Modeling, design and first operation of the novel double phase LAr LEM-TPC detector

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Abstract

Liquid argon Time Projection Chambers (TPCs) are dense, fine grained, fully homogeneous particle detectors with excellent calorimetric and three-dimensional imaging capabilities. The fact that this technology allows to build massive detectors, from the ton to the many kton scale, depending on the application, makes it attractive for neutrino physics, proton decay and direct Dark Matter searches.

The amplification of the ionization charge produced in liquid argon improves the performance of a liquid argon TPC, giving a larger signal to noise ratio and, as a consequence, a lower energy threshold. This amplification can be achieved extracting the ionization electrons from the liquid into the vapor phase, and multiplying them using a Large Electron Multiplier (LEM). This new kind of Time Projection Chamber is called double phase argon LEM-TPC and represents the main topic of this work. The goal of the thesis is to understand if the double phase argon LEM-TPC is a valid concept, to estimate its performance and to identify possible problems.

The LEM is a metal cladded epoxy plate (PCB), with a thickness of about a millimeter and with mechanically drilled holes. Typically, these holes have diameters of less than a millimeter, and there are order of 100 holes per cm$^2$ of LEM. The ionization charge (electrons) drifts in liquid argon from the interaction point towards the liquid-vapor interface under the action of a uniform electric field. The electrons are then extracted into the vapor by means of an electric field applied across the liquid surface using two grids at different potentials (one in liquid and one in gas). The electrons are focalized into the holes of the LEM, where the electric field is high enough to produce charge multiplication via Townsend avalanche. Finally, the electrons induce signals on a two views anode, which has the electrodes segmented into strips along two orthogonal directions and, therefore, gives the position of the ionizing event projected onto the anode plane. The third coordinate is given by the drift time multiplied by the electron drift velocity.

In this thesis we present the modeling, the design, the construction and the operation of a prototype of a double phase argon LEM-TPC with an active volume up to 3 L and with a LEM area of $10 \times 10$ cm$^2$. This is the first detector of this kind to be fully operational. We describe the framework used to model and design the charge amplification and readout system, give a detailed description of the experimental setup, and analyze the data acquired in the exposure
of the detector to cosmic ray muons. This measurement campaign has allowed to benchmark the detector performance and to fix the design parameters of the charge readout system. The maximum effective amplification obtained in stable condition was about 30, that corresponds to a signal to noise ratio for minimum ionizing particles of more than 200.

The experience gained during the extensive R&D campaign on the 3 L detector allowed to design and construct a larger double phase argon LEM-TPC with an active area of $40 \times 80$ cm$^2$, which was successfully operated in 2011. Here we report the first results of a test with cosmic ray muons.
Riassunto

La Camera a Proiezione Temporale (TPC) ad argon liquido è un rivelatore di particelle di alta densità, grande granularità e completamente omogeneo, in grado di fornire la struttura tridimensionale di un evento ionizzante e di misurare l’energia depositata. Il fatto che questa tecnologia permetta di costruire rivelatori di grande massa, da una tonnellata su fino a molte migliaia di tonnellate, la rende attraente per esperimenti di neutrino, decadimento del protone e di ricerca diretta di materia oscura.

L’amplificazione della carica di ionizzazione prodotta in argon liquido migliora le prestazioni di questo rivelatore, aumentando il segnale rispetto al rumore e, di conseguenza, abbassando la soglia energetica di rivelazione. Per ottenere ciò è possibile estrarre gli elettroni di ionizzazione dalla fase liquida a quella gassosa e moltiplicarli in un Large Electron Multiplier (LEM). Questo nuovo tipo di Camera a Proiezione Temporale è noto come LEM-TPC ad argon a doppia fase e rappresenta l’argomento principale di questo lavoro. Lo scopo della tesi è quello di capire se il concetto del LEM-TPC ad argon a doppia fase è valido, di valutarne le prestazione e di identificare eventuali problemi.

La LEM è una lastra di resina epossidica (PCB) metallizzata, con uno spessore di circa un millimetro e forata meccanicamente. Questi buchi hanno un diametro tipico inferiore al millimetro e ci sono più di 100 buchi per cm$^2$ di LEM. La carica di ionizzazione (elettroni) deriva in argon liquido dal punto di interazione verso la superficie grazie all’azione di un campo elettrico uniforme. Gli elettroni sono poi estratti dal liquido al vapore da un campo elettrico perpendicolare alla superficie del liquido, generato da due griglie a potenziali differenti, una in liquido e l’altra in gas. Gli elettroni sono focalizzati nei buchi del LEM, dove vengono moltiplicati in presenza di un campo elettrico abbastanza intenso da causare la valanga di Townsend. Infine gli elettroni inducono impulsi di corrente sull’anodo, che ha l’elettrodo segmentato in strisce lungo due direzioni ortogonalì in modo da fornire la posizione dell’evento ionizzante proiettata sul piano dell’anodo. La terza coordinata è data dal prodotto del tempo di deriva per la velocità degli elettroni.

In questo lavoro presentiamo la modellizzazione, la progettazione, la costruzione e il funzionamento di un prototipo di LEM-TPC ad argon a doppia fase con un volume attivo di 3 L e con una LEM di $10\times10$ cm$^2$. Questo è il primo rivelatore di questo tipo completamente funzionante. Nella discussione trattiamo il modello con il quale il sistema di
lettura e amplificazione della carica è stato modellizzato e studiato, diamo una descrizione dettagliata dell’allestimento dell’esperimento e presentiamo i risultati di esperimenti con il rivelatore esposto ai muoni cosmici. L’interpretazione dei dati è servita a valutare la risposta del rivelatore e a definire i parametri di progettazione del sistema di lettura della carica. Il massimo guadagno raggiunto in condizioni stabili è stato di circa 30. Questo corrisponde ad un rapporto segnale/rumore per particelle al minimo di ionizzazione di più di 200.

L’esperienza maturata durante l’approfondito programma di Ricerca e Sviluppo sul rivelatore da 3 L ha permesso di progettare e costruire una LEM-TPC ad argon a doppia fase più grande con una superficie di 40×80 cm², che ha ben funzionato nel 2011. Qui si riportano i primi risultati di un test con i muoni cosmici.
Acknowledgement

All my gratitude goes to Prof. André Rubbia, who gave me the opportunity to join an extremely stimulating project. Under his supervision and guidance I have gained a lot of experience and knowledge in experimental particle physics and particle detectors. His observations were always food for thought and most insightful. I would like to thank Dr. Alberto Marchionni for investing time and effort to introduce me to experimental physics and for always being willing to help and steer me. I am very thankful to Dr. Alessandro Curioni for the keen and deep discussions we had and for supporting me during the drafting of the thesis. It was a pleasure to work with Dr. Sosuke Horikawa. From him I learned a methodical and scrupulous approach to experimental work. I am very grateful to Dr. Andreas Badertscher, who carefully read and corrected my thesis, suggesting improvements in both form and content. I have received invaluable technical help from Thierry Viant, Gustav Natterer, Adamo Gendotti and Leo Knecht. I would like to thank them, because their experience shortened and eased the solution of many problems that I encountered during my work. I thank Rui De Oliveira and his colleagues of the CERN TS/DEM workshop for sharing their expertise and competence in PCB manufacturing. An enormous thank is to Rosa Bächli and Rita Vonesch, who always efficiently took care of all the administrative formalities and overcame the issues my distraction used to create. I thank all my colleagues with whom I joined the efforts in different situations, in particular Ursina Degunda, Claudia Lazzaro, Lukas Epprecht, Vittorio Boccone, Luigi Esposito, Ulisse Gendotti, Silvestro Di Luise, Khoi Nguyen, Polina Otyugova, Federico Petrolo, Biagio Rossi and Claudia Strabel. They have enriched my passed four years with new experiences and delightful moments. Special thanks go also to Devis Lussi, whom I have most closely worked with. With him I shared the problems, the failures and the successes.
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Chapter 1

Introduction

The Standard Model [1] of particle physics is the theoretical framework where the electromagnetic, the weak and the strong interactions are quantitatively treated. The theoretical ideas behind the model were developed by several people over several years and finalized in the actual form by Glashow, Salam and Weinberg in the 1960s. The Standard Model is a gauge theory (theory invariant under a set of local transformations) with the symmetry group $\text{U}(1) \times \text{SU}(2) \times \text{SU}(3)$. The generators of the symmetries are called weak hypercharge for U(1), weak isospin for SU(2) and color charge for SU(3).

In terms of fundamental particles constituting the matter, the model comprises twelve fermions of spin 1/2, namely six quarks, arranged in doublets (u, d), (c, s) and (t, b), that undergo all the three interactions, three charged leptons ($e$, $\mu$, $\tau$) that undergo electromagnetic and weak interactions, and three neutral leptons, the neutrinos with flavors ($\nu_e$, $\nu_\mu$, $\nu_\tau$) in analogy to the charged leptons, that feel only the weak force. In the Standard Model, the forces are mediated by spin 1 particles, the so called gauge bosons, namely the photon (massless) for the electromagnetic force, the $W^+$, $W^-$ and the $Z$ (all massive) for the weak force, and eight gluons (massless) for the strong force. Finally, there is the spin 0 Higgs boson, a massive particle that interacts with all the massive particles. It is the only particle of the Standard Model not yet experimentally observed\(^1\).

The chirality is a well defined property that coincides with the helicity (direction of the spin with respect to the particle motion) in the case of massless particles\(^2\). The SU(2) charge is carried only by the left-handed chirality components of the fermions and by the right-handed chirality component of the anti-fermions. In the Standard Model, the right-handed neutrinos and the left-handed anti-neutrinos do not exist. Since the mass term mixes the positive and negative chirality components of the fermions, the neutrinos are massless in the

\(^1\)Currently, experiments searching for the Higgs boson are being performed with the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN).

\(^2\)In case of a massive particle, it always exists a reference frame where the particle motion is reversed. This inverts the helicity that, for this reason, cannot be considered a good quantum number, whereas the chirality is conserved.
Standard Model.

Though the Standard Model is a very successful theory, able to explain a large variety of phenomena with an extraordinary precision, it has some limitations in explaining some experimental observations, like the existence of Dark Matter and the phenomenon of neutrino oscillations. In the Standard Model there is no particle that can be regarded as responsible for the Dark Matter and, since the neutrinos are considered massless, the neutrino oscillations are not described.

In this work the development of a novel detector technology suitable for direct Dark Matter search experiments and future neutrino detectors is described.

1.1 Dark Matter and massive neutrinos

What follows in the next paragraphs is not intended to be a complete and exhaustive review on Dark Matter and massive neutrinos, but just a brief introduction. Detailed and comprehensive reviews on Dark Matter\(^3\) and neutrino physics\(^4\) can be found in [2].

1.1.1 Dark Matter

The ordinary matter alone does not explain the observation of the dynamic of galaxies and galaxy clusters. For instance, the rotation speed \(v\) of the hydrogen gas around the galaxies can be measured with the Doppler effect of the 21 cm line of the hydrogen atom. In an equilibrium state, the centripetal acceleration, proportional to the square of the linear speed, must be equal to the gravitational acceleration. Assuming that the mass distribution in the galaxy is proportional to its luminosity, the rotation speed at a distance \(r\) larger than the galaxy radius should asymptotically approach zero as \(v \propto 1/\sqrt{r}\), while the observations show that the speed stays rather constant\(^5\). This behavior can be explained assuming that, far from the galaxy radius, the mass contained in a sphere of radius \(r\) is proportional to \(r\), or, equivalently, that the mass density is proportional \(r^{-2}\). This implies the existence of invisible (dark) matter pervading the galaxy and a large halo around the galaxy.

Another evidence for the existence of Dark Matter comes from the weak gravitational lensing. The image of background galaxies appears deformed due to the presence of matter between the background and the observer, i.e. the light from background sources is bent by the foreground mass according to the general theory of relativity. The statistical analysis of the images provides an estimation of the mass in the foreground, that turns out to be larger than expected counting only the luminous matter.

Due to the mutual gravitational attraction, the Dark Matter and the luminous matter usually are together. There are notable exceptions, e.g. the Bullet Cluster. It is interpreted as

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\(^5\)The anomalous rotation speed is observed in the Milky Way too.
two galaxy clusters colliding. The gases, observed from the emitted X-rays, gather in between the two clusters of galaxies, while the stars and the non-luminous matter, indirectly seen with gravitational lensing, are well separated. This is explained as follows: the intergalactic gas, that constitutes most of the baryonic matter, interacts electromagnetically, and it slows down increasing its temperature. The stars in the two clusters cross each other without being affected, since they interact only gravitationally. Finally, the total mass distribution, evaluated with gravitational lensing, is found to be well separated, in the same location as the star distribution. This is interpreted as Dark Matter that, reluctant to interact, passed through each other similarly to the stars.

Another evidence of the existence of Dark Matter comes from the Cosmic Microwave Background (CMB), the relic radiation left after the photon decoupling. It has an average temperature of 2.73 K (0.235 meV) and temperature anisotropies at the $10^{-5}$ level. These anisotropies are believed to be caused by perturbations in density at the time of the photon decoupling. The contribution to the anisotropies from baryonic and non-baryonic matter can be decoupled, since only baryonic matter interacts with photons. The evaluation is that about 80% of the matter is non-baryonic.

The formation of large scale structures in the Universe suggests that the non-baryonic matter should be non-relativistic, hence excluding the standard neutrinos. Candidates are for instance sterile massive neutrinos, axions and Weakly Interacting Massive Particles (WIMPs). Focusing on the latter, in supersymmetric extensions of the Standard Model the Lightest Supersymmetric Particle (LSP) is the best motivated theoretical candidate.

The WIMPs are expected to be gathered in gravitation potential wells. The WIMP halo around the galaxy behaves like a gas of particle in thermal equilibrium and at rest with respect to the center of the galaxy. The Earth is crossing the WIMP halo at about 245 km/s with an annual modulation of ±15 km/s given by the rotation around the Sun. The signature of the interaction of a WIMP with ordinary matter is the recoil of a target nucleus due to an elastic collision [3]. The recoil energy spectrum is featureless, and it can be described by an exponential with a negative slope that depends on the mass of the WIMP and on the target nucleus. WIMP masses in the range of 10–1000 GeV/c$^2$ would give rise to nuclear recoils of energies in the range of 1–100 keV.

1.1.2 Massive neutrinos

The neutrino was introduced as very light and neutral (almost non-interacting and, therefore, almost undetectable) particle to solve the apparent energy and angular momentum non-conservation in $\beta$ decays. As already mentioned, in the Standard Model the neutrinos are massless, but their mass can be accommodated introducing a right-handed neutrino (SU(2)}

\[\text{\footnotesize 6The Bullet Cluster is not the sole example of such a phenomenon.} \]

\[\text{\footnotesize 7Dark Matter may interact gravitationally and weakly as well, without changing its behavior in this circumstance.} \]
singlet and, therefore, sterile), as it is for all the other Dirac fermions, and this kind of mass is called Dirac mass. If the right-handed component is identified with the antiparticle of the left-handed neutrino, one can introduce another mass term called Majorana mass term. Within the particle content of the Standard Model, the only fermion that can have a Majorana mass is the neutrino, since it is the only one that has no electric and color charges. The Dirac and Majorana mass terms are not mutual exclusive. They can co-exist and merge giving rise to the so called See-Saw mechanism that tries to justify why the neutrinos are much lighter than the other fermions.

Neutrino masses were introduced as an explanation of the strong experimental evidences for neutrino flavor oscillations: when propagating, the neutrinos can change their flavor ($\nu_e$, $\nu_\mu$, and $\nu_\tau$) with a periodical probability along the flight. The neutrinos are produced in a well defined flavor state. However, the flavor states can be different from the mass eigenstates, i.e. they can be expressed as a linear combination of the mass eigenstates. The mixing matrix, analogous to the Cabibbo-Kobayashi-Maskawa (CKM) matrix for the quarks, is known as Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. It is a $3 \times 3$ complex matrix with three angles and one phase, in the case of Dirac neutrinos, or three angles and three phases, in the case of Majorana neutrinos. The Dirac phase $\delta$, if different from zero, is responsible for the CP violation in the leptonic sector, similarly to the CKM phase in the quark sector.

As already mentioned, the neutrinos are generated in a well defined flavor, but the states that freely propagate are the mass eigenstates. This leads to a phase shift between the mass eigenstates during the free flight. In the simplified model of only two flavors ($\nu_\alpha$ and $\nu_\beta$), the probability that a neutrino $\nu_\alpha$ of energy $E$ after traveling a distance $L$ is detected as neutrino $\nu_\beta$ depends on $L/E$ as:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right),$$

where $\Delta m^2$ is the difference of the square of the masses (mass eigenvalues), and $\theta$ is the (in this case only) mixing angle. The mixing angle defines the probability amplitude, and the mass difference defines the oscillation frequency.

The determination of these parameters follows from the measurement of the oscillation probability, that is complicated by the fact that neutrinos are elusive particles. The presently known parameters are $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$ (recently measured to be different from zero [4]), and the absolute values of $\Delta m^2_{21}$ and $\Delta m^2_{32}$ ($\approx \Delta m^2_{31}$). Still to be addressed are the absolute mass scale, the sign of $\Delta m^2_{32}$ (normal or inverted hierarchy), the mass nature (Dirac and Majorana) and the CP violating phase(s).

The CP violating phase $\delta$ appears in the PMNS matrix multiplied by $\sin(\theta_{13})$. The mixing angle $\theta_{13}$ can be studied, for instance, from the oscillation of $\nu_\mu$ to $\nu_e$ in appearance mode [5], in particular detecting $\nu_e$ from a $\nu_\mu$ beam.

\footnote{This result is very recent, and it is not included in the review [2].}
1.2 Detectors for Dark Matter and neutrinos

In order to increase the chance to detect rare events such as neutrino interactions and Dark Matter recoils, the ideal device should be massive and, in order to restrain the dimensions, dense. Since the events are usually few, the detector must be able to effectively discriminate the background on an event-by-event base, a task that is simplified if the event topology can be visualized, and the particle involved can be identified.

The detector that embodies all these characteristics is the liquid argon Time Projection Chamber (TPC). Liquid argon is a suitable target and active medium for a particle detector: it is an excellent scintillator, and the ionization electrons are free to drift in ultra pure liquid argon. In the following, we briefly describe the TPC principle and its applications with liquified noble gases as neutrino and Dark Matter detectors.

1.2.1 The Time Projection Chamber

The Time Projection Chamber (TPC) was invented by David Nygren [6] in 1974. The operation principle is shown in Figure 1.1. A uniform electric field is applied in a volume filled with gas, such that free charges can drift macroscopic distances along the field lines. An ionizing particle crossing a portion of the active volume creates electron-ion pairs along its path. Electrons and ions are separated by the electric field, and they move in opposite direction. During the drift, the electron distribution moves rigidly, leaving its shape essentially unaltered. When the electrons are in the vicinity of the anode, where they are finally collected, they induce current pulses. The electrons are usually multiplied in gas near the anode in order to increase the signal amplitude. When the anode is segmented, the position of the electrode gives the event coordinate projected onto the plane of the anode, and the drift coordinate is proportional to the drift time. The ionization density is proportional to the particle energy loss per unit path, and this gives information on the nature of the particle. In other terms, this technology is capable of three-dimensional imaging and particle identification. Gas filled TPCs, usually immersed in a magnetic field to measure the particle momentum from the curvature of the track, are used as tracking device where a small material budget is needed, e.g. tracker detectors in collider or fixed target experiments.

1.2.2 The liquid argon ionization chamber

Liquid argon ionization chambers exploit the fact that in pure liquid argon the electrons are free to drift under the action of an external electric field. The charge freed by an ionizing particle is proportional to the particle energy released in argon. Two electrodes, the anode and the cathode, delimit a gap filled with liquid argon, and the ionization electrons, moving towards the anode, induce the signal.

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9Except for the smearing due to the electron diffusion, that can be mitigated introducing a magnetic field parallel to the drift direction.
Figure 1.1: Schematic representation of the Time Projection Chamber (TPC) operation principle.

In order to increase the deposited energy (and consequently the charge involved), several anode and cathode electrodes can be alternated in series. The metal of the electrodes, denser than the liquid argon, serves both to slow down the charged particles and to convert the neutral particles (neutron and photons) into charged (and therefore detectable) particles. In this way, the incoming particle stops inside the detector (possibly generating an electromagnetic or hadronic shower), allowing the measurement of its energy. This detector is a sampling calorimeter based on liquid argon as active medium, and it was proposed by Willis and Radeka [7] in 1974. In the same context, low noise preamplifiers suited for this kind of applications were also developed.

1.2.3 The liquid argon TPC and its applications

The idea of replacing the gas in a TPC with liquid argon was proposed in 1977 by Carlo Rubbia [8]. In Tables 1.1 and 1.2 we list the present experiments and the future or proposed experiments based on liquified noble gas TPCs. The liquid argon TPC is the merging of the liquid argon ionization chamber with the TPC technology. It can be thought as an electronic bubble chamber, in analogy to the tracking and particle identification capabilities in a dense medium of the bubble chamber. Moreover, it is an excellent calorimeter for events contained in the active volume.

The liquid argon TPC offers a dense, sensitive and uniform target, and it provides the complete three-dimensional topology of the event, the particle identification from the dE/dx
evaluation and a very good energy resolution. This makes it an ideal detector for neutrino physics: good imaging capabilities are the key point of the background discrimination. For instance, the signature of appearance of $\nu_e$ from a purely $\nu_\mu$ beam is an energetic electron created through a charged current interaction. An important source of background is the neutral current interaction of a $\nu_\mu$ that produces a $\pi^0$ immediately decaying into two boosted photons, that may emulate the electromagnetic shower of the electron. This two kind of events can be discriminated with the reconstruction the event topology and the identification of the particles involved.

The low electron diffusion in liquid argon allows the charge distribution to remain effectively unchanged even when the electrons drift for meters. The largest ever built liquid argon TPC is the ICARUS detector [9], with an active mass of about 500 tons, presently in operation at Laboratori Nazionali del Gran Sasso (LNGS). It operates in single phase mode (to differentiate it from the double phase mode TPCs, see later in the text) without charge amplification, that leads to a signal to noise ratio of the order 10 for minimum ionizing particles. The physics program of ICARUS is mainly the study of the atmospheric neutrinos, the neutrinos from Supernova explosions, and the neutrino oscillations using the CNGS neutrino beam from CERN. An extensive R&D program was needed in the fields of the purification of the liquid argon, the high voltage systems, the charge sensitive low noise electronics, the cryogenics, the safety and other aspects. ICARUS is the result of such a development program, that is still ongoing.

