 6.18). In addition, no dependence on the LEM fields was observed.

Presumably this effect comes from the wetting of the LEM, caused by the LAr recirculation system: since the exhaust of the purification circuit is just on top of the readout sandwich, the purified LAr drips on the readout sandwich, cooling it and favoring the condensation of argon on the LEM surface. Having a wet surface or even holes filled with LAr disables the amplifying capability of the LEM. This observation has already been made with the \(10 \times 10\) m\(^2\) prototype, as reported in [17].

6.5.3 Drift field uniformity

The sample of fully reconstructed crossing muon tracks could be used to investigate the uniformity of the applied drift field, as reported in a dedicated publication [64]. The method described here makes use of the fact that muons produce in average straight tracks of electron-ion pairs. Selecting straight tracks traversing the total height (60 cm) of the drift volume, the distribution of drift times \(\Delta N/\Delta t_d\) must be constant for a uniform drift field. Any deviation from a uniform distribution has to be caused by disturbances of the electric drift
Figure 6.20: Hit coordinates of reconstructed tracks. The selected tracks cross the full drift volume and do not have more than 8 missing hits due to the insensitive regions of the charge readout. Left: (x,y) scatter plot; right: (x,z) scatter plot.

field, generated by the Greinacher voltage multiplier.

Figure 6.20 shows on the left the (x,y) and on the right the (x,z) coordinates of the hits from tracks, passing the event selection. Taking all the events from the highest gain run at 35 kV/cm the first requirement was that none of the tracks crosses the inefficient readout area, as can be seen in the (x,y) plot on the left. In addition, shown in the right plot, the tracks had to cross the full drift volume from the cathode to the extraction.

Finally, the drift time distribution for all the hits from the 147 selected through-going muons is displayed in Figure 6.21. To study first order deviations from a constant field a straight line with offset $p_0 = 604 \pm 8$ and slope $p_1 = 0.09 \pm 0.03$ was fitted to the distribution. Since the number of entries $dN$ of each time bin $dt_d$ is proportional to the drift velocity $v(t_d)$, as derived in Equation (6.2) from [64], the histogram in Figure 6.21 can also be interpreted as drift velocity distribution $v(t_d)$:

$$
\frac{dN(t_d)}{dt_d} \propto \frac{dx}{dt} = \frac{dz}{dt} \propto v(t_d), \text{ with } \frac{dx}{dz} = \text{const.}
$$

(6.2)

It can be seen that the first bin is enhanced due to the high extraction field, causing an increased drift velocity. Using the measured average drift velocity of $\langle v \rangle = 1.39$ mm/µs at $E = 400$ V/cm and the obtained parameters $p_0$ and $p_1$ of the straight line fit, one gets for the drift velocity as a function of the drift time $t_d$

$$
v(t_d) = v_0 - at
$$

(6.3)

with $v_0 = 1.44 \pm 0.02$ mm/µs and $a = (2.1 \pm 0.7) \times 10^{-4}$ mm/µs². This means that the extrapolated drift velocity at the level of the cathode was 94% of $v_0$ at the level of the first field shaper. In terms of the electric field, using the standard function given in Chapter 4,
one obtains that the bottom field is about 10% smaller compared to the field at the top. As explained in more detail in reference [64], this effect is due to the shunt capacitance in the Greinacher circuit.

### 6.5.4 Gain and signal to noise ratio

After the determination of the free electron lifetime, the factor $e^{t_d/\tau_e}$ was used to correct for charge losses due to the electron attachment to impurities. This allows then to measure the effective gain and the signal to noise ratio obtained with the large area double phase readout. As explained in detail in reference [19], the effective gain $g_{\text{eff}}$ of the device is defined as the ratio of the measured charge collected on both views and the initially produced charge after recombination $\langle dQ/dx \rangle_{\text{mip}} \approx 10 \mu \text{C/cm}$:

$$g_{\text{eff}} := \frac{\langle dQ_0/dx \rangle + \langle dQ_1/dx \rangle}{\langle dQ/dx \rangle_{\text{mip}}}.$$  \hspace{1cm} (6.4)