Liquid argon TPCs are also suited for direct Dark Matter searches. Liquid argon provides good self-shielding, and excellent background ($\beta$, $\gamma$ and X-ray events) discrimination can be obtained from the time distribution of scintillation photons and from the ionization charge to the scintillation light ratio. The ionization charge involved in the interesting events is very small, and some sort of signal amplification is required. This can be achieved in the vapor, extracting the electrons from the liquid phase. The double phase TPC concept can be extended to other noble gases, such as xenon (see Table 1.1). The charge is usually readout detecting the proportional secondary scintillation light that is produced by the electrons drifting in the high electric field in the vapor, after their extraction from the liquid. The achievable spatial resolution strongly depends on the dimension of the light sensitive devices. This introduces a tradeoff between the imaging capability, the dimensions and the cost of the detector.

The further evolution of the liquid argon TPC concerns the amplification of the charge and its direct readout. It extends the TPC tracking and imaging capabilities to lower energy thresholds, and this can be achieved using a charge amplification device in gas: the Large Electron Multiplier (LEM). This novel detector, the double phase argon LEM-TPC, provides several advantages:

1. It improves the signal to noise ratio, easing the three-dimensional track reconstruction and the calorimetry of the events.
Table 1.1: Summary of the actual experiments exploiting the liquified noble gas TPC.

<table>
<thead>
<tr>
<th></th>
<th>target</th>
<th>mass</th>
<th>physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 L [10]</td>
<td>argon</td>
<td>65 kg</td>
<td>neutrino cross sections</td>
</tr>
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2. The signal degradation due to charge losses and diffusion in long drift paths can be recovered.

3. Particle tracks below threshold (for instance, soft photons from *bremsstrahlung* in electromagnetic showers or nuclear recoils) in standard liquid argon TPCs can be detected, improving the overall energy resolution.

4. Resolve the spatial separation of tiny signals improves the rejection of the background due to neutrons in direct Dark Matter search experiments.

ArDM [18], a direct Dark Matter search experiment in the Laboratorio Subterráneo de Canfranc (LSC), is pioneering the double phase argon LEM-TPC idea, that has also been proposed for GLACIER [24], a future neutrino and proton decay experiment. Difficulties in the development of this novel technology arise, for instance, from the cryogenic environment (choice of the materials), and from the fact that no quenching gas is diluted in the argon (discharges are favored). The design, the construction and the operation of a first prototype
1.3 Structure of the thesis

In Chapter 2 we review the argon as a target, focussing on the characteristics relevant for the experimental work and the interpretation of the acquired data. In particular, we concentrate on the charged particle and photon interactions in liquid argon, on the production of scintillation photons and electron-ion pairs, and on the transport properties of electrons in argon gas, in liquid argon and at the liquid-vapor interface.

The processes involved in charge avalanches in gas, including the Townsend avalanche, secondary effects and discharge mechanisms, are described in Chapter 3. They are at the base of the signal amplification technique exploited, and they demand a clear understanding.

In Chapter 4 we face the problem of combining the liquid argon TPC with the technology of the charge amplification in gas. We develop a simulation able to compute the formation and the propagation of sparks in gas. With the same formalism we optimize the design of the LEM (charge amplification device), the two views anode (two dimensional signal readout) and the extraction grids (to extract the ionization electrons from the liquid into the vapor).

In Chapter 5 we present the setup where a double phase argon LEM-TPC with fiducial volume up to 3 L was implemented. We describe in details the cryogenics, the argon purification tools, the electronics and the detector, trying to underline the issues and the reasons of the choices made.

The results of measurements in gas and double phase argon with the detector exposed to cosmic muons and radioactive sources are reported in Chapter 6. These results follow an extensive development of the design of the charge readout, of the hardware related to the detector and of the auxiliary components needed to operate it properly. With the help of the informations reported in Chapters 2 and 3, we fully characterize the performance of the
device and demonstrate that we understand its behavior.

In Chapter 7 we point out what, to our view, are the possible improvements of the double phase LEM-TPC in terms of maximum achievable gain and active surface coverage. We describe a bigger double phase argon LEM-TPC designed and constructed following the development of the 3 L detector. We show cosmic ray events from the first operation of such a detector, while its detailed characterization is beyond the scope of this work.
Chapter 2

Liquid argon as target

The choice of liquid argon as active medium is suggested by a series of interesting properties. Liquid argon is easy to deal with, it is equivalent to the liquid nitrogen in terms of cryogenic. It is cheap, in fact it constitutes about 1% of the atmosphere from where it is extracted. Its density is 1.4 g/cm$^3$, this means that crossing particles deposit significant energy and rare interactions are more likely to happen. At the passage of a charged particle it scintillates, it gets ionized, and the freed charge is not immediately reabsorbed. It is chemically inactive, most of the impurities can easily be filtered out to levels better than the part-per-billion. It has a large dielectric rigidity, that eases the use of high voltage.

In Table 2.1 some of the most relevant quantities and properties of the argon are summarized. The argon phase diagram is shown in the plot on the left of Figure 2.1. In the right plot the spectrum of the $\beta$ particles emitted from the decay of $^{39}$Ar is shown. In fact, traces of long-lived radioactive isotopes are present in natural argon, namely $^{39}$Ar and $^{42}$Ar. They both decay through $\beta^-$ emission with endpoint of 600 keV and half life of 32.9 years for the $^{42}$Ar, and 565 keV and 269 years for the $^{39}$Ar [25]. The $^{39}$Ar activity is measured to be 1 Bq per kg of natural argon [26].

2.1 Energy loss of particles in matter

The following section is a brief summary of the processes involved in particle interactions with matter. Complete reviews can be found in [2, 27]. The focus is on the photon and muon interactions with argon, since these aspects are widely used in the following chapters.

2.1.1 Charged particle interactions

A moderately relativistic charged particle heavier than the electron loses its energy traversing a medium mainly in collisions against the electrons of the atoms. The collisions are frequent, and a small amount of energy is generally transferred to a single electron, this makes the energy loss to appear continuous. The atoms are excited and ionized if the energy transferred
is larger than the electron binding energy. The average energy loss per unit thickness of material (normalized to its density) $-dE/dx$, also known as stopping power, is described by the Bethe equation [2]:

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

valid in the range $0.1 \lesssim \beta \gamma \lesssim 10^3$. Here $\beta$ is the velocity of the incident particle normalized to the speed of light ($c$), $\gamma$ is the associated Lorentz factor, $z$ (defined positive) is the charge of the incident particle in units of the electron charge, $K = 0.1535$ MeV g/cm², $Z$ and $A$ are the atomic number and the atomic mass of the absorber, $m_e = 511$ keV/c² is the mass of the electron, $T_{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1+2m_e c^2/M+(m_e c^2/M)^2}c$ is the maximum energy that can be transferred to a free electron in a single collision by the incident particle of mass $M$, $I$ is the mean excitation energy of the absorber (188 eV for argon) and $\delta(\beta \gamma)$ is the density effect correction (see later in the text).

In general, the stopping power is larger for lower velocities of the incident particles. It reaches a minimum around $\beta \gamma \approx 3 - 4$ and the value of the minimum can be parameterized as a function of the atomic number of the absorber with $-(dE/dx)_{\text{min}} \approx (2.35 - 0.28 \log(Z))$ MeV cm²/g. The rise after the minimum, known as relativistic rise, is due to the relativistic effect that increases the electric field component orthogonal to the
2.1. ENERGY LOSS OF PARTICLES IN MATTER

Dense targets, like liquid argon, at the passage of the particle get polarized along the track. The polarization shields the electric field and suppresses the distant-collision contribution to the ionization. This effect is taken into account introducing the parameter $\delta(\beta\gamma)$ that can be approximated for dielectric materials with the following function [30]:

$$
\delta = \begin{cases} 
0 & \text{for } X < X_0, \\
4.6052X + C + a(X_1 - X)^m & \text{for } X_0 < X < X_1, \\
4.6052X + C & \text{for } X > X_1,
\end{cases}
$$

where $X = \log_{10}(\beta\gamma)$ and for argon the parameters are $X_0 = 0.201$, $X_1 = 3$, $a = 0.196$, $m = 3$ and $C = -5.217$ [31]. The net effect of this correction is to suppress the relativistic rise of the average energy loss at high $\beta\gamma$.

The stopping power for different particles in argon is shown in Figure 2.2 (right). Note that the stopping power for the electrons\(^1\) increases much more compared to the other particles. This is due to the radiative effects, discussed later in the text.

Large amounts of energy transferred to a single electron are rare. When the electron receives enough energy to cover a significant distance in the medium and ionize it further, it is called $\delta$ ray. Such electrons with kinetic energy $I \ll T \leq T_{\text{max}}$ are distributed according to [2]:

$$
\frac{d^2N}{dTdx} = K z^2 Z \frac{1}{A \beta^2} \frac{F(T)}{T^2},
$$

where $F(T)$ is a spin dependent factor very close to unity for $T \ll T_{\text{max}}$.

---

\(^1\)The Bethe equation is not valid for the electrons because one of the assumptions to obtain it is that the mass of the impinging particle is much larger than the mass of the target particle.
Figure 2.2: Left: attenuation coefficient of different processes for photon-argon interactions [32]. Right: stopping power in argon for different particles. The curves are computed according to the Bethe equation including the density correction for liquid argon. The points are simulated data [33] in low density argon and taking into account radiative effects. The small difference at energies larger than 3 GeV between the analytical function and the simulated data for the protons is due to the density correction.

If we neglect the $\delta$ rays with energies $T > T_{\text{cut}}$ in the computation of the stopping power, we obtain the so called restricted average energy loss per unit path, that can be written as [2]:

$$\frac{dE}{dx}_{res} = K z^2 Z \frac{1}{\beta^2} \left[ \log \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{cut}}}{I^2} \right) - \beta^2 (1 + T_{\text{cut}}/T_{\text{max}}) - \delta(\beta \gamma) \right].$$

It becomes the Bethe equation for $T_{\text{cut}} \to T_{\text{max}}$, and it differs from it by the non-considered energy loss per unit path $\int_{T_{\text{cut}}}^{T_{\text{max}}} T(d^2N/dTdx)dT$. The relativistic rise due to large energy transferred to few electrons is suppressed, and at large $\beta \gamma$ the restricted energy loss reaches the so called Fermi plateau, that depends on $T_{\text{cut}}$ (see Figure 2.3).

The distribution that describes the energy released by a charged particle crossing a finite thickness $x$ of absorber is the Landau function. It extends to infinity with a large high-energy tail to describe the $\delta$ rays. Beyond $T_{\text{max}}$ the Landau distribution has no physical meaning. In fact, the mean of the distribution extending to infinity is not defined. Experimentally the average energy deposited suffers of large variations due to $\delta$ rays, it is dominated by the tail of the Landau distribution and is therefore very sensitive to cuts. The Landau distribution exhibits a prominent peak, and its position, the so called most probable value $\Delta p$, is a well defined quantity that can be expressed as [2]:

$$\Delta p = \xi \left[ \log \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) + \log \left( \frac{\xi}{f} \right) + j - \beta^2 - \delta(\beta \gamma) \right],$$

$$\xi = K z^2 \frac{x}{\beta^2},$$
2.1. ENERGY LOSS OF PARTICLES IN MATTER

Figure 2.3: Muon crossing liquid argon. Left: comparison of the restricted energy loss for different energy cutoffs $T_{\text{cut}}$ and $\Delta p / x$ for different thicknesses $x$. Right: restricted energy loss versus energy cutoff for different muon energies $T_{\mu}$.

where $x$ is in g/cm$^2$ and $j = 0.2$. As well as the restricted energy loss, also $\Delta p / x$ reaches a Fermi plateau that depends on $x$.

In Figure 2.3 we summarize the characteristics of the energy loss in liquid argon by a muon. The plot on the left shows, as a function of the kinetic energy of the muon, a comparison of the average energy loss per unit path computed from the Bethe equation, the restricted energy loss for different energy cutoffs and $\Delta p / x$ for different liquid argon thicknesses. On the right plot the restricted average energy loss is plotted versus the cutoff energy for different muon kinetic energies.

Radiative processes like electron-positron pair production, bremsstrahlung and photonic interaction become the main source of energy loss above the critical energy, defined as the energy at which the radiative and the ionization energy losses are equal. For electrons in liquid argon it is around few tens of MeV, causing the fast rise of the stopping power shown in Figure 2.2. For muons and pions the critical energy is around few hundreds of GeV and much higher for heavier particles. The critical energy also depends on the absorber material, and for muons it is empirically parameterized as a function of the atomic number with [2]:

$$E_{\mu c} = \frac{7980 \text{ GeV}}{Z + 2.03^{0.879}}$$

for gases,

$$E_{\mu c} = \frac{5700 \text{ GeV}}{Z + 1.47^{0.838}}$$

for solids.

In gases the critical energy is larger than in solids because the density effect is smaller. For liquid argon the muon critical energy is about 500 GeV. The energy loss via radiative processes cannot be considered continuous, because characterized by small cross-sections, large energy fluctuations and production of electromagnetic and hadronic showers.
2.1.2 Photon interactions

Low energy photons interact with matter primarily via Rayleigh scattering, where no energy is transferred to the absorber, and via photoelectric effect. The latter process is characterized by the absorption of the photon and the emission of an electron of energy $E_{ph} - E_b$, where $E_{ph}$ and $E_b$ are the energy of the photon and the binding energy of the electron in the atom. The photoelectric cross-section, that roughly scales with the atomic number of the absorber as $Z^{4-5}$, is a discontinuous function of the photon energy because of different photoionization thresholds, reflecting the atomic levels.

Compton scattering becomes dominant at intermediate photon energies. The photon is scattered by the quasi-free electrons of the absorber, and it transfers a fraction of its energy in the range $0 - 2E_{ph}^2/(m_e + 2E_{ph})$, depending on the scattering angle of the photon. The probability that a photon undergoes Compton scattering is proportional to the number of electrons, that means that it depends linearly on the atomic number of the absorber. The photon may undergo multiple Compton scattering before being absorbed via photoelectric effect.

For energies larger than $2m_e c^2$ the photon interacting in the electric field of the nucleus can annihilate and produce an electron-positron pair. Increasing the photon energy the pair production becomes the most important process of the photon interaction with matter. As a function of the atomic number the pair production cross section scales about as $Z^2$.

The photon absorption coefficient is defined as $(\rho \lambda)^{-1}$, with $\lambda$ the photon mean free path and $\rho$ the absorber density. Figure 2.2 (left) shows the photon absorption coefficient in argon for different processes.

High energy photons and electrons produce in material a cascade process known as electromagnetic shower. In fact, the photons mainly produce electron-positron pairs, while the electrons and the positrons mainly radiate a photon. The cascade evolves until the energy of each particle falls below the critical energy. The average distance over which a high energy electron loses $1 - 1/e$ of its energy by bremsstrahlung, or, equivalently, $7/9$ of the mean free path of a high energy photon, is called the radiation length $X_0$. It is a characteristic of each material, and for liquid argon its value is 14 cm. The radius of a cylinder parallel to the shower axis that contains 90 % of the energy deposited by the shower is called Molière radius, and for liquid argon it is 9.3 cm. These two are the typical quantities used to describe the electromagnetic cascades.

2.2 Ionization

As already described, a particle slows down in matter mainly in collisions against the electrons of the atoms\textsuperscript{2}, ionizing and exiting them. The electron-ion pairs produced tend to recombine

\textsuperscript{2}For particles with speeds comparable to the speed of the electrons in the atom, nuclear collisions become a relevant contribution to the energy loss
with a probability that depends on the local ionization density and on the external electric field applied. In this section we address the amount of charge produced and collected at a given electric field and stopping power.

### 2.2.1 Electron-ion pair production

The mean energy $W$ required to produce an electron-ion pair depends on the absorber material, the energy and the nature of the projectile. From considerations of energy conservation one can write [34]:

$$W = E_i + E_{ex}N_{ex}/N_i + \epsilon,$$

where $N_i$ is the number of singly ionized ions ultimately created at an average energy expenditure $E_i$, $N_{ex}$ is the number of excited atoms at an average expenditure $E_{ex}$, and $\epsilon$ is the average kinetic energy of the $N_i$ electrons with energy below the lowest excitation level. $E_i$ is slightly larger than the first ionization potential $I_1$, because the particle spends energy to ionize and excite atoms already ionized. $E_{ex}N_{ex}/N_i$ takes into account the energy spent in excitation.

It turns out that in practice for argon $W$ is independent of the energy and of the kind of the particle ($\approx 5$ MeV $\alpha$ particles and $\approx 1$ MeV electrons), and its value is 26.4 eV [34] for gas and 23.6 eV [35] for liquid. The value of $W$ is smaller in liquid than in gas, because in liquid the first ionization potential ($I_1 = 15.7$ eV) must be replaced by the conduction band gap $E_{gap} = 14.3$ eV, assuming an energy band structure analogous to the solid argon.

### 2.2.2 Charge recombination

Without electric field the freed electrons recombine in a certain time, defined by two opposing effects: the diffusion, that tends to spread the charge, and the Coulomb attraction, that tends to gather it together. The electron can recombine with the parent ion (initial recombination), or with another ion (columnar or box recombination). Depending on the ionization density, one way is more relevant than the other. The effect of an externally applied electric field is to separate the electrons from the ions. The result is that a fraction $R$ of the initial charges does not recombine.

Taking into account only a single electron-ion pair, the initial recombination under the effect of a low electric field $\mathcal{E}$ can be evaluated as [36]:

$$R = e^{-r_kT/r_0}(1 + \mathcal{E}/E_{kT}),$$

where $r_{kT}$ is the distance at which the thermal energy of the electron equals the Coulomb potential energy, $r_0$ is the average electron-ion distance after the thermalization of the electron, and $E_{kT} = kT/(qe r_{kT})$, with $q_e$ the charge of the electron, is the limit of validity of the
model. The prediction is not accurate at very low fields, since $R \to e^{-r\xi/\rho_0} \neq 0$ for $\mathcal{E} \to 0$, and this is disproved by the experiments, i.e. $R \to 0$ for $\mathcal{E} \to 0$.

The columnar recombination is described with the following differential equations:

$$\frac{\partial n_e}{\partial t} = \mu_e \mathbf{E} \cdot \nabla n_e + D_e \nabla^2 n_e - \alpha n_i n_e,$$

$$\frac{\partial n_i}{\partial t} = -\mu_i \mathbf{E} \cdot \nabla n_i + D_i \nabla^2 n_i - \alpha n_i n_e,$$

where the subscripts $e$ and $i$ refer to the electrons and ions respectively, $n$ is the density, $\mu$ is the mobility, $D$ is the diffusion coefficient and $\alpha$ the recombination coefficient. An approximate solution [37] for gases is found requiring $\mu_e = \mu_i$, $D_e = D_i$ and treating $\alpha n_i n_e$ as a perturbation. The model is not justified in liquid argon because the recombination is large, and the mobility and the diffusion coefficients of the electrons and the ions are very different. An alternative is to consider the ions as stationary particles, neglect the electron diffusion and assume a uniform initial charge distribution in a box of dimension $a$. In this case, one can write the recombination coefficient as [38]:

$$R = \frac{4a^2 \mu_e \mathcal{E}}{N_0 \alpha} \log \left( 1 + \frac{n_0 \alpha}{4a^2 \mu_e \mathcal{E}} \right),$$

with $n_0$ the initial number of electrons and ions in the box. The model has no restriction on the electric field, in fact at zero field all the charge recombines and at infinite field all the charge stays free. The ionization density is taken into account introducing $n_0$ and $a$. Leaving $n_0 \alpha/(4a^2 \mu_e)$ as free fit parameter, it is found that its value is 0.84 kV/cm for $\approx 360$ keV electrons and 470 kV/cm for $\approx 5$ MeV $\alpha$ particles. With these values the data are well reproduced up to fields of 10 kV/cm.

In order to describe with a single formula the effects of the electric field and the ionization density (supposed to be proportional to the average energy loss per unit path), a modified Birks law is proposed [39]:

$$R = \frac{A}{1 + k \frac{d\mathcal{E}}{dx}}.$$

This functional form is suitable for $d\mathcal{E}/dx < 35$ MeV/cm and for electric fields in the range 0.2–0.5 kV/cm. It must be regarded as a phenomenological expression to parametrize the data. The fit of $R$ to the data of protons and stopping muons gives $A = 0.8$ and $k = 0.0347$ kV/MeV. In the left graph of Figure 2.4, $1/R$ is plotted as a function of $\mathcal{E}^{-1}d\mathcal{E}/dx$ for three data sets [39] at $\mathcal{E} = 0.2$ kV/cm, 0.35 kV/cm and 0.5 kV/cm, together with the fitted function. About 70 % of the ionization electrons produced by minimum ionizing muons in liquid argon and an electric field of 0.5 kV/cm is free to drift.
2.3 Scintillation

The scintillation mechanisms of argon are similar for the condensed and gas states and analogous for all the noble gases. The scintillation light is primarily ascribed to the de-excitation of argon dimers (excited diatomic molecular states of argon) with the subsequent emission of a photon in the Vacuum Ultra Violet (VUV) region.

2.3.1 Scintillation of liquid argon

Two processes contribute to the scintillation in liquid, namely the recombination luminescence and the self-trapped exciton luminescence [40, 41, 42]. As the name suggests, the former follows from the recombination of an electron and an ionized state according to [43]:

\[ \text{Ar}^+ + \text{Ar} \rightarrow \text{Ar}_2^+ \]
\[ \text{Ar}_2^+ + e \rightarrow \text{Ar}^{**} + \text{Ar} \]
\[ \text{Ar}^{**} \rightarrow \text{Ar}^* + \text{heat} \]
\[ \text{Ar}^* + \text{Ar} \rightarrow \text{Ar}_2^* \]
\[ \text{Ar}_2^* \rightarrow \text{Ar} + \text{Ar} + h\nu. \]

An ionized argon atom \( \text{Ar}^+ \) forms an ionized argon dimer \( \text{Ar}_2^+ \), that, colliding against a thermal electron \( e \), forms a highly excited argon atom \( \text{Ar}^{**} \). \( \text{Ar}^{**} \) de-excites non-radiatively to an excited state \( \text{Ar}^* \), that, colliding with a neutral argon atom \( \text{Ar} \), forms an excited argon dimer \( \text{Ar}_2^* \). \( \text{Ar}_2^* \) finally decays to two argon atoms in the ground state emitting a photon with
energy \( h\nu \). The self-trapped exciton luminescence starts from an excited argon atom and is described by the last two steps of the previous process:

\[
\text{Ar}^* + \text{Ar} \rightarrow \text{Ar}_2^*
\]

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

The two cases can be disentangled applying an electric field strong enough to avoid the electron recombination. The amount of light is expected to decrease with the increase of the electric field. The amount of light produced at infinite electric field is only due to the self-trapped exciton. In Figure 2.4 (right) this behavior is shown when the argon is bombarded with \( \approx 1 \) MeV electrons. Note that the sum of the ionization charge and the scintillation light is independent of the electric field.

The spectrum of the scintillation photons is dominated by a broad structure (\( \approx 10 \) nm wide) peaked at 128 nm [44, 45], called second continuum. The argon is transparent at this wavelength, because the photon is not energetic enough to be absorbed via photoelectric effect, but it can be absorbed by impurities diluted in the liquid, and it can be elastically scattered according to the Rayleigh scattering. The short wavelength makes the photons difficult to be directly detected, a problem usually solved by using a wavelength shifting molecule\(^3\) that absorbs a VUV photon emitting a visible or UV photon.

The excited dimer relaxes with two characteristic times of \( \tau_1 = 6 \) ns and \( \tau_3 = 1.6 \) \( \mu \)s (independently of the external electric field applied and of the radiation causing the scintillation [42, 47]) attributed respectively to the singlet and triplet state of the excited dimer \( \text{Ar}_2^* \). The measured value of \( \tau_3 (\tau_1,3^{eff}) \) depends on the purity of the liquid argon, a quantity difficult to estimate independently. For this reason the values of \( \tau_1,3^{eff} \) cited in the literature are in the range of 1–1.6 \( \mu \)s. The collision of a dimer and an impurity molecule (for instance \( \text{O}_2, \text{N}_2, \text{H}_2\text{O} \)) can de-excite the dimer without the emission of a 128 nm photon. For recent measurements see [48, 49]. The probability that a scintillation photon is emitted in a time interval between \( t \) and \( t + dt \) is the product of the dimer de-excitation probability \( e^{-t/\tau_1,3^{eff}} \) and the probability that the dimer has not collided with impurities yet \( \int_t^\infty e^{-x/\tau_{imp}} dx = \frac{e^{-t(1/\tau_1,3^{eff}+1/\tau_{imp})}}{\tau_1,3} \),

where \( \tau_{imp} \) is the average time between the excited dimer production and the collision against the impurity molecule. The impurities decrease the number of photons emitted by a factor \( \tau_{imp}/(\tau_1,3 + \tau_{imp}) \) and, since the process is more probable for the dimers that de-excite later, the effective (and measured) relaxation time \( \tau_1,3^{eff} \) is smaller than the intrinsic \( \tau_1,3 \), namely \( \tau_1,3^{eff} = (1/\tau_1,3 + 1/\tau_{imp})^{-1} \). \( \tau_{imp} \) is inversely proportional to the impurity contamination and, though both \( \tau_1 \) and \( \tau_3 \) are affected, only the slow component is significantly influenced with

\(^3\)Evaporated Tetraphenyl-Butadiene (TPB) [46] is very popular in liquid argon applications.
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a ppm level concentration of impurities. The measurement of the slow scintillation time can be used as an estimation of the liquid argon purity.

The populations of the singlet $I_1$ and triplet $I_3$ states depend on the nature of the interacting particle. A possible explanation of this phenomenon is the super-elastic collision between a singlet state excited dimer and a thermal electron resulting in the singlet-to-triplet transition [47]. The probability of this process increases with the number of free thermal electrons, that in turn depends on the recombination time. For low Linear Energy Transfer (LET)$^4$, where the ionization density is low, the electrons before the recombination have the chance to transform a singlet state into a triplet state. The measured values of $I_1/I_3$ are 0.3, 1.3 and 3 for scintillation induced by relativistic electrons, $\alpha$ particles and fission fragments respectively [47]. According to another interpretation [50], for low LET the singlet and triplet states are produced following the statistical weights $I_1 : I_3 = 1 : 3$ and at large LET some non-specified mechanism transforms the triplet states into singlet states. The dependence of $I_1/I_3$ on the ionization density is very important for the direct Dark Matter search experiments, because it allows to discriminate the background ($\beta$ and $\gamma$ radiation) from the signal (nuclear recoil) by using the pulse shape of the scintillation signal [16, 51].

The maximum number of scintillation photons produced per unit energy deposited equals the sum of the number of ionized atoms $N_i$ plus the number of excited atoms $N_{ex}$. In this case, the energy $W_{ph}$ spent by a particle to produce a scintillation photon is related to the energy $W$ spent to produce an ion-electron pair by:

$$W_{ph} = \frac{W}{(1 + N_{ex}/N_i)}.$$  

Considering that $W = 23.6$ eV [35] and $N_{ex}/N_i = 0.19–0.21$ [41], one gets $W_{ph} = 19.5$ eV [43]. However, the photon production can be suppressed by some sort of quenching. Two examples of scintillation reduction already discussed are the presence of an external electric field and the presence of impurities diluted in the liquid. In addition, LET dependent processes like $Ar^* + Ar^* \rightarrow Ar + Ar^+ + e$, at high LET, and escaping electrons $^5$, at low LET, may occur. All these mechanisms result in an increase of $W_{ph}$. In absence of impurities and without electric field, the energy required to produce a scintillation photon becomes 27.1 eV for $\approx 5$ MeV $\alpha$ particles and 24.4 eV for 1 MeV electrons. For a review of these processes see [52] and references therein. According to what was already discussed, a minimum ionizing muon is expected to have a LET similar to a 1 MeV electron, for this reason we can estimate that in liquid argon a muon produces about $8.5 \times 10^4$ scintillation photons per centimeter.

---

$^4$The energy per unit path released by the particle in the vicinity of its track. It differs from the stopping power because of the $\delta$ rays and all the processes that tend to release the energy non-locally.

$^5$Electrons that miss the prompt recombination and recombine in milliseconds.
2.3.2 Scintillation of argon gas

In argon gas the photon emission spectrum of the primary scintillation is similar to the one of the gas scintillation proportional counters [53, 54] and of the discharge [53, 55, 56], and this analogy extends to all the noble gases. This suggests that the scintillation mechanisms are similar and they can be summarized as follows [57]:

\[ \text{Ar}^* + \text{Ar} + \text{Ar} \rightarrow \text{Ar}_2^{**} + \text{Ar} \]
\[ \text{Ar}_2^{**} \rightarrow \text{Ar} + \text{Ar} + h\nu \text{ (first continuum)}, \]
\[ \text{or} \]
\[ \text{Ar}_2^{**} + \text{Ar} \rightarrow \text{Ar}_2^* + \text{Ar} + \text{heat} \]
\[ \text{Ar}_2^* \rightarrow \text{Ar} + \text{Ar} + h\nu \text{ (second continuum)}, \]

where \( \text{Ar} \) is the neutral noble atom, \( \text{Ar}^* \) is the excited atom, \( \text{Ar}_2^{**} \) is the vibrationally excited molecular dimer, \( \text{Ar}_2^* \) is the vibrationally relaxed molecular dimer and \( h\nu \) is the VUV photon. The recombination of the ion \( \text{Ar}^+ \) is shown to be not relevant for pressures below 3 atm, since the amount of photons produced is observed to be independent of the electric field applied. The three-body process is justified by the fact that the rising time of the signal is inversely proportional to the square of the gas pressure [57, 58].

The emission spectrum in the VUV region consists mainly of two peaks referred to as first continuum, due to the de-excitation of \( \text{Ar}_2^{**} \), and the second continuum, shifted to larger wavelengths peaked around 128 nm, attributed to the de-excitation of \( \text{Ar}_2^* \) and analogous to what happens in liquid. The abundance of the first continuum with respect to the second continuum diminishes with increasing the gas density, because the non-radiative process \( \text{Ar}_2^{**} + \text{Ar} \rightarrow \text{Ar}_2^* + \text{Ar} \) becomes more probable. The first continuum disappears at high pressure [53, 59]. A structure, called third continuum, is also observed at larger wavelengths, and it is attributed to the doubly ionized argon atoms [60].

Similarly to the liquid case, the scintillation happens with two characteristics time constants that depend on the density and purity of the gas. The slow component is the dominant one and the measured values of \( \tau_3 \) in the literature lay in the range 2.5–3.5 \( \mu \text{s} \) for gas at room pressure and temperature. The difference in the measured values must be attributed to the non-well controlled purity of the argon.

2.4 Electron transport

The presence of an electric field induces the free electrons, both in gas and in liquid argon, to acquire a net motion called drift, along the field. According to the standard kinetic theory of gases, the drift velocity is an increasing function of the electric field \( \mathcal{E} \) (at least for small values). Electron atom collision cross sections are well known and extraordinary agreement
2.4. ELECTRON TRANSPORT

between computed and measured quantities is achieved in gas. In Chapter 3 we discuss more in details the transport properties of electrons in gas. Here we focus on the transport properties of electrons in liquid argon, namely the drift and the diffusion, and on the effects that electronegative impurities have on the drifting electrons.

2.4.1 Drift and diffusion

Typical approximations valid in gas, i.e. short time spent by the electrons in a collision with respect to the free flight time, cannot be used in liquid, complicating the treatment of electron transport. The scattering potential must be changed into effective potentials that consider the liquid polarization due to free charges and external electric fields, and the overlap of the potentials of neighboring atoms (the electron can never be considered free). Doing this in particular for liquid argon, it is found that the Ramsauer minimum in the electron-argon cross section disappears [61] and reasonable agreement to the measured drift velocity is achieved up to electric fields of 10 kV/cm.

Though the liquid argon cannot be considered as a very dense gas, some characteristics typical of the gas are maintained. For instance, traces of molecular dopants, like nitrogen, increase the drift velocity [62], and this can be explained in the framework of the standard kinetic theory of gases. In fact, in pure argon the electrons with energies below the first excitation potential (around 12 eV, see the left plot in Figure 3.1) cannot lose their energy through inelastic collisions, while in the presence of nitrogen they can lose energy exciting the nitrogen molecules to the vibrational and rotational states with energies around 2–3 eV. In this way the equilibrium energy of the electrons is reduced, and the same happens to the electron-argon cross section, since the momentum transfer cross section in the range 1–10 eV (after the Ramsauer minimum) increases with the electron energy. According to the standard kinetic theory of gases, the drift velocity is inversely proportional to the product of the square root of the average electron energy and the total cross section. It follows that the drift velocity increases as long as the amount of impurities is a small fraction, and the majority of the electron collisions happens against the argon.

In order to explain two distinct phenomena of electron transport observed in liquid argon, the drift velocity as a function of the field and the increase of the drift velocity in doped argon, two interpretations are needed, and we are not aware of a single theory able to describe both phenomena.

The electron drift velocity as a function of the electric field has been measured with great precision [63, 64], and the results are shown on the left plot of Figure 2.5. It depends on the temperature, and an empirical function [63] approximates both the dependence on the electric field, in the range 0.5–13 kV/cm, and on the temperature, in the range 87–94 K. The result can be summarized saying that the drift velocity decreases with a rate equal to -1.72 %/K. For electric fields smaller than 0.5 kV/cm the previous empirical approximation is not valid, and the data at 89 K are approximated in the range 50 V/cm–1 kV/cm by a
polynomial function [64].

The measurement of the diffusion coefficient $D$ in liquid argon is much poorer than what concerns the drift velocity. From the Einstein model of electrons in thermal equilibrium, the ratio of the diffusion coefficient and the mobility is $D/\mu = kT/q_e$, where $k$, $T$ and $q_e$ are the Boltzmann constant, the absolute temperature and the electron charge. At 87 K, $kT = 7.5$ meV, which is a much lower value than what is measured from the ratio $D/\mu$ in the presence of an electric field [65, 66, 67], as shown on the right plot of Figure 2.5. One can conclude that already at 1 kV/cm the electrons are out of thermal equilibrium, and they can be considered warm with respect to the liquid argon. Similarly to what happens in the gas phase, the diffusion is expected to be not isotropic, when an external electric field is applied. The values of $D$ cited here refer to the orthogonal (or transverse) component with respect to the electric field. The diffusion coefficient computed by multiplying $D/\mu$, reported in [66], with $\mu = v_d/E$, reported in [63], is slowly rising from 15 cm$^2$/s to 20 cm$^2$/s in the electric field range 2–10 kV/cm. No data are available for lower electric fields, though the limit for $E \to 0$ should be $D = 3.8$ cm$^2$/s, deduced from the Einstein relation and from the mobility at fields lower than 100 V/cm [68].

2.4.2 Impurity effect

Small amounts of dopants, in addition to speed up the drift velocity, may quench the amount of drifting charge. Electronegative impurities like O$_2$, N$_2$, H$_2$O, CO$_2$, SF$_6$, N$_2$O capture the free electrons, and negative charged ions drift about three orders of magnitude slower than free electrons. Taking as example the oxygen, the attachment process can be schematically represented with:

$$O_2 + e^- + X \rightarrow O_2^- + X,$$

where $X$ is a molecule or atom to stabilize the process [69]. The need of $X$ is because the oxygen molecule gets into an excited state capturing the electron, and it can de-excite either liberating the electron or colliding against the third body $X$ [70]. The attachment cross sections for O$_2$ are about two orders of magnitude larger than for N$_2$ and CO$_2$ [69, 71] and much smaller than for SF$_6$ and for N$_2$O [70]. The cross section depends on the electric field applied, e.g. for O$_2$ it decreases increasing the field, a trend that is observed by all the authors [69, 70, 71]. Contaminations of oxygen and nitrogen are of great interest for liquid argon detectors, since atmospheric impurities can be diluted in the argon. The dynamical behavior of the amount of electrons $n_e$ in the presence of impurity concentrations $[N_i]$ is described by the following differential equation:

$$\frac{dn_e}{dt} = - \sum_i (K_i[N_i])n_e,$$
Figure 2.5: The plot on the left shows the drift velocity of electrons in liquid argon as a function of the electric field. The measurement was performed in liquid argon at 89 K by Amoruso and collaborators [64] and at 87 K by Walkowiak [63]. The plot on the right shows the ratio of the electron diffusion coefficient $D$ and the electron mobility $\mu$ changing the electric field as reported in [66]. The diffusion coefficient is computed multiplying $D/\mu$ by the drift velocity measured by Walkowiak and dividing by the electric field.

where the sum runs over the different impurities, and $K_i$ are the so called attachment coefficients proportional to the attachment cross sections. Considering that the impurity density is much larger than the electron density (and for this reason it is not appreciably affected by changes), the amount of charge as a function of time is:

$$n_e = n_0e^{-t/\tau_e},$$

with $\tau_e = 1/\sum_i(K_i[N_i])$ is the drifting electron lifetime and $n_0$ the initial number of electrons (after recombination). An estimation of $1/K$ for the oxygen is done in extremely low concentration [68, 71] resulting in $\tau_e[\mu s] \approx \frac{300}{[O_2][ppb]}$. The purity of argon is usually given in term of the electron lifetime $\tau_e$ or as oxygen equivalent concentration, assuming that all the impurity is indeed oxygen. An extraordinary low contaminant concentration of 0.03 ppb $[O_2]_{eq}$ was achieved with the purification system based on chemical reactions involving oxidation [68, 71].

2.5 Electron extraction from liquid to vapor

The transfer of electrons in excess from a condensed non-polar fluid to its saturated vapor using an electric field is a phenomenon investigated since the seventies [72]. In particular, in argon it is experimentally shown that the electrons are extracted in two stages. Near the triple point part of the charge is emitted on time scales that can be as high as 1 ms, strongly dependent on the electric field applied [73, 74], while at larger temperatures the emission takes less than 100 ns. At high electric fields the slow extraction time reduces,
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Figure 2.6: The left picture shows the dependence of the extraction time on the electric field in liquid argon (T = 87.4 K) as reported in [74]. The picture on the right [73] shows the extraction efficiency for fast and slow components as a function of the electric field in liquid argon (T = 90 K). As described in the paper, due to limitations of the electronics the measurement of the slow component has a semi-qualitative character.

and the fraction of the slowly extracted electrons becomes negligible (see Figure 2.6). This behavior can be understood in the framework of the Schottky model of electric field enhanced thermionic emission [75].

2.5.1 Transition mechanism

An electron in the vicinity of a dielectric surface feels the force of the charge induced on the surface by its presence. In analogy to a conductor surface one can compute, with a method similar to the mirror charge method [76], the potential energy of the electron.

In the presence of an external electric field orthogonal to the liquid-vapor interface of argon, the energy potentials in the liquid (\(\Phi_l\)) and in the vapor (\(\Phi_v\)) as a function of the vertical position \(z\) (the surface is set at \(z = 0\)) are [73, 74, 77]:

\[
\Phi_l = -V_0 - q_e \mathcal{E}_l z - \frac{A_l}{z} \quad \text{and} \quad \Phi_v = -q_e \mathcal{E}_v z - A_v/z, 
\]

with

\[
A_l = \frac{q_e^2}{16\pi\epsilon_0 \epsilon_l \epsilon_l + \epsilon_v} \quad \text{and} \quad A_v = A_l \epsilon_l / \epsilon_v, 
\]

where the terms inversely proportional to \(z\) are due to the presence of the dielectric, \(-q_e\) is the charge of the electron, \(\mathcal{E}_l\) and \(\mathcal{E}_v = \mathcal{E}_l \epsilon_l / \epsilon_v\) are the electric fields in the liquid and in the vapor respectively, \(\epsilon_l\) and \(\epsilon_v\) are the dielectric constants of the liquid and of the vapor respectively, \(\epsilon_0\) is the permittivity of the vacuum, \(-V_0\) is the minimum of the conduction band in the liquid with respect to the vapor (about \(-0.2\) eV [77]). The discontinuity of the
2.5. ELECTRON EXTRACTION FROM LIQUID TO VAPOR

potential on the surface is unphysical, but also not relevant for the discussion. The regulated potential around \( z = 0 \) is shown in the plot on the left in Figure 2.7 for different externally applied electric fields.

The minimum and the maximum of the potential in the liquid and in the vapor phase are:

\[
\Phi^\text{min}_l = 2 \sqrt{A_l q E_l} - V_0, \quad \text{for} \quad z^\text{min}_l = -\sqrt{A_l/(q E_l)},
\]

\[
\Phi^\text{max}_v = -2 \sqrt{A_v q E_v}, \quad \text{for} \quad z^\text{max}_v = \sqrt{A_v/(q E_v)}.
\]

It is interesting to notice that the presence of the electric field reduces the potential barrier by:

\[
\Delta \Phi = 2(1 + \epsilon_l/\epsilon_v)\sqrt{A_l q E_l},
\]

so that the gap becomes \( V = V_0 - \Delta \Phi \).

An electron with momentum \( p_z \) perpendicular to the liquid argon surface for which \( p_z^2/(2m_e) > V \) (with \( m_e \) the mass of the electron) is transferred to the vapor. The electrons with kinetic energy \( T > V \), but not satisfying the requirement on \( p_z \), are reflected towards the liquid. They undergo several elastic collisions that randomize the momentum direction almost without loss of energy, and they reach the liquid surface again. If \( p_z \) is not yet big enough, they repeat the process until all electrons are extracted in few tens of nanoseconds. These are the so called hot electrons (or fast component).

The electrons with \( T < V \) are thermalized on the liquid surface and are emitted according to the thermionic emission with a characteristic time that depends on the energy gap [74]. These electrons are the cold ones (or slow component).
The electrons in liquid argon gain energy from the electric field. At around 1 kV/cm, the electron average kinetic energy is of the order of 0.1 eV [61, 81], larger than the thermal energy and comparable to the liquid-vapor interface energy gap.

The experimental facts can be summarized and explained:

1. at low temperature the electrons are emitted also slowly because their energy is not always larger than the potential barrier,

2. increasing the electric field the fraction of electrons with energy above the potential barrier increases,

3. the extraction time for the cold electrons decreases at high field because the energy gap reduces.

The electrons can be trapped by electronegative impurities diluted in the liquid argon and never be emitted in the vapor. Similarly to what happens to the scintillation light in the presence of impurities, the amount of charge extracted decreases by a factor $\tau_{\text{imp}}/(\tau_{\text{ext}} + \tau_{\text{imp}})$, and the effective extraction time can be written as $\tau_{\text{ext}}^{\text{eff}} = (1/\tau_{\text{ext}} + 1/\tau_{\text{imp}})^{-1}$, where $\tau_{\text{ext}}$ is the extraction time with no impurities and $\tau_{\text{imp}}$ is inversely proportional to the electronegative impurity concentration.

### 2.5.2 Proportional scintillation in gas

The proportional scintillation in argon, also referred to as secondary scintillation and luminescence, is the phenomenon of generating photons in gas or vapor in the presence of free charges and an electric field. In a defined electric field window, that depends on the density of the argon, the amount of photons is proportional to the number of electrons, to the electric field and to the length of the path covered by the electrons.

The electric field range is defined such that between two successive collisions the drifting electrons, accelerated by the electric field, gain enough energy to excite argon atoms, but not ionize them. In the case the electric field is lower, no photons are produced, in the case it is larger, because new charge is created, the amount of light grows nearly exponential with the field and the path length. For the discussion on the charge amplification in gas see Chapter 3.

In order to take into account the argon density, the quantity used is the reduced electric field, defined as the electric field divided by the argon atomic density (1 Td = $10^{-17}$ V cm$^2$), and the reduced light yield, defined as the number of photons produced per electron per unit path length divided by the argon density (the justification of this choice is given in Section 3.1). On the right of Figure 2.7 the simulated [78, 79] and measured [80, 82] reduced light yield at room temperature and pressure is plotted versus the reduced electric field. The measured proportional scintillation threshold and ionization threshold are respectively 2.34 Td and 12.4 Td [82], slightly lower than the simulated ones, but still in good agreement.
2.6. SIGNAL INDUCTION

The electrons, when extracted from the liquid argon to the vapor, produce proportional scintillation. From the data at room temperature and pressure one can extrapolate that in an electric field of 4.5 kV/cm, corresponding to an extraction field of 3 kV/cm in liquid, over 1 cm one electron generates about 200 photons. Since the total amount of light produced is proportional to the charge extracted, this method is used by some double phase noble gas experiments for the direct Dark Matter searches [15, 16] to detect the ionization charge.