This means, that this factor includes the intrinsic Townsend avalanche as well as losses at the liquid-gas interface, the top extraction grid or the LEM. Using the run with the highest amplification field of 35 kV/cm, Figure 6.22 first presents a study of the $dQ/dx$ that is proportional to the effective gain $g_{\text{eff}}$ as a function of the readout plane coordinate $(x,y)$ (left plot) and the time since the beginning of the run $t$ (right plot). Despite the limited statistics it can be seen in the left plot that there are no significant fluctuations, except in...
Figure 6.22: \( \langle dQ_0/dx \rangle \) from the highest gain run at a field of 35 kV/cm across the LEM. Left: \( \langle dQ_0/dx \rangle \) as function of the \((x, y)\) coordinate of the readout plane. Right: scatter plot of the \( dQ_0/dx \) values of all the hits as a function of the acquisition time from the start of the run, which was stopped by a voltage breakdown. The average values \( \langle dQ_0/dx \rangle \) are presented with red dots.

Figure 6.23: \( dQ/dx \) distribution for both views for selected straight tracks from a run with an amplification field of 35 kV/cm. A Landau function, convoluted with a Gaussian is fitted to the distributions.

non-efficient regions that have already been discussed in Section 6.5.2. Within the 30 min run at the highest gain, no time dependence is seen. The two plots in Figure 6.23 show the \( dQ/dx \) distributions for view 0 and view 1 from the run with the maximum amplification field of 35 kV/cm, superimposed with a fit of a Landau distribution convoluted with a Gaussian. Using Equation (6.4), an effective gain \( g_{eff} \approx 14 \) is computed.

Besides the effective gain it was important to verify, that the strips of each view collect the same amount of charge. We use again the measured \( dQ/dx \) distributions of both views to compute the asymmetry factor

\[
\frac{\langle dQ_1/dx \rangle - \langle dQ_0/dx \rangle}{\langle dQ_1/dx \rangle + \langle dQ_0/dx \rangle} \approx 7\%.
\]
6.5. RESULTS

Figure 6.24: Effective gain of the detector (left) and the corresponding obtained signal to noise ratios (right) for runs with different nominal amplification fields from 33 kV/cm to 35 kV/cm. Both data sets are superimposed with an exponential fit to guide the eye.

In addition to a high gain and a good sharing of the charge among the two views, we also measured an excellent signal to noise ratio of about 30. To compute this ratio, we used the lifetime corrected mean amplitude of cosmic muon induced signals divided by the average noise, defined as the average RMS value for all the readout channels.

Figure 6.24 finally shows the effective gain as a function of the applied electric fields across the LEM on the left and the corresponding signal to noise ratios on the right. The values of all the other fields, defined in Table 6.2, were kept constant.

6.5.5 Delta ray study

In order to demonstrate the tracking performance of the detector we have used reconstructed δ-rays from the run with the highest amplification field of 35 kV/cm. The number of reconstructed δ-rays \(dN\) per unit length \(dx\) from the cosmic data is presented in Figure 6.25 in dependence of the reconstructed kinetic energy \(T\). In order to estimate the kinetic energy of the δ-ray electron one can either reconstruct the track length or choose the calorimetric approach of summing the energy related to all the tagged δ-ray hits. The calorimetric approach was chosen since it does not require any tracking of the δ-ray hit. Therefore practically all δ-rays exiting from the main track are properly identified by the automatic event reconstruction. The drawback of the calorimetric approach is that the reconstructed energy is always underestimated, based on the fact that it is difficult to separate the initial part of the electron track from the main track.
CHAPTER 6. THE LARGE AREA DOUBLE PHASE LEM-TPC

Figure 6.25: The reconstructed energy of $\delta$-rays from the collected cosmic muon sample from the run with the maximal amplification field of 35 kV/cm, superimposed with MC generated muon events with a uniform momentum distribution between 1 and 10 GeV/c. The dashed line represents the theoretical behavior $d^2N/(dTdx) \propto T^{-2}$ at low kinetic energies [65]. [See text for more details.]