2.6 Signal induction

A moving charge always induces electrical currents on the electrodes. Under the assumption that the electric field propagates instantaneously, the Shockley-Ramo theorem [83, 84] states that the current $i$ induced on a given electrode is given by:

$$i = -\sum_k q_k \vec{v}_k \cdot \vec{E}_w,$$

where $q_k$ are point-like charges (with sign) moving with velocity $\vec{v}_k$, and $\vec{E}_w$ is the so called weighting electric field, computed neglecting the free charges and setting the weighting potential on the interested electrode to 1 and on the other electrodes to 0. Note that in this case the potential is a dimensionless quantity and the field has the dimension of the inverse of a length. Integrating $i$ over the drift time, the total charge induced on the given electrode is:

$$Q = \sum_k q_k \Delta \phi_{wk},$$

where $\Delta \phi_{wk}$ is the weighting potential difference between the positions of the k-th charge at the end and at the beginning of its motion.

Considering only one drifting charge $q$, $i = -q \vec{v} \cdot \vec{E}_w$ and $Q = q \Delta \phi_w$. Since the weighting potential has values in the range 0–1, only a fraction ($|\Delta \phi_w| \leq 1$) of the initial charge is induced.

Considering two charges of opposite signs generated at the same position, as in the case of ionizing events, $Q = q(\Delta \phi^+ - \Delta \phi^-)$. Since the positive and negative charges are collected on different electrodes, the total induced charge can either be $+q$, $-q$, or 0, depending on whether the considered electrode collects positive, negative or no charge. However, often this is not a practical case. Due to the slow motion of the ions and constraints on the charge integration time, usually only the electron induced charge contributes to the signal.

A TPC can be modeled as an infinite parallel plate chamber where the actual electric field and the weighting electric field are uniform. The current and the charge induced on the (infinite) anode by drifting electrons are $i = q \vec{v} / d$ and $Q = qz / d$, where $z$ is the initial distance between the anode and the ionizing event and $d$ is the gap between the two plates.
Figure 2.8: Current induced in a liquid argon TPC. Left: two-dimensional projection along the anode strips direction of a region in the vicinity of the anode. The bottom part is the drift volume. The anode segmented into strips (1 cm wide) is the top plane. Four wires of the grids are visible 1 cm below the anode. The field lines of the actual field (blue) and of the weighting field (red) are shown. The color scale is proportional to the current induced on the central strip (see text for more details). Right: Current induced on the central strips by electrons following different paths. The instant when the electrons cross the grid is shown with the vertical line.

Note the dependence of the induced charge on the initial position of the ionizing event.

For the same conditions, considering an anode segmented into pixels, the weighting potential drops to zero fast with increasing distance to the interested pixel. This gives a stronger weight to the charge drifting in the vicinity of the pixel and reduces the dependence on \( z \). When a grid at a fixed potential is installed in front of the anode, the weighting potential differs notably from zero only between the anode and the grid. The grid must let the drifting electrons pass, while it shields the anode from the induction of charge in the drift region.

Let’s focus on a simplified case of a practical liquid argon TPC, considering an infinite parallel plate chamber with the anode segmented along one direction into strips and with a grid of wires parallel to the strips placed in front of the anode. The current induced by electrons coming from the drift volume is shown in Figure 2.8. The left image represents a portion of the TPC in the vicinity of the anode. The blue lines coming from the drift volume and squeezed between the wires are the field lines of the actual electric field. Neglecting the diffusion the electrons follow these paths. The red lines between the anode and the grid are the field lines of the weighting field associated to the strip in the center. The color in the coordinates \((x, z)\) represents the current induced on the central strip by an electron in \((x, z)\) with the velocity defined by the actual electric field. The right plot of Figure 2.8 shows the induced current versus the drift time following different electron paths, namely the straight trajectories passing in the middle of two wires and ending in the center of the strips. The electrons below the central strip induce a negative current, that integrated along the entire drift gives the initial charge, i.e. \( \Delta \phi_w \approx 1 \). The charge drifting below the neighboring strips

...
also induces signals on the central one, but their integrals are zero and their amplitudes decrease with the distance to the central strip. This electrodes configuration enhances the weighting field in the vicinity of a single strip, in this way the charge induced practically equals the initial charge, and it is independent on the depth of the ionizing event. Moreover, the drifting electrons induce a current mainly on the strip directly above them and only a small signal on the immediately neighboring strips.

In order to retrieve the three-dimensional geometry of the ionizing event one needs to readout independently the two coordinates perpendicular to the drift. The standard way of doing this in liquid argon TPCs is using two sets of wires along each coordinate and record the current induced on each wire independently. The signal induction on the wire plane where the charge is collected is analogous to the simplified TPC case described above. This wire set is usually called collection view. On the other plane of wires, usually called induction view and analogous to the grid of Figure 2.8, the integrated charge is zero, and the current induced is bipolar-shaped, since the drifting charge first approaches the wire and afterwards moves away from it. This behavior has a notable drawback when the spatial distribution of the drifting charge is extended in space along the drift direction. In this case, it can happen that while the charge is moving away from the wire, a similar amount of charge is approaching, canceling the signal. This effect, absent in the collection view, depends on the electrodes geometry and it cannot be generalized further.
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Chapter 3

Charge amplification in gas

In this chapter we describe the most relevant mechanisms involved in the electron multiplication and in the discharges in gas, and we give a brief review of the most important charge amplification detectors working in gas.

3.1 Townsend avalanche

In a gas an electron accelerated under the action of an electric field ($E$) gains energy that is released in collisions against neutral atoms. In addition to the diffusive random motion of the electron, a net velocity ($v_d$) in the direction of the field (but opposite) is obtained, and the phenomenon is called electron drift. Under the assumption that the duration of the scattering is short compared to the average time between collisions $\tau_c$, and that the electrons undergo elastic collision only, so that the absolute magnitude of their speed does not change appreciably (the mass of the atom is much larger than the electron mass), the drift velocity can be written as [85]:

$$v_d = q_e E \tau_m / m_e,$$

where $q_e$ is the charge of the electron, $m_e$ is the mass of the electron, $\tau_m = \tau_e / (1 - \overline{\cos(\theta)})$ is the effective collision time for momentum transfer, and $\overline{\cos(\theta)}$ is the average cosine of the scattering angle $\theta$. $\tau_m$ is inversely proportional to the gas density $\rho$ and the momentum transfer cross section $\sigma_m$ [85]. In general, it depends on the energy of the electrons and therefore on $E$. This makes $v_d$ proportional to $E$ only for low electric fields.

One should point out that the kinetic energy due to the drift is much smaller than the kinetic energy due to thermal motion. A more realistic computation should take into account the details of the electron velocity distribution. The kinetic energy of the electrons increases by (1) decreasing the gas density and the electron-atom cross section and (2) increasing the electric field. In other words, the peak of the electron energy distribution moves to higher energies with the increase of the electric field, as shown in the right plot of Figure 3.1. It
Figure 3.1: Left: electron argon atom cross sections for different kind of interactions [87]. Right: energy distribution of free electrons under the action of an external electric field in pure argon gas at 1 atm and 20° C simulated with Magboltz 8.4 [86].

displays the results of a computation done using Magboltz 8.4 [86] in pure argon gas at 1 atm and 20° C.

Magboltz is a software that calculates diffusion coefficients, drift velocities and first Townsend coefficients (see later in the text) for gas mixtures in the presence of electric and magnetic fields. The program inputs are tables of cross sections like the one reported on the left plot of Figure 3.1, provided in [87].

The high energy tail of the electron energy distribution extends beyond the first ionization potential, that for the argon is about 15.7 eV [88]. This means that a fraction of collisions gives rise to ionization of neutral atoms and to the production of new free electrons. This process is called Townsend avalanche and is at the base of all the signal amplification techniques in gas chambers.

The bigger the electric field is, the more populated becomes the tail above the ionization energy, and the larger the ionization rate is. When the electric field is high enough that the majority of the electrons have an energy above the ionization potential, the ionization rate saturates, and its behavior reflects the ionization cross section dependence on the electron energy. The first Townsend coefficient ($\alpha$) is the quantity that describes the number of ion-electron pairs created by an electron per unit drift length. A very useful empirical approximation of the first Townsend Coefficient as a function of the electric field and the gas density is:

$$\alpha = A \rho e^{-B \rho E},$$

(3.1)

where $A$ and $B$ are constants depending on the gas.

It is interesting to notice that the expression $\alpha/\rho$ is a function of $E/\rho$ (also called reduced electric field). The reason of this comes from the following considerations:
3.1. TOWNSEND AVALANCHE

1. The electron mean free path ($\lambda$) can be written as $(\sigma \rho)^{-1}$, where $\sigma$ is the electron-atom total cross section (generally dependent on the electron energy, see Figure 3.1).

2. The energy gained by a free electron between two collisions is proportional to the product of the electric field $E$ and the mean free path $\lambda$, i.e. $E/(\sigma \rho)$.

3. $\alpha \lambda$, i.e. $\alpha/(\rho \sigma)$, can be regarded as a quantity proportional to the number of electron-ion pairs produced by an electron per collision.

Given a defined gas, or in other words, defined cross sections, in conditions where $E$ and $\rho$ are changed, but $E/\rho$ is kept constant, the electron-atom collisions are not distinguishable, i.e. same energy and, therefore, same ionization probability per collision (proportional to $\alpha/\rho$). This concept is fundamental to the understanding of what follows.

For the very weak assumption that the mean free path of the electrons is much smaller than the size of the avalanche, the total number of electrons $n_e$ created along a path $p$ starting from $n_{0e}$ electrons can be written as:

$$n_e = n_{0e} e^{\int \alpha ds}, \quad (3.2)$$

and the gain $G$ is defined as $n_e/n_{0e}$. In a parallel plate gap of length $x$ with a uniform electric field, where the Townsend coefficient is constant, the above expression becomes:

$$n_e = n_{0e}^{0} e^{\alpha x}, \quad (3.3)$$

and in this case $G = e^{\alpha x}$.

The above cited quantities must be considered as average values. In fact, the Townsend avalanche is a stochastic process with the following behavior. When $n_e < 10^5$, the number of electrons involved in an avalanche generated by a single electron follows the so called Furry distribution [89]. The probability that an electron frees a second electron traversing an infinitesimal distance $dx$ is $\alpha dx$. As computed in [90], given one initial particle entering into the uniform field of the multiplication region, the probability that $n$ particles emerge is

$$P(n) = (1 - 1/G)^{n-1}/G.$$ 

The most probable number of particles at the end of the path is one, the average is $G = e^{\alpha x}$, and the variance is $G^2 (1 - 1/G)$. For large gains the standard deviation of the distribution can be approximated with $G$, and for the central limit theorem, given a large number $n_{0e}$ of electrons at the beginning of the multiplication path, the distribution of the number of emerging electrons is a Gaussian with average $G n_{0e}$ and standard deviation $G \sqrt{n_{0e}}$. To be noticed is that the relative width of the distribution is independent of the gain, and it decreases the larger the number of electrons at the beginning is.
3.2 Secondary effects

Other processes may occur during the electron multiplication. They are usually not the main source of electron-ion formation, but they become relevant processes in the case of electrical breakdown.

3.2.1 Photon feedback

During an electron avalanche the gas atoms are both ionized and excited. The excited states de-excite to the ground states emitting photons, that can ionize other species in the gas mixture or extract electrons via photoelectric effect from, for instance, metal surfaces.

The photon emission can follow different and complicated mechanisms, depending on the gas mixture. As an example, the excited state of an argon atom, colliding with argon atoms in the ground state, forms an excited dimer ($\text{Ar}_2^*$), that emits a photon of wavelengths peaked at 128 nm with a broad continuum to 300 nm, that depends on the gas density (see Section 2.3 for details on the argon scintillation).

Photon feedback depends strongly on the gas mixture, since the emitted photon must have sufficient energy (typically VUV region) to further ionize or extract an electron from a metal (the photoelectric work function of most metals is below 5 eV).

The consequence of the photo-ionization is on one hand to increase the Townsend coefficient (an electron-ion pair can locally be generated starting from an excited state), and on the other hand the propagation of the avalanche can spread, because new electrons are extracted non-locally from the metal surfaces.

3.2.2 Ion feedback

The ions created in the Townsend avalanche drift slowly (ions are three orders of magnitude slower than the electrons) in the opposite direction with respect to the electrons. The ion drift is almost diffusion free, and it ends on the cathode, where the ion is generally neutralized. During the impact the ion may extract some electrons, that on average cover backwards the same path as the ion. The ion feedback consequence is analogous to the one of the photon feedback, even though it is a much slower effect.

3.2.3 Penning effect

In gas mixtures where the ionization energy of one of the species is lower than the excitation levels of another species, the so called Penning effect can take place. Normally the gas mixture is composed by a noble gas ($N$) and a molecular gas ($M$) in small percentage. If energetically allowed, the metastable excited states of the noble gas can transfer energy to the molecular gas ionizing it: $N^* + M \rightarrow N + M^+ + e^-$. An example of such a mixture is argon, that
3.3 DISCHARGES MECHANISMS

has the first ionization potential at 15.7 eV and the lowest excitation state at 11.6 eV, and isobutane, that has a first ionization potential of 10.7 eV.

One of the effects of adding a molecular dopant to a noble gas is to lower the average ionization energy. In fact, a noble gas atom excited by the interaction with a charged particle (that, because the relative abundance, releases mainly its energy to the noble gas atoms) can still ionize a molecule via Penning transfer. A second effect is to increase the Townsend coefficient. In fact, during the electron avalanche an excited noble gas atom can locally transfer energy to a molecule admixture and creates an electron-ion pair.

3.3 Discharges mechanisms

An electrical discharge in gas is a self sustained process for which a part of the gas becomes an electron-ion plasma. There are different kinds of discharges relevant in the field of the gas detectors. A discharge can damage (temporarily or permanently) the device and affect its operation. The optimization of detectors aims also to reduce the spark rate and to limit its consequences. A description of the most important discharge mechanisms follows.

3.3.1 Townsend discharge and Paschen’s law

The Townsend discharge is sustained by the photon and ion feedback. The process depends on the electric field configuration and on the presence of dielectric or metal surfaces, but the mechanism can be described referring to the case of the parallel plate chamber of gap $x$.

Given $n_e^0$ electrons at the beginning, during the path to the anode they are multiplied to $n_e = n_e^0 e^{\alpha x}$. Under the assumption that the atoms are ionized only once, the number of created ions is $n_i = n_e - n_e^0$, and the number of photons produced is assumed to be proportional to the total number of electrons $n_{ph} = \beta n_e$.

A fraction of the ions ($\gamma n_i$) and of the photons ($\delta n_{ph}$) hitting the cathode extract secondary electrons that undergo the Townsend multiplication before reaching the anode. When the number of secondary electrons equals the number of initial electrons, the process does not extinguish. This is the condition for the Townsend discharge:

$$e^{\alpha x} = \frac{1 + \gamma}{\gamma + \delta\beta} = k,$$

and it is independent of the initial number of electrons.

The electric field $E$ in a parallel plate chamber is $V/x$ ($V$ applied voltage). Substituting the formula 3.1 into the condition for the Townsend discharge and solving for $V$, one finds that the ignition voltage of this kind of discharge is:

$$V_{ign} = \frac{B\rho x}{\log(A\rho x) - \log(\log(k))}.$$
This is called Paschen’s law. The dependence on the product $\rho x$ comes from similar considerations previously made about the first Townsend coefficient (see the Section 3.1). In fact, for a fixed applied voltage both the number of electron-atom collisions and the electron energy depends on $\rho x$. Two systems with different densities and lengths, but with the same $\rho x$, are not distinguishable in terms of the electron transport, when the drift time is neglected.

The ignition potential has a minimum at $(\rho x)_{\text{min}} = e^{1 + \log(\log(k))} / A$ with $V_{\text{ign}}^{\text{min}} = B(\rho x)_{\text{min}}$. The rise after the minimum is due to the fact that at high densities the electron needs to be accelerated more to further ionize. At low densities the increase of $V_{\text{ign}}$ decreasing $\rho x$ is due to the lack of collisions. In the extreme case where there is vacuum, the Townsend discharge cannot occur. In the expression for the ignition potential, the denominator can be equal zero. This unphysical behavior is related to the assumption that the mean free path of the electron is much smaller than the path length, so that the gain can be written as $G = e^{\alpha x}$.

The Townsend discharge is a slow process since it involves the drifting of the ions to the cathode and the drifting of the electrons through the amplification region. The ion feedback is negligible compared to the photon feedback (the factor $\gamma$ can be assumed to be zero), since the photon feedback is almost instantaneous, while the ion propagation happens on a time scale about three orders of magnitude larger than the electron drift time. The typical way to prevent this kind of discharges is to add in the gas mixture quenchers, molecules that absorb photons de-exciting non-radiatively (or radiatively but with innocuous photon energies), preventing the generation of secondary electrons on the metal surfaces.

### 3.3.2 Corona, Glow and Arc

Even though corona, glow and arc are not the most relevant discharges in gas detectors, a short description follows for completeness.

The corona discharge is a self sustained process that occurs in the presence of a high electric field gradient, typically produced in the vicinity of a sharp electrode at high voltage. It is characterized by a glowing region where the electric field is high and the electron avalanche occurs. In this region the gas becomes a plasma of electrons and ions and therefore conductive. There are two kinds of corona discharges: positive, if the electrons move towards the electrode, and negative in the other case. In the first case, the electrons are mainly produced by photoionization of the gas molecules, and the electrons undergo Townsend avalanche moving towards the electrode. In the second case, the electrons are extracted from the electrode by photoelectric effect, and they are multiplied while moving away from the high electric field region. Corona discharges can be the trigger or the precursor of the more violent electric sparks, where two electrodes are interconnected by a plasma channel.

Glow discharges are Townsend discharges at voltages higher than the ignition voltage, and typically they occur in a low density gas. They are characterized by a non-uniform light emission between the cathode and the anode, that reflects the electron energy distribution in different zones.
Increasing the current involved, the discharge becomes an arc. It is a process that relies on the thermionic electron emission from the cathode. The main source of electrons is not the Townsend avalanche, but the emission from the cathode that becomes hot because of the Joule effect. It is characterized by currents of the order of amperes and low voltages. In fact, the impedance of the system is small due to the large emission of electrons from the cathode.

### 3.3.3 The streamer

The streamer is probably the most important type of discharge regarding gas detectors. It is an extremely fast process (order of nanoseconds, depending on the typical dimensions of the device), and it involves high charge densities. To trigger such a spark, the total number of electrons must be larger than $10^6 - 10^8$, the so called Raether limit. The ignition of the spark is driven by the electric field distortion due to the space charge, and its evolution relies on the photon feedback (both on the gas and on the metal surfaces) and on the electron diffusion [91, 92, 93].

For the discussion we take as an example a parallel plate device with uniform electric field. The electron density moving towards the anode is peaked in the direction of the drift, because, in addition to the production of new electrons, the ones already present move forward. The ion distribution is broader and peaked behind the electrons, since the ions are moving towards the cathode. In the direction from the cathode to the anode, first there is an excess of positive charge and afterwards of negative charge, as sketched in Figure 3.2.

The electric field lines, parallel in absence of space charge, are deformed and attracted near the charge distributions. The effect is an increase of the electric field in front of the electrons (between the negative charge distribution and the anode) and behind the ions (between the cathode and the positive charge distribution). As a consequence, the Townsend coefficient in these regions increases, the same does the ionization rate, and the newly generated charge exacerbates the field distortion. This sort of positive feedback is the cause of the streamer.

The avalanche growth is faster and larger than what would be in the case of a uniform field, but it may not be sufficient to trigger a self-maintained process. What is experimentally shown [93] is that the discharge propagates in both directions. The interpretation of the discharge propagating towards the anode is obvious, while for the one in the cathode direction it is more subtle. The electrons in the high field region behind the ions are also subjected to a faster multiplication, but since they drift away from the high field region, the streamer propagation towards the cathode relies on:

1. the electron diffusion, because a fraction of the electrons moves against the drift direction,
2. the electron drift, because free electrons are already present along the path of the avalanche,
3. photon feedback, because the photons emitted in the high field region photo-ionize the surrounding atoms, also in the direction of the cathode.

Figure 3.3 shows the electron and ion spatial distributions at different positions along symmetry axis of the avalanche, corresponding to different times (for the details on the computation refer to Section 4.1). The two images represent the time evolution of a streamer generated in a gas gap, where the cathode is at 0 mm and the anode at 1 mm. The image on top represents the initial phase, when the avalanche transforms into a streamer (a curve every 5 ns). The image at the bottom shows the streamer propagation in the cathode direction (a curve every 0.2 ns).

In the early stage of the avalanche the charge clouds, located in the vicinity of the cathode, are Gaussian shaped, they grow exponentially with time, and the peak of the ionization rate (number of produced electron-ion pairs per unit time and volume) is located at the center of the electron distribution. As soon as the electric field distortion takes place, the peak of the ionization rate moves in front of the electron cloud, this makes it broader. The maximum of the electron density moves faster than the drift of the electrons, because it is mainly due to the new ionization electrons. At the same time, behind the maximum of the ion density, a second peak of the ionization rate is formed, and it moves against the electron flow, causing the electron distribution to extend towards the cathode. We stress the fact that, neglecting the diffusion and the ions, there are no particles moving towards the cathode. The process is
completely driven by the deformation of the electric field and the electron ionization. When the two tips of the discharge reach the anode and the cathode, a conducting channel of plasma is established between the two electrodes.

Figure 3.3: The images show the electron and ion densities and the ionization rate as a function of the position along the symmetry axis of the streamer at different times. The cathode is at 0 mm and the anode at 1 mm. In the top plot the time between two curves is 5 ns, while in the bottom it is 0.2 ns.
3.4 Electron amplification devices

Multi Wire Proportional Counters (MWPC) were invented by Charpak and collaborators [94] in 1968. Fast signals, large instrumented areas, fine spatial resolution and detection of small amount of charge are the key features and the reasons of the vast use of such a detector.

For decades MWPCs were developed and improved reaching the intrinsic limits of the device, namely:

1. the maximum rate is limited by the ions produced around the wires during the multiplication and drifting slowly towards the cathode,

2. the positive space charge can locally modify the electric field and consequently the gain,

3. the best achievable spatial resolution is of the order of few millimeters, limited by the electrostatic wire repulsion that can cause mechanical instabilities for long wires.

In order to overcome these limits in 1988 Oed [95] invented the MicroStrip Gas Chamber (MSGC), starting a new era of detector technology, generally called Micro Pattern Gaseous Detector (MPGD).

An enormous variety of technologies was developed in the last twenty years. In the following pages a short description of the most important ones is reported. A complete review on the topic can be found in [96].

3.4.1 MicroStrip Gas Chamber

The MSGC consists of a set of parallel metal strips on an insulating substrate, obtained with photolithography techniques. The strips are alternately connected to the anode and cathode potential, and the anode strips are usually less wide (few tens of micrometer) than the cathode ones. The electric field lines from the drift region are squeezed on the anode strips (see Figure 3.4), where the electric field is high enough to trigger the electron multiplication.

The avalanche is confined around the anode and the electrons drift a small distance before being collected. This makes the signals fast. Because of the electron diffusion, ions are produced diffused in the vicinity of the electrode. As a consequence, a large part of them is neutralized fast on the cathode strips, reducing the space charge effects and increasing the maximum sustainable rate. Moreover, since the strips are constrained on a rigid insulating support, the mechanical instabilities arising from the electrostatic repulsion of the strips are no longer an issue.

This type of detector is known not to be robust to sparks, that can permanently damage the strips. Long term operations showed gain fluctuations due to accumulation of charge on the non-conductive support. These effects are more pronounced at high interaction rates.

With the same philosophy of shaping the electric field using cathode electrodes in the vicinity of the anode, Microgap [97] and Microdots [98] devices were proposed as improved design of the MSGC.
3.4. ELECTRON AMPLIFICATION DEVICES

Figure 3.4: Electric field lines and equipotential lines in a MSGC (left), GEM (center) and Micromegas (right). The images are taken from [96]. The volumes at the top of the images are the drift regions. The amplification regions are where the field lines from the drift regions gather. In the GEM case the field lines are de-focalized before being collected on the anode.

3.4.2 Gas Electron Multiplier

The Gas Electron Multiplier (GEM) invented by Sauli [99] in 1996, is a thin (order of 50 $\mu$m) polyimide foil, chemically perforated (diameter of the holes of the order of 100 $\mu$m) and metal cladded on both sides.

A high electric field is obtained in the holes by applying a potential difference to the two conducting sides. The electric field lines from the drift region are focalized into the GEM holes (see Figure 3.4), where the electron avalanche occurs. Despite of the fact that all the drift lines from the drift region traverse the GEM and end on the anode, due to diffusion, part of the multiplied charge is collected on the bottom electrode of the GEM.

The unique feature of this technology is that the charge amplification can be separated in different stages by stacking GEM foils one on top of the other. This allows to reach very high gains (larger than $10^5$) even at high rates.

The walls of the holes absorb the photons generated during the avalanche, acting as a mechanical quencher and confining the streamer in the hole. This is the reason why the GEM can be operated in pure noble gases. Fast signals, very good spatial resolution and fast ion neutralization are typical features of the GEM.

Devices that use the same design principles are the so called Large Electron Multiplier (LEM) [100], also known as Thick GEM [101]. Contrary to the GEM, the dielectric material is glass epoxy, its thickness is of the order of a millimeter, and the holes are mechanically drilled.
3.4.3 Micromesh Gaseous Chamber

The Micromegas, invented by Giomataris and collaborators [102] in 1996, consists of an anode plane, usually segmented, with a metallic mesh at a distance of the order of 50–100 µm, kept constant by dielectric spacers every few millimeters. An almost uniform electric field is attained in the gap (see Figure 3.4).

The Micromegas technology exploits the saturation behavior of the Townsend coefficient as a function of the electric field, improving the energy resolution and the uniformity of the response over large areas. The high electric field and the small gap guarantee fast rising signals. Most of the ions created during the avalanche in the gap are quickly neutralized on the mesh. This avoids the drawback of the space charge effects in the drift region. The detector has sub millimeter spatial resolution, and it sustains high rates.

With an analogous technology the mesh can be installed on top of a CMOS sensor. This device, called GridPix [103], has an extraordinary spatial resolution, it is characterized by a very low intrinsic noise, and the signals are immediately digitized in the chip (it can keep the timing information).

3.4.4 Remarks

The performance of the devices mentioned above depends on design parameters (typical sizes), materials, construction techniques, gas mixtures, and they are all optimized for room temperature operation. We are interested in a device capable of operating in pure argon vapor and in a cryogenic environment. Not all the mentioned devices are suitable for this kind of use, and the geometry optimization done so far may not be valid.

In pure argon gas the VUV photons propagate freely, and they may extract secondary electrons from the metals. To quench the photon propagation a GEM-like geometry is preferable. In fact, the operation of GEMs is proven in pure noble gases at room temperature [104, 105], and small prototypes were tested in cryogenic conditions [106, 107].

The device must resist to the stress arising from being produced at room temperature, but operating at cryogenic temperatures, i.e. the elasticity and the thermal expansion coefficients of the materials must be carefully chosen.

We are interested in the scalability to a large active area, this means that the device should be stiff and self supporting (a quality that facilitates the mechanical engineering of the detector), and the production of prototypes of the order of one square meter should be possible.

Another suitable quality for such a device is the spark hardness, the ability to sustain discharges without being permanently damaged.

All these considerations focus the interest on the LEM/Thick GEM, device that will be described in the next chapter.
Chapter 4

Design of the double phase argon LEM-TPC

This chapter is dedicated to the description of the double phase (liquid-vapor) argon Large Electron Multiplier Time Projection Chamber, the merging of the liquid argon Time Projection Chamber (TPC) with the signal amplification technology of the Large Electron Multiplier (LEM). The double phase argon LEM-TPC is a tracking and a calorimetric radiation detector, capable of signal amplification. It maintains the three dimensional tracking abilities of the liquid argon TPC, and it improves the signal to noise ratio, that results in a lower energy threshold and a better image quality.

The double phase is required because the charge amplification is impossible in the liquid, but it is allowed in the dense argon vapor. A scheme of the operation principle is shown in Figure 4.1. A charged particle interacts in the liquid argon ionizing it. The electron-ion pairs left after the recombination are separated by the uniform electric field applied in the drift volume of the TPC. The electrons, drifting upwards, reach the liquid level, where they are extracted to the vapor phase. The electrons drift towards the LEM, and they are focussed into its holes, where the charge avalanche occurs. The multiplied charge, exiting the holes, induces current pulses on the readout electrodes. A cryogenic Photo Multiplier Tube (PMT), mounted below the transparent cathode, records the prompt photons from the liquid argon scintillation. This signal provides the trigger and the time reference to the event. The reconstruction of the three dimensional position of the event is analogous to the one in a standard TPC.

In the following sections we discuss the design of:

1. the extraction grids, the device that makes possible to efficiently transfer the electrons from the liquid to the vapor phase,

2. the LEM, focussing on the streamer development in a hole,

3. the two views anode, the device that allows to readout two orthogonal sets of strips
4.1 Design of the Large Electron Multiplier

As already mentioned, the Large Electron Multiplier (LEM) is a millimeter-scale sister of the Gas Electron Multiplier (GEM) device. It is a Printed Circuit Board (PCB) made out of standard glass epoxy cladded with metal on both faces and with holes mechanically drilled in a honeycomb pattern. Applying a sufficient potential difference to the two metal faces, an almost uniform electric field strong enough to trigger the electron avalanche is attained in the holes. To some extent, the LEM is a transparent object for the drifting electrons, in the sense that the charge that is focalized into the holes exits from them, after being multiplied, continuing the drift. The photons produced during the avalanche are absorbed by the dielectric walls of the holes, ensuring the confinement of the multiplication in absence defining the coordinates on a plane orthogonal to the drift.

The details of the construction of these parts are addressed in Chapter 5, what follows is their conceptual design and the description of their expected behavior. We begin with the details of the LEM design, because we introduce a computation framework that is used also for the design of the anode and the extraction grids.

4.1 Design of the Large Electron Multiplier

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4.1. DESIGN OF THE LARGE ELECTRON MULTIPLIER

<table>
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<th>value</th>
</tr>
</thead>
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</tr>
<tr>
<td>hole diameter</td>
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<tr>
<td>hole pitch</td>
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<td>electrode thickness</td>
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</tr>
<tr>
<td>rim</td>
<td>50 (\mu m)</td>
</tr>
</tbody>
</table>

Table 4.1: Values of the geometry parameters of the standard LEM.

of quenching gases. The LEM is suited for the operation in cryogenic conditions because the thermal expansion coefficient of the metal and of the glass epoxy are well matched. It sustains without any damage abrupt cooling down and warming up cycles, and it is a device known to be sturdy and spark resistant.

4.1.1 LEM geometry

The important geometry parameters of a LEM are the following:

1. the thickness of the PCB,
2. the hole diameter,
3. the distance between the centers of two neighboring holes (hole pitch),
4. the thickness of the metal electrodes,
5. the size of the area around each hole where the metal is etched away leaving the dielectric material exposed (rim),
6. finally the active area.

We call the region before and after the LEM the transfer volume and the induction volume respectively, and the electric fields applied are called the transfer field and the induction field. The electric field in the LEM holes is referred as amplification field. Concerning the electric field, we always refer to the nominal electric fields, namely the voltage between two electrodes divided by their distance.

The values of the geometry parameters for what we consider the standard LEM are summarized in Table 4.1. It is called standard because, after the optimization through different experimental tests, this configuration is the best compromise between the design requirements and the production limitations.

4.1.2 Streamer simulation in a hole

As discussed in Section 3.3, the streamer discharge is the most relevant kind of discharge concerning electron amplification gas detectors. We already described the mechanism of the
CHAPTER 4. DESIGN OF THE DOUBLE PHASE ARGON LEM-TPC

streamer discharge, in the following paragraphs we describe the tool developed in order to simulate the formation and the propagation of the streamer in an arbitrary geometry. The approach to the computation is inspired by the work of Fonte on the streamer computation presented in [108, 109].

The computation is based on Comsol Multiphysics\(^1\), a proprietary Finite Element Analysis (FEA) software able to find a numerical approximation on an arbitrary mesh of the solution \(u\) of a set of second order partial differential equations, that can be written as:

\[
e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} - \nabla \cdot (c \nabla u + \alpha u - \gamma) + \beta \cdot \nabla u + au = f \quad \text{in } \Omega,
\]

\[
\vec{n} \cdot (c \nabla u + \alpha u - \gamma) + qu = g - hT u \quad \text{on } \partial\Omega,
\]

\[
hu = r \quad \text{on } \partial\Omega,
\]

where \(\vec{n}\) is a vector orthogonal to the surface \(\partial\Omega\) of the domain \(\Omega\), and the other coefficients can depend on unknowns. In other words, the program allows to interconnect different physics problems through the choice of the coefficients. This is the strength of the program and the reason why it was chosen.

As the base point of the discussion, we consider a single hole of the standard LEM (sketched in Figure 4.2) in pure argon gas at 1 bar and at 20° C. The reason why the simulation is performed with gas at room temperature is because in practice most of the optimization tests are done at room temperature, since the experiments in cryogenic conditions are more difficult, time consuming and expensive. Moreover, at room temperature the gas density can be easily changed varying the pressure.

In the computation the length of the transfer volume and the induction volume is fixed to 1 mm. The transfer field and the induction field are 1 kV/cm and 3 kV/cm respectively. The streamer regime is reached at a nominal amplification field of 22.9 kV/cm. The local electric field where there are sharp edges strongly depends on their curvature. We assume that the construction and cleaning procedures smooth the edges with a typical radius of 5 \(\mu m\).

Even though this is a simplified model, the main features and trends of the real device are reproduced, and the computation can be used to optimize the geometry parameters and understand the limits of the LEM.

\(^{1}\)http://www.comsol.com
4.1. DESIGN OF THE LARGE ELECTRON MULTIPLIER

Figure 4.2: Left: the axial symmetric geometry of the LEM hole. The PCB is depicted in orange, the metal of the electrodes in white and the argon gas in dark gray. Right: the color scale shows the electric field strength in the LEM hole without (left) and with (right) charging up of the dielectric.

Mathematical formulation of the problem

The problem of calculating the evolution in time of the streamer can be simplified and expressed in terms of the following set of partial differential equations:

\[
\vec{\nabla}^2 V = -\frac{q_e}{\epsilon}(n_i + n_e),
\]

\[
\frac{\partial n_e}{\partial t} = (\alpha - \eta)P|\vec{W}_e|n_e - \vec{\nabla} \cdot (\vec{W}_e n_e - D_e \vec{\nabla} n_e),
\]

\[
\frac{\partial n_i}{\partial t} = (\alpha - \eta)P|\vec{W}_e|n_e,
\]

where \( V \) is the electric potential, \( q_e \) is the electron charge, \( \epsilon \) is the permittivity of the gas (approximately the permittivity of vacuum \( \epsilon_0 \)), \( n_e \) and \( n_i \) are the electron and ion spatial distributions. \( \vec{W}_e, D_e, \alpha \) and \( \eta \) are the electron drift velocity, the electron diffusion tensor, the first Townsend coefficient and the attachment coefficient\(^2\) respectively, all dependent on the electric field. \( P \) is the fraction of atoms not yet ionized per unit volume. The unknowns are \( V, n_e \) and \( n_i \).

The first equation is the first Maxwell equation for the potential, written in differential form. The second and the third equations are the diffusion and the convection equations for the negative and positive charges respectively. The time variation of the local charge density

\(^2\)The attachment coefficient \( \eta \) is the probability per unit path that a free electron is trapped by an electronegative atom or molecule.
is due to two distinct phenomena:

1. the rate of electron-ion pairs production, that can be written as the drifting electron flux \( |\vec{W}_e| n_e \) multiplied by the probability per unit path length to create (and not recombine) new electron-ion pairs \((\alpha - \eta)\), times the probability that the collision happens against an atom not yet ionized \((P)\),

2. the movement of the existing charges due to the drift, i.e. convection \((-\nabla \cdot \vec{W}_x n_x)\) and the diffusion \((\nabla \cdot D_x \nabla n_x)\).

In this model the first approximation is to treat the ions as stationary particles in the time range of few hundreds of nanoseconds. Their speed and diffusion coefficient are set to zero, and consequently no ion feedback is taken into account.

A more important approximation is the absence of photon feedback. The discharge propagation against the electron drift is supported by the electron diffusion only. One of the possible ways to treat the photon flux \(\Psi\) is described in [110], and it implies to add in the set of partial differential equations the following one:

\[
-\frac{\lambda}{3} \nabla^2 \Psi + \frac{1}{\lambda} \Psi = \zeta \alpha P |\vec{W}_e| n_e,
\]

where \(\lambda\) is the photon absorption length in the gas, and \(\zeta\) is the number of photons produced per ionization. In addition, a term proportional to the absorbed photons should be added as source of new electron-ion pairs. The proportional constants should be treated as effective quantities that average all the possible photon energies and, in case of gas mixtures, all the cross sections.

The approximation of neglecting the photons is justified by the fact that we are interested in the computation of streamer formation and propagation in pure argon gas, where the self photoionization is not possible. Photons arising from the de-excitation of neutral argon atoms are by definition not enough energetic to further ionize. Lines with energies larger than 17 eV are present in excited states of the single ionized argon [111, 112], but they cannot contribute to the photoionization because (1) the local fraction of the ionized atoms do not exceed \(10^{-3}\) of the to total argon atoms, making unlikely that a drifting electron can excite an ion, and because (2) the lifetimes of excited neutral and ionized argon atoms are of the order of several nanoseconds [113, 114], much longer than the typical time between atom collisions in dense gas. Therefore, the excited molecular state of argon is formed from an excited argon atom via the three body collision \(Ar^* + 2Ar \rightarrow Ar_2^* + Ar\) [115], and it de-excites emitting a 128 nm photon [53].

The 128 nm photons from the dimer de-excitation may be able to extract electrons via photoelectric effect from the material in the detector. The quantum efficiency of dielectric materials is supposed to be very small and can be neglected. Photoelectric efficiencies for VUV photons on metals are not negligible (order of few percent [116]), but, in the geometry
4.1. DESIGN OF THE LARGE ELECTRON MULTIPLIER

we are interested in, the electrodes are either shadowed by dielectric material, or the emitted electron would immediately drift into the electrode because of the electric field. Nevertheless, this is one of the first phenomena to be taken into account to improve the performance of the computation. One must be aware that the effect of neglecting the photon feedback is to increase the discharge limit.

Another simplification of the model is that the second (and further) ionizations are neglected because the small relative abundance of ions, and the fact that the second ionization potential of argon is 27.6 eV, much larger than the typical kinetic energy of the involved electrons.

Part per million level impurities that can be diluted in the argon gas are neglected in this context, and also the Penning effect (see Section 3.2) is not considered. The attachment coefficient for argon is set to zero, and no negative ions are taken into account.

Approach to the computation

The solution of the described set of partial differential equations is approximated with numerical techniques. Some advantages in using Comsol Multiphysics to solve the problem are:

1. Comsol is a ready-to-use, cross-platform and very customizable program,
2. Comsol allows to describe complex geometries without the help of a CAD program,
3. the simulation requires computation of the electric field (dependent on the space charges), the transport of electrons (convection and diffusion), and the creation of electron-ion pairs according to the Townsend multiplication mechanism. This is easily setup using the transport of diluted species package and electrostatic package, already implemented in Comsol,
4. the electron drift velocity, the diffusion coefficients parallel and perpendicular to the electric field and the first Townsend coefficient depend on the electric field (that is an unknown of the problem) and can be provided as input parameter. They are computed with Magboltz 8.4 [86] and shown in Figure 4.3,
5. to our knowledge, Comsol is the only program that can find an approximate solution to a set of interconnected partial differential equations.

As an alternative the standard Monte-Carlo approach is possible for the transport of the charged particles, but it requires as input the electric field map, that depends on the charge spatial distribution. This means that an iterative approach using the tracking software (Monte-Carlo) and the field computation software (typically FEA) is required. Moreover, when the particles involved are a significant fraction of a billion, the computational time diverges and non-conventional Monte-Carlo strategies must be used.
Figure 4.3: The three plots display the electron drift velocity, the longitudinal and transversal (with respect the electric field) diffusion coefficients and the first Townsend coefficient as a function of the electric field in argon gas at 1 atm and 20° C. The computation was performed using Magboltz 8.4 [86]. The curves are input parameters of the COMSOL computation.

Nevertheless, the implementation in Comsol introduces approximations and limitations. First of all, due to the fact that the computation is extremely demanding in terms of CPU time and RAM usage, the three dimensional problem is approximated by a two dimensional axial symmetric problem. This implies that any asymmetry in the coordinate $\phi$ cannot be reproduced. In addition, on the side of the two-dimensional volume the normal electric field component and the electron flux are constrained to be zero.

The charging up of the dielectric is treated as a dynamic equilibrium process. The field configuration of a non-charged-up LEM has the field lines crossing the dielectric. This leads the charges to be accumulated on the walls until the electric field lines become parallel to the dielectric surfaces (see Figure 4.2). To maintain the equilibrium an electron must be released from the dielectric surface when one diffuses against it. With this assumption the normal component of the electric field on the dielectric surfaces is kept at zero.

The first Townsend coefficient ($\alpha$), the drift velocity ($v$) and the diffusion coefficients ($D$) are computed with Magboltz 8.4 [86] at 1 atm at 20° C. To evaluate the parameters at different
gas densities ($\rho$) scaling laws are used. Namely, for a fixed reduced electric field ($E/\rho$), $\alpha/\rho$, $v$ and $D\rho$ are constants. We already explained in Section 3.1 that the reduced electric field is a quantity proportional to the kinetic energy gained by an electron between two collisions, consequently, fixing $E/\rho$ one fixes the electron energy distribution. We also explained that $\alpha/\rho$ is proportional to the ionization probability per collision, constant for a given electron energy. For the drift velocity the considerations are analogous. In the approximation where the electron is at rest after a collision with an atom, the drift velocity equals the average speed of the electron between two collisions. It depends on the product of the acceleration and the mean free path, a quantity that is proportional to $E/\rho$. Concerning the diffusion coefficient, the considerations are a bit more subtle. Let’s first recall that the electron mean free path ($\lambda$) is inversely proportional to the gas density, and that the number of collision ($n$) in a given distance ($\Delta x$) is directly proportional to the gas density. The transversal displacement of an electron between two collisions is proportional to the electron mean free path (it is the projection of the electron free flight on the transversal plane), and we can write it as $\xi \lambda^3$. All the collisions are independent, so that the random displacements after each one must be summed in quadrature to obtain the total displacement $\sqrt{2D\Delta x/v}$. It means that $\xi \lambda\sqrt{n} = \sqrt{2D\Delta x/v}$, that implies that $D\rho$ is proportional to $\xi^2$, a quantity related to the electron-atom collision and, therefore, constant for a given $E/\rho$.

During the streamer formation the electric potential on the electrodes is kept constant. This is ensured by the fact that the charge on the electrodes is much larger than the charge in the avalanche, in fact the latter is of the order of 10 pC, and the charge on a LEM of surface 1 cm$^2$ and thickness 1 mm powered with 2 kV is of the order of 10 nC.

The geometrical imperfections and dissimilarities between the holes cannot be taken into account. The geometry reproduced is the one of the average hole, without defects.

Also the avalanche statistics cannot be taken into account. One can think of the computation as the simulation of the evolution of the average spark, even though it is not a well defined concept. The statistics of the avalanche is very important to define the discharge probability of a device, because, as it is explained in the next paragraph, the discharge limit is strongly coupled to the total number of electron-ion pairs produced in the avalanche. In the context of the Furry distribution (see Section 3.1), we consider the avalanches with an average gain $G$ generated by a single electron. The fraction of avalanches that contains more than $m$ electrons is $(1 - 1/G)^m$. Approximately this means that $10^{-k}$ of the avalanches contains more than about $2.3kG$ electrons or, in other words, when the spark limit is ten times larger than the average gain, about $5 \times 10^{-5}$ of the incoming electrons would generate a discharge.

Naturally, neglecting the imperfections of the holes and the statistics of the avalanche can change the discharge limit. The simulation computes the average streamer in a perfect average hole. In reality the discharge happens in a single hole (maybe with a defect) during

$^3\xi$ is the dimensionless proportionality constant dependent only on the collision process.
an avalanche that, because of statistical fluctuations, contains more charge than the average.