However, the MC simulation package with a VMC interface to Geant4, which was implemented in the context of the beam test, allowed to perform a consistency check. Using the reconstructed track angles from Figure 6.15 as well as the three dimensional coordinates at which the muons entered the detector, allowed to run a MC simulation with similar conditions. Since the energy of the triggered cosmic rays as well as the trigger efficiency is unknown, we generated muons with a uniform momentum distribution between 1 and 10 GeV/c (the initial cosmic muon spectrum at ground is flat below 1 GeV and decreases gradually towards higher energies [22]). Due to the fact that the in-active area (see Section 6.5.2), which was to one part due to the wetting and to another part due to the segmentation of the LEM and the spacers, had an influence on the reconstructed $\delta$-ray statistics, a similar mask has been used for the simulation. The final result of the reconstructed MC $\delta$-rays statistics (red line) is shown in Figure 6.25, superimposed with the cosmic data (black dots with errors). Good agreement between the MC and the recorded cosmic data is seen above 3 MeV. At lower energies the reconstruction efficiency of the MC generated events is slightly underestimated. Low energy $\delta$-rays can due to the short range not be identified with the used reconstruction algorithm. The expected reconstruction efficiency drop below $\sim$ 5 MeV is visualized by the dashed line, representing the theoretical behavior $d^2N/(dTdx) \propto T^{-2}$ at low kinetic energies (the complete formula is given in Equation (2.4)).
Chapter 7

Conclusions

After the proof of principle of a small scale prototype [19] the main focus of this thesis was on the development towards large area double phase readout systems.

An important requirement for the successful operation of new prototypes was the careful design of a charge sensitive preamplifier. We have adapted an existing layout to the needs of the LAr (LEM-) TPC, taking into account the small charges to be measured with large detector capacitances as well as the occasional occurrence of voltage breakdowns. The final preamplifier version worked with the expected performance, independently on the detector capacitance. Besides the charge sensitive preamplifiers we have also developed a complete data acquisition system that was used to acquire data from different detectors.

The first prototype that is described in this thesis is a 120 L single phase LAr TPC with a single and very coarse charge readout plane having a pitch of 1 cm. In view of future beam tests with large LAr LEM-TPC, addressing the detector performance, the first step was to demonstrate that the detector can be remotely operated in a beam test environment. We have operated the detector in a low momentum charged particle beam at the J-PARC slow extraction facility. Due to the sophisticated beamline instrumentation we could efficiently tag different particle types. Despite a relatively poor signal to noise ratio of $< 10$ for mips, which could not be improved during the run-time, it was possible to reconstruct through-going pions as well as the stopping power of protons and kaons. The missing second readout plane and the coarse readout pitch made a detailed MC simulation necessary. Implementing realistic noise and a non-uniform electric field led to a very good agreement with the reconstructed data, therefore validating the MC simulation. The most important result of this test is that the commonly used Birks’ model [30] to describe electron-ion recombination could be confirmed for stopping kaons and protons.

The final part of the thesis is devoted to the development and first test of a large area double phase readout system. Since large areas can be covered by independent charge readout units, we have directly designed and built a so called charge readout sandwich, which fully embeds two extraction grids, the LEM, the 2D anode as well as the HV and the signal.
distribution planes. Being the readout of a new 200 L double phase LAr LEM-TPC, it was
operated during more than 4 weeks in the cryostat of the ArDM experiment under cosmic ray
exposure. Recorded straight tracks with $\delta$-rays were reconstructed and allowed to precisely
study the response of the detector. Besides a measurement of the purity evolution throughout
the run, we have also measured the field uniformity and we demonstrated that also large area
devices can reach a significant gain $> 10$.

To summarize, we have fully described the response of 200 L scale prototypes exposed to
beam particles and cosmic rays. We have demonstrated the operation of a LAr TPC in a
beam test and most importantly we have proven that significant charge gains can be reached,
not only with small $10 \times 10$ cm$^2$ prototypes [19], but also for larger area devices [64, 65].
This is considered to be an important step towards the development of next generation giant
double phase LAr LEM-TPCs.
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