4.1.3 Results of the computation

The images in Figure 4.4 show the snapshots every 2 ns of the avalanche propagation. The pictures represent the hole in cylindrical coordinates, displaying in orange the dielectric and in blue the argon gas. The nominal electric field in the LEM hole is 23 kV/cm. The avalanche is created by a single electron leaving from the bottom LEM electrode and being multiplied in the region close to the dielectric. In about 15 ns the charge crosses the hole and accumulates in the high field region at the top corner of the dielectric. Here is where the electric field is distorted and the streamer is triggered. The rainbow-colored contour lines represent the electron distribution, and the grey scale contour lines represent the ion distribution. The number of electron-ion pairs produced per unit volume and unit time (ionization rate) is displayed with the continuous color map.

The streamer formation and its propagation are shown in Figure 4.5. The drift velocity is displayed with arrows with length proportional to the electron speed. In the different snapshots the velocity changes according to the electric field distortion due to the space charge, that, we recall, is the driving phenomenon of the streamer discharge, together with the electron diffusion. The peak of the ionization rate moves against the electron drift and, when it reaches the bottom electrode of the LEM, a plasma channel interconnects the two electrodes discharging the LEM and lowering the potential difference of the two electrodes.

Changing the most relevant parameters of the LEM, the described features of the discharge stay the same. We summarize the behavior of the LEM in the following tables, taking as starting point the standard LEM. The quantities taken into account are:

1. the number of electrons \( n^0_e \) at the entrance of the LEM hole and their position (the center of the holes or the edge of the bottom electrode),
2. the nominal electric field in the LEM hole \( E_0 \), defined as the ratio of the voltage applied between the electrodes and the dielectric thickness,
3. the maximum electric field \( E_{\text{max}} \) in argon gas, usually obtained in the corners of the dielectric,
4. the gain \( G \), defined as the charge collected on the anode divided by the charge at the input,
5. the total number of created pairs, identified with the total number of ions \( n_{\text{ion}} \).

The spark limit is well defined by the total number of electron-ion pairs produced. This is evident from the data in Table 4.2, that summarize the spark limit configuration obtained for different numbers of input electrons. Exceeding about \( 1.7 \times 10^7 \) electron-ion pairs the streamer is triggered, and therefore the maximum gain achievable depends on the initial
Figure 4.4: Snapshots at different times (every 2 ns) of an avalanche that evolves in a streamer. The orange volume is the LEM dielectric with the electrodes on top and on the bottom (note the dielectric rim). The blue volume represents the argon gas. The electron distribution is shown with the rainbow-colored contour lines, and the ion distribution is shown with the gray scale contour lines. The continuous color map represents the ionization rate.
Figure 4.5: Snapshots at different times (every 1 ns) of the streamer formation. The streamer begins around the top edge of the LEM dielectric, where the hole wall and the rim join. In addition to what is displayed in Figure 4.4, here the drift velocity (approximately proportional to the electric field) is shown with arrows of length proportional to the electron speed.

Multiplying the gain with the initial number of electrons, one does not obtain the total number of electron-ion pairs, because more than half of the charge is produced in the vicinity of the top edge and collected on the top LEM electrode. The values of $Gn_e^0$ are different for the three conditions, because the edge effect becomes more important the higher the maximum electric field is.

The LEM transfer efficiency is defined as the fraction of the charge produced in the
hole that reaches the anode. It depends on the ratio between the induction field and the amplification field. The bigger is this ratio, the larger the fraction of the charge reaching the anode is. In the extreme case where the induction field is larger than the amplification field, all the electrons end on the anode. In the opposite extreme case where the induction field is opposite to the amplification field, the electrons are totally collected on the LEM.

The efficiency to focus the electrons coming from the drift region into the holes depends on the ratio between the amplification field and the drift field. In the standard LEM case a field ratio of the order of 10 is sufficient to be 100% efficient. This is due to the fact that the entire bottom electrode of the LEM repels the electrons. This is no longer valid when the hole density is too small (pitch too large).

The multiplication in the hole depends on the initial position of the charge. In the central zone of the hole the electric field is weaker than in the region close to the hole wall (side region). The charge multiplied in the center region is efficiently transferred to the anode, while the one produced in the side region is collected on the top electrode. There are two ways for the charge to reach the side region: (1) due to diffusion the electrons coming from the drift region can migrate towards the walls, and (2) the charge is created in the vicinity of the bottom electrode (gas ionized by natural radioactivity or electrons emitted from the metal). In addition, in the region close to the dielectric rim and the electrode there are sharp edges, and the electric field is considerably larger than everywhere else. The charges collected by the top electrode undergo an amplification boost just before being collected.

Since the spark limit is well defined by the total charge in the avalanche, the maximum gain of the central region is limited by the gain of the side region. We define as the maximum amplification field the one for which a single electron leaving from the bottom electrode produces a discharge. Associated to this field we also define the maximum gain as the total charge collected on the anode, starting from a single electron aligned to the center of the hole. We use these quantities as benchmark of the design and to understand the behavior of the LEM, though we do not expect that the model can reproduce the absolute values of maximum gain and field, because of the mentioned approximations (mainly the impossibility to take into account the hole imperfections and the avalanche statistics).

An important design parameter is the size of the rim. Intuitively the bigger it is the more the two electrodes are protected, and the higher the spark limit is. This is also the outcome of the computation. In the Table 4.3 the relevant parameters are reported for different rim sizes. The maximum electric field reduces with the rim size, and this allows to increase the applied

<table>
<thead>
<tr>
<th>( n_0 )</th>
<th>( E_0 ) (kV/cm)</th>
<th>( E_{\text{max}} ) (kV/cm)</th>
<th>( G )</th>
<th>( n_{\text{ion}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>23.8</td>
<td>72.1</td>
<td>6.29 \times 10^7</td>
<td>1.67 \times 10^7</td>
</tr>
<tr>
<td>100</td>
<td>22.5</td>
<td>68.1</td>
<td>7.17 \times 10^4</td>
<td>1.68 \times 10^7</td>
</tr>
<tr>
<td>1000</td>
<td>21.1</td>
<td>63.8</td>
<td>8.17 \times 10^3</td>
<td>1.71 \times 10^7</td>
</tr>
</tbody>
</table>

Table 4.2: Spark limit of the standard LEM for different input charges.
voltage, improving consequently the maximum gain. The wide rim has also disadvantages, in fact there are indications [117] that the bigger the rim is, the less stable is the LEM response, due to charging up effects.

Table 4.4 shows that the maximum achievable gain is increasing with the thickness of the LEM electrodes (thickness of the metal). The thick electrodes have also the benefit of being more spark resistant. This is mainly due to the fact that the heat from the Joule effect is dissipated more efficiently.

Decreasing the PCB thickness we find that the maximum gain reduces, as shown in Table 4.5. The electric field in the LEM hole increases not sufficiently to compensate the reduction of the amplification length. The difference in gain between the side region and the central region increases. This can be understood from the fact that the uniformity of the field in the LEM hole worsens. Nevertheless, on the thickness of LEMs there are also other constraints. The mechanical stability becomes an issue for devices of large area (order of 1 m²) and, to avoid structures that reduce the active area, a large LEM thicknesses is preferable. If the LEM is too thick, the collision of the electrons against the dielectric due to diffusion and the consequently charging up of the hole wall may become a dominant effect.

The last parameter that is worth mentioning is the gas density (pressure). The results of the scan are reported in Table 4.6. Increasing the density by a factor three, the maximum gain decreases more than a factor ten. The gain difference between high field region and low field region increases with the gas density.

It is interesting to notice that between the gas density and the device dimensions there is an analogy. We already showed in Sections 3.1 and 3.3 that two systems with the same value of $\rho x$ are equivalent. In other words, keeping the geometry proportions and the voltage configuration unchanged, scaling the device size by a factor $f$ and the gas density by a factor $1/f$, the number of collisions the electron undergoes and its energy (but not the drift velocity) are the same. To some extent, the same behavior is expected for thick LEMs in rarefied gas and thin LEMs in dense gas. From the results reported in Table 4.6, this means that scaling down the LEM dimensions the spark limit can be improved in dense argon gas.
4.1. DESIGN OF THE LARGE ELECTRON MULTIPLIER

Table 4.5: Spark limit configurations changing the dielectric thickness.

<table>
<thead>
<tr>
<th>dielectric (mm)</th>
<th>$E_0$ (kV/cm)</th>
<th>$E_{max}$ (kV/cm)</th>
<th>$G$</th>
<th>$n_{ion}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>22.9</td>
<td>69.3</td>
<td>$3.13 \times 10^9$</td>
<td>$8.58 \times 10^9$</td>
</tr>
<tr>
<td>0.8</td>
<td>25.3</td>
<td>73.2</td>
<td>$1.20 \times 10^5$</td>
<td>$3.02 \times 10^5$</td>
</tr>
<tr>
<td>0.6</td>
<td>29.3</td>
<td>79.1</td>
<td>$3.86 \times 10^4$</td>
<td>$8.47 \times 10^4$</td>
</tr>
</tbody>
</table>

Table 4.6: Spark limit configurations changing the gas pressure (density).

<table>
<thead>
<tr>
<th>P (atm)</th>
<th>$E_0$ (kV/cm)</th>
<th>$E_{max}$ (kV/cm)</th>
<th>$G$</th>
<th>$n_{ion}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>19.8</td>
<td>59.9</td>
<td>$3.88 \times 10^5$</td>
<td>$8.90 \times 10^5$</td>
</tr>
<tr>
<td>1.0</td>
<td>22.9</td>
<td>69.3</td>
<td>$3.13 \times 10^5$</td>
<td>$8.58 \times 10^5$</td>
</tr>
<tr>
<td>2.0</td>
<td>35.7</td>
<td>108</td>
<td>$7.20 \times 10^4$</td>
<td>$1.92 \times 10^5$</td>
</tr>
<tr>
<td>3.0</td>
<td>46.9</td>
<td>143</td>
<td>$3.10 \times 10^4$</td>
<td>$6.55 \times 10^4$</td>
</tr>
</tbody>
</table>

4.1.4 Summary of the LEM design study

The performance of the LEM can be summarized recalling that the maximum gain achievable improves:

1. the smaller the input charge is,

2. increasing the rim size,

3. increasing the electrode thickness,

4. the more rarefied is the gas and, analogously, scaling down the dimensions of the device keeping the proportions unchanged.

The choice of the parameters should take into account other constraints or limitations for instance:

1. to have a perfectly aligned rim to the hole, its size is limited by construction procedures (described in details in Section 5.3),

2. the thickness of deposited metal on PCBs are standards,

3. the thickness of the PCB is constrained on the low side by rigidity requirements and on the high side by the electron diffusion,

4. to efficiently focus the electrons from the transfer volume into the holes, it is convenient to have a high hole density, but it implies less mechanical stability, higher cost and higher risks to have some holes with defects.

From these considerations, in order to build the detector described in Chapter 5, we opted for what was called standard LEM. Overcoming the mechanical and cryogenic problems, a promising device would be the GEM. In fact, because of the reduced size, the expected maximum gain in dense argon vapor is larger, and the electric fields are obtained applying relative low voltages.
4.2 Two views projective anode

The charge that leaves the LEM must be readout in such a way that allows to reconstruct the image projection on the plane orthogonal to the drift. The anode mounted on top of the LEM can be segmented into pixels, but the number of channels increases quadratically with the linear dimension of the anode. The anode can be divided into independent readout strips (along one direction), and the same can be done on the top electrode of the LEM (along the other direction), but the sharp edges due to the segmentation makes the LEM more prone to discharges (see also the appendix). An alternative is to print on the anode two independent orthogonal sets of strips. This is implemented in the so called two views anode, proposed for the first time in [118]. The advantage of this configuration is that both views have the same signal shapes, the charge sharing is independent of the electric field configuration of the LEM, and the amplification stage is completely decoupled from the readout stage. Moreover, since the two views are both collection views, they do not suffer the signal cancellation due to extended charge distributions along the drift (typical problem of the induction view discussed in Section 2.6). Tracks parallel to the drift direction are properly recorded with this kind of anode.

The anode consists of thin metal strips glued on wider orthogonal strips and insulated with a dielectric material (polyimide), as the Figure 4.6 shows. The two sets of strips are at the same potential, and the sharing of the charge is determined only by the geometry. The goal is to define the parameters for which the charge is equally divided and collected on the two sets of strips.

The computation is based on the electrostatic computation of the electric field. The number of electric field lines uniformly distributed in the uniform electric field region and ending on a strip is proportional to the amount of charge collected on it. As shown in Figure 4.6, in order to collect the same amount of charge on the two orthogonal set of strips, the exposed strips (directly facing the LEM) are less wide than the covered strips (partially hidden by the thin ones), because they act as a sort of shield. The charge sharing is independent of the value of the electric field between the anode and the LEM, but, since some charge ends on the top LEM electrode, increasing this field the collection of the total charge on the anode improves.

The geometry parameters are chosen taking into account that the smallest electron cloud exiting the LEM must illuminate both views. The charge cloud leaving a hole is bigger than the hole itself and smaller than the distance between two holes. For this reason the distance between two parallel strips is chosen to be 600 µm. The optimal parameters are reported in Table 4.7. They take into account the typical thickness of the metal and the polyimide (for the insulating layer) commercially available.

The segmentation that guarantees a proper sharing of the charge even for the small electron clouds is generally too fine for the readout. The strips can be connected together
4.3 EXTRACTION GRIDS

From Figure 2.6 it is evident that the electron extraction is 100% efficient and fast when an electric field larger than 2.5 kV/cm is applied in the liquid orthogonally to its surface. In order to implement such a condition one can apply the electric field over the entire drift region, or only in a well-defined slice in the vicinity of the liquid surface. The first solution is unfeasible for detectors of large drift distances, because it requires very large potential differences that are difficult to deal with (usually the drift field is lower than 1 kV/cm). The

We underline the fact that the charge is shared between the two views, this means that the signal amplitude on each one is half of what would be recorded using an anode segmented in one direction only. This fact is not a critical issue in the double phase LEM-TPC, because the charge is amplified before being collected.

4.3 Extraction grids

Figure 4.6: Overview (top) and schematic view (bottom right) of the two views anode. Result of the electrostatic computation (bottom left) showing the drift lines collected half on the exposed (thin) strips and half on the covered (thick) strips.

in groups (outside the sensitive area), forming effective strips of wider pitch, suitable for the readout.

We underline the fact that the charge is shared between the two views, this means that the signal amplitude on each one is half of what would be recorded using an anode segmented in one direction only. This fact is not a critical issue in the double phase LEM-TPC, because the charge is amplified before being collected.
second alternative can be realized using two parallel grids across the liquid-vapor interface and with them confining the high field region.

The electric field on the liquid surface must be uniform, the electrons must pass through the grids without being collected on them, and the spatial distribution of the charge before the grids must be maintained as much as possible in the vapor in order to avoid image distortions. This condition can be achieved using grids consisting of a set of parallel conducting wires at a fixed pitch. The two grids must be parallel to the liquid level, with the wires of both grids running in the same direction, well aligned and exactly one on top of the other.

The grids performance was studied using a model similar to the one used to simulate the streamer discharge. The problem is simplified because the electric field in gas is too weak to trigger the electron avalanche, and the amount of charge is not enough to modify the electric field. The simulation concerns only the transport of electrons in two media with different propagation characteristics. The extraction efficiency and the extraction time dependence on the electric field are not considered in this section, because these processes are completely disentangled from the geometry of the grids.

In addition to the electrons transport properties in gas, we need the electron drift velocity and diffusion in liquid argon around 87 K. In liquid argon the drift velocity is well measured, and the results are reported in Figure 2.5. In the computation the velocity is parametrized by a smooth function approximating the data.

The knowledge on the diffusion coefficient is more limited, and the experimental data are scarce. The measurements are summarized in Figure 2.5. For the computation we assume the diffusion in liquid to be isotropic, and we use an electric-field-independent value for the diffusion coefficient of 15 cm$^2$/s. Slight variation of this value does not affect the output of the computation.

For reasons of symmetry the grids are described in a two-dimensional space with mirror symmetry conditions on the borders parallel to the drift, as it is shown in Figure 4.7. This image shows the time evolution (one snapshot every 0.5 µs) of a planar charge distribution approaching the grids. The electrons are repelled by the wires in liquid, this means that there is no risk that the charge is lost on this part. The charge distribution is deformed because the electrons are squeezed between the wires. In this region the field is almost uniform, larger than the drift field and high enough to allow the effective extraction of the electrons. In the

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strip pitch</td>
<td>600 µm</td>
</tr>
<tr>
<td>exposed strip width</td>
<td>120 µm</td>
</tr>
<tr>
<td>covered strip width</td>
<td>500 µm</td>
</tr>
<tr>
<td>metal thickness</td>
<td>30 µm</td>
</tr>
<tr>
<td>insulating foil thickness</td>
<td>50 µm</td>
</tr>
</tbody>
</table>

Table 4.7: Optimal design parameters for the two views anode.
4.3. EXTRACTION GRIDS

Figure 4.7: The top figure shows the time evolution of the charge extraction from the liquid to the vapor phase. The time interval between the pictures is 500 ns. The color scale is proportional to the logarithm of the electron density. The electric field lines are drawn in black. The white circles highlight the position of the wires and the liquid argon level is in the middle between them. The nominal electric field configuration is 500 V/cm for the drift volume in liquid argon, 2500 V/cm for the extraction and 750 V/cm for the transfer field in gas. The curve on the bottom plot is the normalized amount of charge in the considered volume as a function of time. The drop around 5.5 $\mu$s is due to the charge collected on the grid in gas.

In gas phase the electrons are subjected to larger diffusion and, crossing the grid in gas, part of the charge is collected on it. The role of the grid in gas is to partially restore the electron spatial distribution and lower the electric field after the grids. As shown in the plot on the bottom of Figure 4.7, about the 75 % of the charge survives the passage of the grids, and it drifts freely in the uniform field in gas.

The considered volume can be thought as divided in three parts: the drift volume (below the grid in liquid), the extraction volume (between the grid in liquid and the one in gas) and the transfer volume (above the grid in gas), each one with the respective electric field. In Table 4.8 the geometry parameters are summarized, together with the typical nominal electric fields.
parameter & value \\
--- & --- \\
wire diameter & 100 µm \\
wire pitch & 0.5 cm \\
transfer length & 1 cm \\
grid distance & 1 cm \\
drift length & 1 cm \\
transfer field & 0.75 kV/cm \\
grid field & 2.5 kV/cm \\
drift field & 0.5 kV/cm \\

Table 4.8: Geometry parameters and nominal electric fields used for the computation of the performance of the extraction grids.

Approximating the grids as two planar capacitors in series, one between the lower grid and the liquid argon surface, and the other between the surface and the upper grid, one finds that the nominal extraction field, defined as the electric field in the capacitor filled with liquid, is:

\[ E_{\text{liq}} = \frac{\Delta V}{x + (d - x)\frac{\varepsilon_{\text{liq}}}{\varepsilon_{\text{vap}}}} \]

where \( \Delta V \) is the potential difference between the two grids, \( d \) is their distance, \( x \) is the distance between the liquid level and the grid in liquid, \( \varepsilon_{\text{liq}} \) and \( \varepsilon_{\text{vap}} \) are the relative permittivity of the liquid argon (\( \approx 1.5 \)) and the argon vapor (\( \approx 1 \)). The electric field in the capacitor in vapor is \( E_{\text{vap}} = E_{\text{liq}}\frac{\varepsilon_{\text{liq}}}{\varepsilon_{\text{vap}}} \).

The grid transparency is defined as the fraction of the charge that reaches the transfer volume. This quantity is shown in Figure 4.8 varying some parameters. Changing the nominal extraction field between 2 kV/cm to 3 kV/cm, the transparency does not vary significantly, but considering the extraction efficiency this parameter is required to be at least 2.5 kV/cm (see Section 2.5). We remark that the actual field is different from the nominal field and the difference depends on the whole field configuration. For instance in the configuration of Table 4.8 the nominal extraction field is of 2.5 kV/cm, while the actual field just below the liquid level is about 2 kV/cm.

A stronger dependence of the grid transparency is on changing the transfer field. The larger it is, the more transparent the grids are, but the less the shape of the charge distribution is restored. In the extreme case where the actual transfer field is larger than the field in the gas between the liquid and the grid, the electron distribution is squeezed even more, and all the electrons reach the transfer volume. In the opposite extreme case where the actual transfer field is in the opposite direction with respect to the drift, all the charge is collected on the grid in gas.

Increasing the liquid argon level, the transparency improves because in liquid the electrons diffuse less, and therefore they stay closer to the electric field lines for a longer path, reducing the chance to be collected on the grid in gas. In addition to this effect, lowering the liquid
4.3. EXTRACTION GRIDS

Figure 4.8: The four images represent the output of the simulation of the extraction grids. Starting from the standard nominal electric field configuration of 500 V/cm for the drift in liquid argon, 2500 V/cm for the extraction and 750 V/cm for the transfer field in gas, the grid transparency is shown as a function of the nominal extraction field, the nominal transfer field, the wire pitch and the liquid argon level. See the text for more details.

level causes the actual extraction field to decrease.

The distance between the wires can also be changed, and the transparency improves increasing its value, while the actual extraction field decreases considerably. What suffers the most by increasing the pitch is the electric field uniformity, important for the electron extraction efficiency.

The drift field is also a relevant parameter. The effect of increasing its value is similar to the one obtained decreasing the transfer field: more field lines fall on the grid in gas. When the ratio between the transfer field and the drift field equals $\epsilon_{\text{liq}}/\epsilon_{\text{vap}}$, all the field lines from the drift region reach the transfer region, and all the field lines from the grid in liquid end on the grid in gas. A perfect symmetry with respect to the liquid level is established.

The transparency is independent of the wire diameter as long as it is small compared to the wire pitch.
4.4 Summary

In this chapter the operational principle of the double phase argon LEM-TPC was presented. We introduced the concepts of the LEM as a charge amplifying cryogenic device and of the two views anode, that allows the simultaneous readout of two orthogonal sets of electrodes in the same electronic device. The so called extraction grids, the devices to connect the liquid argon TPC with the gas amplification device, were also described and characterized.

A tool to compute the streamer formation and the transport of charged particles in fluids was developed, and it was used to motivate the design of each part of the detector and explain their behavior and trends.

We finally propose in Figure 4.9 the global view of the double phase argon LEM-TPC with a typical electric field configuration. These devices were produced and experimentally tested. The results and the description of the setup are described in the next chapters.
Figure 4.9: Possible electric field configuration of the double phase argon LEM-TPC in the drift region (a), at the liquid-vapor interface (b), in the transfer region (c), in the LEM holes (d) and in the induction volume (e).
CHAPTER 4. DESIGN OF THE DOUBLE PHASE ARGON LEM-TPC
Chapter 5

3 liter setup

The operation of single and double stage small LEM prototypes in pure argon gas at room temperature and pressures up to 3.5 bar\(^1\) and in pure argon gas at cryogenic temperatures was already demonstrated in [119]. In order to prove the principle of the double phase argon LEM-TPC in realistic conditions, we needed to build a bigger setup able to host a sizable detector. The choice of the dimensions follows from the requirement of increasing both the active area and the drift length, in order to record cosmic muon events and reconstruct them three-dimensionally, but still fitting the detector in a vessel built with standard Ultra High Vacuum (UHV) flanges. The challenges mainly come from the cryogenic environment and the high purity of the argon. In fact, the former requires a careful selection of materials and components, the latter makes the entire system prone to electrical discharges. The solutions were implemented in the so called 3 L setup installed in building 182 at CERN and described in details in the following paragraphs. The prototype can be considered as the first implementation of the double phase argon LEM-TPC.

5.1 The cryogenic setup

The experimental setup is schematically shown in Figure 5.1. The detector, described in Sections 5.2 and 5.3, is mounted in a closed chamber full of liquid argon hosted in an open bath in order to maintain stable thermodynamic conditions. The detector vessel is connected to a gas recirculation system that ensures the purity of the liquid argon. In the following we describe in details the parts composing the cryogenic infrastructure of the setup and the procedures to operate it.

5.1.1 Argon containers

The detector vessel (25 cm of diameter and 65 cm high, see Figure 5.2, right), also called internal vessel, is a stainless steel container built with Ultra High Vacuum (UHV) standards.

\(^1\)Which gives a density of 5.75 g/L, roughly equivalent to the density of argon vapor at 1 bar and 87 K.
Most of the connections are ConFlat (CF), where both the flanges and the gasket are in metal. This guarantees the tightness of the system also in cryogenic conditions, a mandatory requirement not to spoil the liquid argon purity.

The electrical and gas feedthroughs are all at room temperature, connected to the top flange (DN250) through welded extensions. Though the dewar is not a pressure vessel, it can withstand pressure slightly larger than 1 atm. This is very important during the filling procedure, when the pressure increases up to 1.2–1.4 bar. For safety reasons an overpressure valve rated to open at 0.6 bar above the atmospheric pressure is installed.

During the filling, the liquid argon is fed at the bottom of the detector through the spiral tube wound around the detector chamber (see Figure 5.2). During the argon purification, thanks to the wide surface of the spiral in thermal contact with the external bath, the purified argon gas from the cartridge is liquified and injected again in the detector vessel.

An open stainless steel vacuum insulated dewar of 120 L (40 cm of diameter and 95 cm high, see Figure 5.2, left) is used as container for the liquid argon bath. It is equipped with three stands, that can be regulated in height in order to level the detector with respect to the liquid argon surface.

The detector vessel, hosted in the external dewar, is immersed in a liquid argon bath that maintains stable the pressure and the temperature of the inner volume. In fact, the detector chamber, tightly closed and filled with pure liquid argon, is in thermal contact with the liquid argon bath at about 87 K, the boiling temperature of argon at 1 bar. This forces the liquid contained in the internal vessel to be at about 87 K, and consequently its vapor stays at
5.1. THE CRYOGENIC SETUP

Figure 5.2: The setup of the 3 L detector. Left: the electronic rack, the gas purification structure and the external bath that hosts the detector vessel inside. Right: the detector chamber with the spiral radiator to liquify the purified argon gas.

about 1 bar, i.e. the internal pressure follows the atmospheric one. In order to dissipate the heat input coming from the walls of the dewar and from the inner vessel (some parts extend outside the bath, at room temperature), the liquid argon in the bath boils and evaporates. Even though the dewar is open at the top in order to ensure an efficient evaporation of the liquid, during normal operation (without argon purification, see later in the text) the refilling is required only once a day.

The liquid argon is stored in a commercial 6000 L cryostat installed outside the building and connected directly to the setup with vacuum insulated lines. An auxiliary 250 L movable dewar is used as liquid argon buffer for the daily refilling of the bath.

5.1.2 Argon purification system

To ensure a high enough purity of the argon in the detector chamber, it is purified in two steps (see Figure 5.1). The first purification stage is during the filling procedure: the liquid argon passes through the input cartridge\(^2\). The second purification stage is during the operation: a gas recirculation system can be turned on in order to maintain the argon purity for weeks.

Before filling, the detector vessel is evacuated to residual pressures of the order of \(10^{-6}\) mbar in order to remove air traces, that would pollute the argon, and to favor the outgassing of the

\(^2\)Before the filling the pipes between the cryostat and the input cartridge are flushed with argon from the cryostat in order to remove air traces that would spoil the input cartridge.
CHAPTER 5. 3 LITER SETUP

The materials inside the detector vessel behave to some extent as sponges: water molecules are trapped on the surfaces when exposed to air. Since the outgassing increases rising the temperature, during pumping the vessel is baked at 50°–60° C. The vacuum is obtained using a turbo molecular pump\(^3\) directly mounted on one of the extensions of the top flange.

The input cartridge (see Figure 5.3) is a home made filter to trap water and oxygen molecules from liquid argon. A 50 cm long and 6.3 cm diameter stainless steel cylinder, closed with two valves at the ends, is half filled with millimeter sized copper grains and half with a molecular sieve\(^4\). Two stainless steel porous sintered disks at both ends of the cylinder contain the powder, but let the liquid argon pass through.

At the passage of oxygen molecules the copper oxidizes (Cu + O\(_2\) → CuO\(_2\)), trapping the oxygen, while the water molecules are absorbed in the molecular sieve. The cartridge needs to be activated before it can be used and regenerated when the initial purity is not satisfactory. During the assembly the compound is exposed to air, and it quickly saturates of oxygen and water. In order to activate the copper, the reaction CuO\(_2\) + 2H\(_2\) → Cu + 2H\(_2\)O is induced heating up the filter to more then 150° C and flushing an argon/hydrogen mixture through the cartridge. The high temperature favors also the outgassing of the water from the molecular sieve, making it effective. The argon/hydrogen mixture enters from the side of the molecular sieve and exits from the side of the copper grains, in this way the water produced in the reaction of the copper oxide with the hydrogen is flushed away by the argon flow and not absorbed in the molecular sieve. The procedure stops as soon as no appreciable amount of moisture comes out from the cartridge.

In order to purify the argon in the detector, a gas recirculation system is implemented. The argon vapor, evaporated with the help of heating resistors in the liquid argon, is pushed by a metal bellows pump\(^5\) through a commercial getter\(^6\). This getter removes O\(_2\), H\(_2\)O, CO, CO\(_2\), H\(_2\) and some organic molecules to better then 0.1 ppb. The purified argon gas is re-condensed into the detector vessel through the input serpentine. The gas flow is regulated by means of a needle valve at the input of the pump. At 7.5 slpm the whole liquid argon volume is recirculated in about two days.

The argon gas recirculation is also used during the pre-cooling of the detector, just before the filling with liquid argon. Pure argon gas (99.9999 % argon) is used to fill the warm detector vessel, and it is recirculated through the cartridge. This procedure has two advantages: the outgassed molecules are trapped in the getter, and the presence of gas favors the fast and uniform cooling of all the parts.

Figure 5.4 shows the effectiveness of the gas argon purification system in two different occasions. Impurities diluted in liquid argon affect the scintillation light and the drifting

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\(^3\)Pfeiffer TMH 260.
\(^4\)ZEOCHEM Z3-01.
\(^5\)ANSYCO MB-111.
\(^6\)SAES MicroTorr MC400-903.
charge. The effective decay time $\tau_3$ of the slow component of the scintillation light and the number of scintillation photons decrease in the presence of ppm level of O$_2$, H$_2$O, N$_2$. The drifting electrons are trapped by electronegative impurities with a probability per unit time that is proportional to their concentration, consequently an exponential charge loss along the drift is expected. For a more quantitative description see Sections 2.3 and 2.4.

The scintillation characteristic time is fitted from the average Photo Multiplier Tube (PMT) signal and plotted as a function of time in Figure 5.4, left. It increases while the purification is on and it saturates at around 1.25 $\mu$s. This value is lower than the nominal 1.6 $\mu$s, and the discrepancy is attributed to some traces of N$_2$. In fact, nitrogen is a molecule that the getter is not able to trap, and ppm concentrations almost do not affect the electron drift.

The charge attenuation along the drift time is fitted with an exponential, and the inverse of the drifting electron lifetime is plotted in the graph on Figure 5.4, right. It is a quantity proportional to the concentration of electronegative impurities, and it worsens because of small leaks towards the atmosphere and because of the outgassing of the materials inside the detector. Operating the recirculation system, the purity improves and reaches values comparable to the one at the beginning of the filling. When the purification pump is on (highlighted bands), the liquid argon level changes, and the detector cannot be operated. The consumption of liquid argon in the external bath increases due to the additional thermal input (evaporate the liquid and condense the warm gas), and the refilling is needed every $\approx 10$ hours.

\footnote{For more details see Section 6.2 and in particular Figure 6.8 and the related text.}
Figure 5.4: Monitor of the liquid argon purity in two different runs. Left: effective lifetime $\tau_3$ of the slow scintillation component. Right: inverse of the lifetime of the drifting electrons. In the periods highlighted the gas recirculation was turned on, and no data were taken. The two overlapping series of points refer to the two readout coordinates.

5.1.3 The slow control system

The slow control monitors the values of the vacuum (residual pressure), the pressure, the temperature, the liquid argon level in the detector vessel and the argon gas flow in the recirculation system. A commercial vacuum sensor\textsuperscript{8} is installed on one of the extensions of the top flange. Three piezoelectric sensors\textsuperscript{9} monitor the pressure in the detector vessel, at the entrance and at the exit of the gas purification cartridge. A series of platinum resistors Pt10000 is used to measure the temperature at different heights inside the detector chamber. The measurement of the gas flow is performed with a mass flow meter\textsuperscript{10} installed before the purification cartridge (see Figure 5.1). The liquid argon level is monitored with a custom made capacity meter that is described in the next section. The values of all these quantities are digitized and stored in a database.

5.2 The liquid argon TPC

The detector is described in details in the following sections using the picture and the scheme in Figure 5.5 as a reference. The entire structure hangs from the top flange attached with four Nylon threaded rods. From top to bottom, one finds the charge readout and the signal routing planes, described in a Section 5.3, the extraction grids, the drift cage, the cathode and the cryogenic PMT.

\textsuperscript{8}Pfeiffer Vacuum Compact Full Range PKR 251.
\textsuperscript{9}Keller Serie 21.
\textsuperscript{10}MKS Mass-Flo 179B.
5.2. THE LIQUID ARGON TPC

Figure 5.5: Left: picture of the detector hanging from the top flange. Right: schematic representation of the detector showing the PMT (1) and its protection grid (2), the cathode (3), the field shaping electrodes (4), the extraction grids (5), the LEM (6), the two views anode (7), the connection to the strips (8), the 500 MΩ decoupling resistor (9), 270 pF high voltage decoupling capacitor (10), the surge arrester (11), the current limiting 33 Ω resistor (12), the preamplifier (13), the flange and the electrical feedthroughs (14), the high voltage power supply (15), the low pass filter and the resistor divider (16). Elements from (8) to (13) are replicated for each readout channel.

5.2.1 The drift cage

The uniformity of the field is guaranteed by a set of field shaping electrodes that delimit the detector active volume on the sides. They are made out of 1 mm thick stainless steel plates with a 10x10 cm$^2$ cut hole. They are stacked in a pile at a distance of 5 mm from each other and kept fixed by four Macor$^{11}$ pillars, hanging from the top flange. The number of plates can vary depending on the desired drift length, that can be as long as 30 cm (usually set at 20 cm). The high voltage to the field shapers is provided through a resistor chain (each resistor of 940 MΩ) from the cathode to the top field shaper.

The drift cage is limited on top by the liquid argon level, set between the two extraction grids, and at the bottom by the cathode grid. The extraction grids (shown in Figure 5.6) are made out of field shaping electrodes plated with gold (to facilitate the soldering), where stainless steel wires (100 µm of diameter) are soldered every 5 mm. The distance between the grids is 1 cm, and they are installed in such a way that the wires are aligned within 0.5 mm, i.e. the wires of the upper grid are exactly above the wires of the lower grid. The material

$^{11}$Macor® is a machinable glass-ceramic.
of the wires and of the frame is the same in order to perfectly match the thermal expansion coefficient and to avoid the failure of the grids in cryogenic conditions. While soldering, the wires were stretched with a 200 g weight to avoid sagging and deformation of the grids due to their weight and the electrostatic repulsion during the operation. The cathode and the protection grid of the PMT are done in the same way, because this geometry ensures good transparency for the scintillation light.

The extraction grids serve also as capacitive level meter, because the capacity between them depends on the position of the liquid argon level. Approximating the system as two parallel plate capacitors in series with area $A$ and dielectric constant $\varepsilon_l$ and $\varepsilon_v$ for the part in liquid and in vapor respectively, the total capacity is:

$$C = \frac{\varepsilon_0 \varepsilon_l \varepsilon_v A}{(d - x)\varepsilon_l + x\varepsilon_v},$$

where $x$ is the distance between the liquid argon level and the grid in liquid (normally 0.5 cm), and $d$ is the distance between the grids (1 cm).

The calibration of the level meter is performed during each detector filling measuring the capacity when the level is below the grids and when both the grids are completely immersed. The former is performed when the detector is cold (thermal contractions affect the capacity between the grids) before the liquid argon reaches the grids. The latter measurement is possible because the liquid argon is pushed upwards by the pressure of the external line, temporarily covering also the grid in gas.

The measurement of the capacity (order of 10 pF) is almost independent of the stray capacity of the cables\(^{12}\). It is performed with a circuit analogous to the one sketched in Figure 5.6 that consists of an integrator stage and a non-inverting Schmitt trigger as feedback loop. The level meter capacitance, in parallel to the first op-amp, is charged up by a constant current provided by the output of the Schmitt trigger, that is driven by the output voltage of the integration stage. The frequency of the output square pulse is inversely proportional to the grid capacity.

### 5.2.2 The light readout

A cryogenic Photo Multiplier Tube (PMT) Hamamatsu R6237-01 is mounted at the bottom of the detector below the cathode (see Figure 5.5). It is a square 70x70 mm\(^2\) active area PMT with 30 % quantum efficiency at 400 nm, but insensitive to photons with wavelength shorter than about 280 nm. The wavelength shifter TetraPhenyl Butadiene (TPB) is evaporated on the glass of the photocathode. The TPB absorbs VUV photons and emits photons with wavelengths peaked around 430 nm [46], allowing to detect signals from the liquid argon scintillation. The maximum gain of the PMT is only $2.7 \times 10^5$, but it is sufficient to measure single photoelectrons using the oscilloscope.

\(^{12}\)The capacity meter was tested connecting the capacity with LEMO cables up to 20 m long.
5.2. THE LIQUID ARGON TPC

Figure 5.6: Picture of an extraction grid (left) and the scheme (right) of the capacity meter used to measure the liquid argon level. Note the capacitive level meter (1) and the stray capacitances of the cables (2). The output of the charge integrator (3) is a triangular waveform, while the output of the Schmitt trigger (4) is a square waveform. Their frequency is inversely proportional to the capacity (1) and almost insensitive to the stray capacitances (2).

The PMT protection grid, mounted at 1 cm from the photocathode, serves to keep the electric field on the photocathode surface approximately at zero, regardless of the voltage applied to the cathode. The scintillation light is used to monitor the liquid argon purity with the measurement of the characteristic scintillation time and to provide the trigger to the charge readout. Since the primary scintillation is instantaneous, the PMT signal gives the time reference to the ionization events. The acquisition trigger is generated using a discriminator\textsuperscript{13} on the PMT signals, that are typically displayed (and, if needed, recorded) with a LeCroy Waverunner 44 MXi digital oscilloscope.

5.2.3 The high voltage system

The high voltage needed for the operation of the detector varies from about 100 V up to about 30 kV. The voltage is produced externally and fed into the vessel by means of vacuum tight feedthroughs.

The FUG HCN 35 HV supply is able to supply up to 35 kV, 1 mA, and it is used to power the cathode. For the extraction grids and the charge readout a CAEN SY1527, equipped with ±8 kV boards is used. In addition NIM high voltage modules are used as spare and to power

\textsuperscript{13}Nuclear Instrumentation Module (NIM) LeCroy 621 CL.
CHAPTER 5. 3 LITER SETUP

Figure 5.7: Pictures of the high voltage and the low voltage feedthroughs. Left: the two ends of the 30 kV HV feedthrough. Top right: 8 kV HV feedthrough mounted on the setup. Bottom right: charge signal feedthrough.

the PMT. In general, to suppress the noise from the power supplies, the voltages are filtered with first-order RC low pass filters with cutoff frequencies of about 1 Hz.

We use two kinds of custom made high voltage feedthroughs (see Figure 5.7) that cope with the tendency of the argon gas to develop electrical discharges. For voltages lower than 8 kV the feedthrough consists of a CF flange in which high voltage coaxial Kapton\textsuperscript{14} cables (FILECA F 1703-182) pass through holes drilled in the metal. On the air side each cable is soldered to a SHV connector fixed on a wall of a box welded on the flange. The box is filled with glue that prevents electrical breakdown and makes the drilled CF flange vacuum tight.

For voltages up to 30 kV a female LEMO 30 KV connector is installed on a CF flange. On the argon side a 1 m long stainless steel cylinder (connected to ground) and a concentric rod (connected to high voltage) are welded. The space between the cylinder and the rod is filled with Araldite\textsuperscript{15}, specially chosen to match the expansion coefficient of the stainless steel. It makes the flange vacuum tight and avoids discharges in argon. In order to further reduce the discharge probability, during the operation the high voltage pin is immersed in liquid argon that has a very high dielectric strength.

\textsuperscript{14}Kapton\textsuperscript{®} is a polyimide insulating film.
\textsuperscript{15}Araldite\textsuperscript{®} is a bi-component epoxy resin.
5.3. **THE CHARGE READOUT**

<table>
<thead>
<tr>
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<th>value (µm)</th>
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</thead>
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<tr>
<td>hole pitch</td>
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<tr>
<td>dielectric rim</td>
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</tr>
<tr>
<td>metal thickness</td>
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<tr>
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</tr>
<tr>
<td>active area</td>
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</tr>
</tbody>
</table>

Table 5.1: Relevant design parameters of the constructed LEM

### 5.3 The charge readout

The charge readout consists of the amplification stage (LEM), the readout stage (two views anode) and the stage to prepare the signals to be readout by the electronics (signal routing plane). Mechanically the stages are stacked one on top of the other, and they all operate in cryogenic conditions in cold argon gas.

#### 5.3.1 The LEM

Figure 5.8 shows the LEM used in the 3 L detector and a closeup view of its holes. The device was produced in the CERN TS/DEM workshop. About 17000 holes are mechanically drilled with standard PCB techniques in the copper cladded glass epoxy plate. The metallization extends about one centimeter outside the drilled holes in order to properly shape the electric field at the edge of the active volume. The particular shape is required to fit in the detector vessel. The relevant parameters and their values, motivated in Section 4.1, are summarized in Table 5.1.

It is empirically shown [120], and we proved it with the discharge simulation (see Section 4.1), that the maximum achievable gain increases with increasing rim size. A naive way to produce the rim is to etch the metal using a photolithographic mask and afterwards perforate the PCB where it is exposed. However, the alignment of the holes to the etched discs is limited by the CNC drilling machine precision. A perfect alignment is guaranteed by two innovative rim production methods developed at the CERN TS/DEM workshop [121]. One is suitable for rims smaller than 50 µm and the other is suitable for bigger rims, but of more difficult realization. The relevant steps of the production are sketched in Figure 5.9. In the case of small rims (left), the glass epoxy plated with copper is drilled and the thickness of the metal is reduced with electrochemical polishing techniques. This procedure forms the rims and removes sharp edges. Naturally, it is limited by the metal thickness. In the case of large rims (right), the glass epoxy plated with copper is covered on both sides with a resistive layer (not attacked by the electrochemical polishing) and then drilled. The etching acts only on the metal left exposed without reducing its thickness. The resistive layer is removed and a mild electrochemical polishing may be performed to smooth the edges. During the drilling care must be taken to avoid any fragment of resistive layer to obstruct the metal surface that
must be etched away. The second method is the one used in this LEM.

The copper is finally plated with a few microns thick layer of gold in order to avoid oxidation. Moreover, the work function of gold is larger than the one of copper, and this reduces the probability of electron emission induced by VUV photons.

Before installation the LEM is cleaned in an ultrasonic bath filled with pure alcohol. In order to test the absence of resistive contacts between two electrodes, the LEM is powered in air. The location of the discharge in air is monitored to be sure that there is no particular region more susceptible to sparks. The controlled sparks train the LEM, because the spark itself smooths the edges (imperfections) that cause the discharge.

The high voltage is supplied to the two electrodes through metal pins insulated with Macor cylinders. The 500 MΩ resistor between the high voltage connector and the electrode is a spark protection device. It limits the charging up current and, as a consequence, after a discharge the voltage across the LEM cannot be restored quickly enough, therefore quenching the spark.

A platinum resistor Pt10000 is used to monitor the temperature of the argon vapor in the vicinity of the LEM.

5.3.2 The two views projective anode

Two independent readout planes are implemented on the same PCB, printing every 600 µm two orthogonal sets of strips of different width. The design parameters, summarized in
5.3. THE CHARGE READOUT

Figure 5.9: Schematic representation of the procedure to produce small (left) and big (right) dielectric rims. In order to produce a small rim the bare material (a.1) is drilled (a.2), the copper is etched away reducing its thickness (a.3) and leaving the rim (a.4). Concerning the big rim the bare material is coated with a resistive layer (b.1) and drilled (b.2), the metal is etched away (b.3) and finally the resistive layer is removed (b.4).

<table>
<thead>
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<td>readout pitch</td>
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<td>exposed strip width</td>
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<td>covered strip width</td>
<td>500 µm</td>
</tr>
<tr>
<td>metal thickness</td>
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</tr>
<tr>
<td>insulator thickness</td>
<td>50 µm</td>
</tr>
<tr>
<td>active area</td>
<td>10x10 cm²</td>
</tr>
</tbody>
</table>

Table 5.2: Design parameters of the constructed two views anode.

Table 5.2, are motivated in Section 4.2. The two views anode, built at the CERN TS/DEM workshop, and a closeup of the strips are shown in Figure 5.10.

The two sets of copper strips are printed with photolithographic techniques on the two sides of a 50 µm thick polyimide foil. The face with the wide strips is glued on a rigid glass epoxy plate. The polyimide left exposed is chemically removed uncovering part of the wide strips. No gold cover is used to avoid the risk of producing an electrical bridge between the two views. The copper is passivated\(^\text{16}\) to prevent the corrosion. Similarly to the LEM, the metallization extends beyond the active area to maintain the uniformity of the electric field on the edges.

In order to reach the final readout pitch of 3 mm, the strips are connected outside the sensitive area in groups of five, resulting in 32 independent channels per view. The anode can operate at high voltage to facilitate the setting of the electric field. In order to decouple the high voltage, the signals are fed to the electronics through high voltage capacitors (see

\(^{16}\text{Passivation is a controlled oxidation of the metal surface to protect it.}\)
CHAPTER 5. 3 LITER SETUP

Figure 5.10: Picture of the two views anode (left) and a close up of the strips (right). Visible are the exposed thin strips (horizontal) and the wide covered strips (vertical and dark).

Before the installation in the detector the device is cleaned with pure alcohol in an ultrasonic bath, and the insulation between the strips is checked with a multimeter. The resistive connections found were always due to either dust or dirt that could be restored with further cleaning. The two views anode is mounted 2 mm from the top of the LEM using four spacers outside the active area.

5.3.3 The signal routing plane

The signal routing plane decouples the signals from the high voltage bias of the anode and protects the electronics against potential discharges. The components of the signal plane are sketched on the right scheme of Figure 5.5 and reported in Figure 5.11, where also pictures of the device are shown. Each strip is powered through a 500 MΩ resistor to decouple the strips from each other and from the HV power supply. A HV capacitor of 270 pF connected to each strip decouples the input of the electronics from the high voltage, allowing the fast signals to pass. After the capacitor a surge arrester to ground avoids the voltage to increase above 90 V. A 33 Ω resistor is installed on the signal path to limit the current in case of a discharge. The connection to the two polyimide flat cables, shown in Figure 5.7, is done through four ZIF connectors. All the components work in cryogenic environment and are made out of materials harmless for the purity of the liquid argon.
5.3. THE CHARGE READOUT

Figure 5.11: Top: picture of the signal plane connected to the anode with the high voltage decoupling capacitors. Bottom: schematic representation of the electronic chain to feed the high voltage to the strips and to decouple the signal from the high voltage.

5.3.4 Charge readout electronics

The signals coming from the detector must be amplified and shaped before being recorded. In collaboration with CAEN S.p.A.\textsuperscript{17} a complete signal readout system was developed. The SY2791 crate is equipped with a linear power supply and eight A2792 boards, each one hosting sixteen two-channel preamplifiers. One crate manages up to 256 channels and two crates were successfully used to record 512 channels. Each board contains both the analog and digital sections, and the charge preamplifiers are exchangeable.

The preamplifier output is continuously digitized by 12 bit 2.5 MS/s ADCs in the range of 0–3.3 V and saved on a circular memory buffer. A DAC controls the value of the preamplifier output baseline. The programmable FPGA provides a sophisticated trigger logic and zero suppression algorithms. Each channel operates independently, and the data are made available when the digitized signal crosses a programmable threshold. The trigger on one channel lowers the trigger thresholds on the other channels in order to be able to record lower signals. The connection to the computer is done with an optical fiber to an A2818 PCI board.

A simplified schematic of the custom made charge sensitive preamplifier [122], inspired from [123], is shown in Figure 5.12 together with the picture of one sample. The two diodes (2) in series at the input and the JFET (3) act as a protection of the preamplifier against discharges, keeping the input voltage within the rated values of the input op-amp. Another

\textsuperscript{17}www.caen.it
precaution against discharges is the surge arrester installed inside the detector, as already described (see Figures 5.5 and 5.11). The active components of the operation amplifier in the first stage are four JFETs connected in parallel (to reduce the intrinsic noise [123]) in cascode configuration. The resistor and the capacitor in parallel make this part of the circuit a charge integrator with charge sensitivity of about 1 mV/fC and a time constant of about 470 µs. The RC-CR filter that follows has RC = 0.6 µs for the integration section and CR = 2.2 µs for the differentiation section. It shapes the signal to match the sampling frequency of the digitizer and to reduce the electronic noise. The falling time is chosen such that two signals separated by 2 µs can be distinguished. The following non-inverting linear amplifier has a gain of 30. Given the bandwidth of the op-amp and the 47 pF capacitor in parallel to it, this part of the circuit can be modeled with an ideal linear amplifier with a low pass filter at the output. The measured sensitivity of the entire preamplifier is about 12 mV/fC, and the dynamic range is matched to the 3.3 V of the CAEN system. The intrinsic noise (RMS) is about 1 mV with an input capacitance of 200 pF.

Under the assumption of an infinite characteristic time constant of the charge integrator,

\[ 18 \text{At a drift field of 500 V/cm this corresponds to a distance of 3 mm.} \]


### Table 5.3: Average values over 32 channels of the shaping time constants appearing in the preamplifier response, as reported in [124].

<table>
<thead>
<tr>
<th>variable</th>
<th>value (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>2.84 ± 0.09</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>0.47 ± 0.02</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>0.46 ± 0.02</td>
</tr>
</tbody>
</table>

Given any input signal $i(t)$, the preamplifier output is the convolution of $i(t)$ with $h(t)$. The input charge is proportional to the integral of the output waveform, but not necessarily to its amplitude. In fact, $i(t)$ is usually a current pulse that differs from zero for a time of the same order of the shaping time constants. The net effect is the broadening of the preamplifier output. As shown in the left plot of Figure 5.13, three input pulses of the same total charge give different output signals when spread on various times. The relative amplitude of the output as a function of the input width is given in the plot on the right. 1 fC at the input gives at the output always a signal with an integral of about 51.9 mV µs. The same charge, if concentrated in a time negligible with respect to the characteristic time constants, gives a signal with an amplitude of about 11.8 mV.

The signals are brought out from the detector vessel by means of the feedthrough shown in Figure 5.7 (bottom right). It consists of a CF flange with two thin slits through which two custom made Kapton flat cables pass. The slits are filled with Araldite to make the feedthrough vacuum tight and mechanically stable. On the argon side the cable is coupled to a ZIF connector, and on the air side a 68-pin IDC connector is soldered.
Figure 5.13: Left: preamplifier output waveform for different Gaussian input pulses of the same total charge. Right: relative amplitude of the signal as a function of the Gaussian input pulse width $\sigma$. 
Chapter 6

Results from the 3 liter setup

The Table 6.1 reports the most significant tests performed in order to optimize the double phase argon LEM-TPC. The main results are summarized in three publications [125, 126, 127] and briefly described in the Appendix. In this chapter we describe the measurements, published in [128], with the final detector configuration that showed the best performance. This is the result of an extensive and systematic development of the entire detector, comprising strong efforts to improve the charge amplification and readout devices and the TPC, but also the cryogenics, the argon purification system, the readout electronics and the slow control.

The chapter is divided into two parts where we separately report the test performed in pure argon gas at room temperature and the tests in double phase conditions. Tests at room temperature and different pressures are used to characterize the LEM behavior in terms of discharge and gain. The double phase tests with the 1 mm thick LEM and the two views anode proves the potentiality of the detector as tracking and calorimetric device. Low energy X-rays and cosmic muons are used to quantitatively characterize the detector response in gas and double phase operation respectively. To do this, three-dimensional reconstruction of straight tracks is required. The liquid argon purity, the electron drift velocity and the effective gain for different field configurations are measured.

6.1 Measurements in gas

Two LEMs with the same characteristics except for the thickness (1.6 mm and 1 mm) were tested in pure argon gas at room temperature. They showed similar behavior generally explained by the spark simulation described in Chapter 4.

For the tests in warm gas the detector was setup in a simplified version compared to the one described in Chapter 5. The extraction grids were removed, since no extraction is needed. The PMT was not used, since the primary scintillation light is weak in the low density gas. For this reason the acquisition trigger was set on the charge signals. The drift length was set at 10 cm, and the cathode grid was replaced with a solid plate where an $^{55}$Fe source
was installed. The anode used was segmented in one direction only with sixteen 6 mm wide strips, allowing to measure only one projection.

First, the detector vessel was pumped to few $10^{-6}$ mbar, and pure argon gas\(^1\) was then fed into the detector through the gas recirculation cartridge. The detector was filled in steps performing measurements at different pressures. To be sure of the reproducibility of the tests, this procedure was repeated different times for both the LEMs.

6.1.1 Discharges at different gas densities

Figure 6.1 shows the breakdown voltage applied across the 1.6 mm thick LEM as a function of the gas pressure. The drift and the induction fields were kept at zero, and the amplification field was increased until the first sparks occurred. In the different tests the sparking voltage could be reproduced within few volts. This difference can be understood from the uncertainty on the pressure and considering that the quality of the argon purity could differ between the four tests. In fact, the purity may affect the sparking limit \([129]\) and, though the filling procedure remained the same, the impurities concentration varies with the time elapsed from the filling because of the outgassing of the materials inside the detector.

The curve is reminiscent of the shape of the Paschen’s law described in Section 3.3, though two different discharge regimes characterize the low density and the high density regions. In the former case, the discharge is a continuous silent current of few nano-amperes and the discharge limit is very sharp. It appeared as an increase of the power supply output current with a more-than-proportional dependence on the voltage. In the latter case, the discharge is audible, violent, and discharges the LEM completely, tripping the power supply. The two

\(^1\)Commercial argon gas with less than 1 ppm impurity contamination, generally denoted with argon 60.
6.1. MEASUREMENTS IN GAS

Figure 6.1: Breakdown (spark) voltage of a 1.6 mm thick LEM as a function of the argon gas pressure.

processes may represent the Townsend discharge and the streamer discharge respectively.

The aim of these preliminary tests was to find the discharge limit of the devices and to qualitatively describe the spark behavior. In order to avoid damages to the LEMs, immediately after the discharges the high voltage was turned off. The operation was repeated several times to prove that no significant degradation of the sparking limit was caused by the discharges.

6.1.2 Measurement of the $^{55}$Fe spectrum

The quantitative measurements were made with a $^{55}$Fe source and turning on the drift field (typically 200 V/cm) and the induction field (typically 2 kV/cm). The $^{55}$Fe decays to $^{55}$Mn (stable) by electron capture [25] and is a source of X-rays. The most important X-ray transitions are 5.89 keV, 5.90 keV and 6.49 keV with relative intensities of 0.5, 1 and 0.18 respectively. The first two lines are not resolvable for most detectors, and, in order to resolve the 6.49 keV line, the energy resolution must be better than 10 % at 5 keV. This is not the case for the LEM, and for this reason we can consider the $^{55}$Fe as a monochromatic source of 5.9 keV X-rays.

A photon with energy $E_{ph}$ below few tens of keV interacts with argon mainly via photoelectric effect with the electrons of the argon K shell (see Figure 2.2). As a result an electron of energy $E_{ph} - E_K$ is emitted from the atom, where $E_K = 3.20$ keV [130] is the binding energy of the electron in the K shell. The electron vacancy is filled by an electron of the outer shells (in this case L or M) with the consequent emission of an Auger electron or an
X-ray with a probability of about 85 % and 15 % respectively [131]. The Auger electron has two characteristic energies of 2.95 keV and 3.19 keV (on average 3.07 keV). In this case, most of the initial photon energy is locally transformed into kinetic energy of two electrons (photo-electron and Auger electron) and transferred to the surrounding argon atoms through ionization. In case the filling of the first vacancy is followed by the emission of an X-ray, the photon has an energy of $E_K - E_{L,M}$, of the order of 3 keV. The attenuation length of photons of these energies in argon gas at STP is of the order of 3 cm. This means that the energy is released non-locally and the photon may even escape from the detector. Both in the case of the emission of an X-ray and in the case of the emission of an Auger electron, the excited argon atom de-excites with the emission of low energetic Auger electrons or soft X-rays immediately absorbed, until the ground level electron configuration is re-established.

For these reasons the energy deposited in the active volume shows two peaks, namely the full energy peak at 5.9 keV and the escape peak at $(5.9 - 3.07 = 2.83)$ keV. As an example Figure 6.2 shows the $^{55}$Fe spectrum recorded with the 1.6 mm thick LEM operating at a gain of about 600 in pure argon gas at 0.8 bar. The energy transferred to the medium via ionization is proportional to the charge collected on the anode. The plot is obtained numerically integrating the signals induced on each strip and summing the result of adjacent channels. In case of multiple hits not connected, only the largest cluster is considered.
6.1. Effective gain at different pressures

Recalling that the average energy required by an electron in argon gas to produce and electron-ion pair is \( W_g = 26.4 \text{ eV} \) (see Section 2.2) and that the electron-ion recombination under the action of an electric field is negligible in gas, we can evaluate the effective gain of the device from the \(^{55}\text{Fe} \) full energy peak, dividing the charge collected on the anode with the primary ionization charge freed by 5.9 keV X-ray \((5.9 \text{ keV}/26.4 \text{ eV} \approx 225 \text{ electrons})\). The collected charge is evaluated from the integral of the signal as described in Section 5.3.

The plots in the left column of Figure 6.3 show the effective gain at different gas pressures for the 1.6 mm thick LEM (top) and 1 mm thick LEM (bottom) as a function of the potential difference \( \Delta V \) applied across the LEM. The maximum gains are limited by the occurrence of discharges. The higher the gas pressure \( P \) (and consequently the density), the larger is the voltage to be applied in order to reach a given gain. The maximum gain decreases when the gas density increases, a trend expected from the spark simulation (see Section 4.1). This kind of behavior has also been noted in GEMs operated in pure noble gases and gas mixtures \([105, 132, 133]\).

The two plots on the right column in Figure 6.3 display \( \log(G)/P \) versus \( \Delta V/P \) with a curve on top of the data points to guide the eye. According to Section 3.1, in the uniform field approximation from equations 3.1 and 3.3 the \( \log(G)/P \) is a function only of \( \Delta V/P \). The deviation at low densities from this scaling law (noted also in GEMs \([105]\)) is due to the non-uniformity of the electric field in the holes.

With both the LEMs, a gain of the order of 1000 can be reached. The discharges at low pressure are milder, and we noted that in general the discharges of the 1 mm thick LEM are less violent in terms of noise and current delivered by the power supply. The voltage required to operate the thinner LEM is considerably lower, and this makes the 1 mm thick LEM preferable for the operation in double phase condition, though LEMs 1.6 mm thick were also operated in double phase tests (see Appendix).

6.1.4 Comparison with the expectations

In Chapter 4 we described a simulation to compute the formation and the propagation of a streamer in a LEM hole. The model takes into account the transport properties of electrons in argon gas and the electric field distortion due to spatial charge distributions. The LEM hole can be ideally divided in two regions, one in the center of the hole and the other near the dielectric walls where the electric field is larger. The maximum achievable gain in the central region is limited by the occurrence of a streamer in the side region.

LEMs with smaller dielectric rims and with thinner electrodes were tested in pure argon gas, and they showed poorer performance and smaller maximum achievable gain, as expected from the simulation. Increasing the gas density, the computation describes also the decrease of the maximum gain and the increase of the required voltage across the LEM to obtain
a defined gain. Nevertheless, as already pointed out, due to important limitations of the model (impossibility to take into account the statistical fluctuations of the avalanches and the defects of the holes), the computed maximum gain is not expected to reproduce in full detail the experimental results. Therefore, the model, which by itself is quantitative, provides only qualitative guidelines in understanding the LEM behavior. In addition, due to the very nature of the R&D work, also the experimental results are not always consistent: the production methods, the accuracy in defining the parameters, the defects of fabrication, and so on play an important role in the early stage of the development.

6.1.5 Photon feedback

In Section 3.2 we introduced the photon feedback as a secondary effect of the electron multiplication in gas. In this paragraph we give an example of this phenomenon. The VUV photons created in the holes of the LEM during the charge amplification propagate to the cathode, where they extract electrons via photoelectric effect. This charge drifts to the LEM
6.2. MEASUREMENTS IN DOUBLE PHASE

The 1 mm thick LEM tested in gas was used for the experiment in double phase. The detector was setup as described in Chapter 5, and different double phase tests were needed to fully characterize the detector.

The proportional scintillation light in vapor was used to benchmark the drift cage, and the ionization charge was used to probe the argon purity and the charge readout performance. The trigger was always set on the primary scintillation light, that gives the time reference to the event. Cosmic ray muons were used for the quantitative characterization, because they release a known amount of energy per unit path, they cross the entire active volume, and they are an abundant and free source.

The final experiment with the charge readout operational lasted seven days, and the liquid argon purity was good enough so that no use of the gas argon purification circuit was

and is amplified inducing a signal delayed by the drift time.

The event display reported in Figure 6.4 shows an example of an event with photon feedback. The left plot shows on the X-axis the strip number, on the Y-axis the drift time, and the grey scale represents the signal amplitude. The waveforms of each strip of the same event are shown on the right plot. The time interval that separates the equally spaced peaks is 35 μs, i.e. the time taken by the electrons to drift 10 cm in an electric field of 200 V/cm.

In the example the amplitude of the peaks diminishes because the charge extracted from the cathode is smaller than the primary one. Increasing the LEM gain the amplitude of the secondary peaks relative to the first one would increase and the discharge would be triggered. The photon feedback is prominent in the low density gas. At higher density the discharge appears in a different form, before the photon feedback becomes relevant: the LEM discharges without signal precursor on the microsecond time scale. This suggests to describe the LEM discharge as streamer in dense vapor (see Section 4.1).
required. During the operation the temperature, the pressure and the liquid argon level were extremely stable. The only significant fluctuations were observed when the liquid argon level of the external bath dropped below the top flange of the detector vessel.

### 6.2.1 Drift velocity and proportional scintillation light

In order to characterize the drift cage, the electron drift velocity is measured using the proportional scintillation light recorded with the PMT. No voltage is applied to the LEM in order to avoid the production of photons during the charge amplification. The drift length is set to 10 cm (from the grid in gas to the cathode), and the potential on the grid in liquid is defined through a resistor divider by the voltages applied to the grid in gas and to the cathode. The resistor divider fixes the ratio of the extraction field and the drift field to be about 4. After the extraction the charge is collected on the bottom electrode of the LEM and on the grid in gas.

The proportional scintillation (for details see Section 2.5) is expected to happen only in the gas between the extraction grids, the only region where the electric field is high enough for the electrons to excite the argon atoms. In a uniform electric field the electron drift velocity and the argon excitation probability are constant, therefore the time distribution of the argon excitation is flat, and it lasts the time taken by the electrons to transit through the high field region. In this case, it is between 0.2–0.4 \( \mu s \), depending on the electric field. The argon de-excitation with the emission of a photon is distributed in time according to an exponential with a characteristic time of the order of few microseconds (slow component), depending on the purity and on the density of the argon vapor. We measured values between 4.1 \( \mu s \) and 4.6 \( \mu s \).

Considering a point-like charge being extracted, the time distribution of the emitted photons is the convolution of the two functions (the flat square pulse and the exponential), but considering that the characteristic time of the excitation is one order of magnitude less than the de-excitation time, it can be approximated with the exponential function only.

In the case of a cosmic muon, the time distribution of the proportional scintillation light is the convolution of the exponential function just described with a square pulse, to take into account that the muon releases charge in an extended portion of the drift region. The pulse width is at most the total drift time for the muons crossing both the extraction grids and the cathode. Using the PMT signals and triggering on the primary scintillation light (a typical event is displayed in Figure 6.8), the drift velocity can be extracted from the endpoint of the proportional scintillation. Naturally, the light produced by the muons crossing the surface of the PMT is more efficiently detected, and this biases the trigger, but not the evaluation of the proportional scintillation endpoint. No event selection is performed, i.e. muons crossing not completely the drift volume are included, since the interest is not on the shape of the waveform, but on the trailing edge.

In Figure 6.5 we report the average PMT waveform (change of sign) at different drift
6.2. MEASUREMENTS IN DOUBLE PHASE

Figure 6.5: Average PMT signals due to the proportional scintillation during the extraction of the electron into the vapor phase at different drift fields. The peak at 0 $\mu$s is due to the primary scintillation light. The region around the endpoint of the extraction is enlarged in the plot on the right. The analytical fitting function is also shown (see text).

The proportional scintillation signal increases with the drift field, not only because the electron-ion recombination diminishes, but mainly because the extraction field and, consequently, the electric field in gas are fixed with respect to the drift field by the resistor divider.

The drift velocity is computed dividing the drift length by the drift time, and the result is plotted as a function of the drift field in Figure 6.6. The measurement was done in two different experiments with the detector equipped in the same way. The uncertainty on the time comes from the fit, and it is less then 0.5 $\mu$s ($< 1\%$). The uncertainty on the drift length comes from the measurement of the liquid argon level, and it is estimated to be 1 mm ($\simeq 1\%$). A small systematic effect that tends to overestimate the drift velocity is introduced by the fact that the drift field and, consequently, the drift velocity increase between the grids, causing the total drift time to be shorter by 1 $\mu$s at most.

The agreement within the errors and systematic uncertainties with the Walkowiak empirical function [63] is the proof that the drift cage, the extraction grids and the PMT behave as expected, and we can conclude that there are no strong deviations of the actual drift field from the nominal field.
6.2.2 Event gallery

Turning on the transfer field between the grid in gas and the LEM, the amplification field in the holes of the LEM and the induction field between the LEM and the anode, the detector works as a liquid argon TPC with amplification. Figure 6.7 shows examples of how cosmic muon tracks appear in the event display, in particular we report two similar straight tracks at different amplification factors (note the increase of the signal amplitude).

Each event has associated two plots, one showing the signals on each channel as a function of time and the other visualizing the two-dimensional (X-Z view and Y-Z view) projected images of the event. In the latter the grey scale is proportional to the signal amplitude, the channel number is displayed on the X-axis and the drift time on the Y-axis. The channel number represents the position in the corresponding coordinate and the drift time is proportional to the depth. The trigger is set to 50 $\mu$s, and this time corresponds to the liquid argon level. Given the drift velocity at 500 V/cm, 170 $\mu$s corresponds to the position of the cathode.

The charge coming from a given depth induces signals on the two views at the same time, this means that the beginning and the end of the tracks happen at the same time in both views. These two points are necessarily on the edges of the drift volume, namely liquid level, cathode or one of the four side walls. The number of channels involved depends on the angle (direction) of the cosmic muon.
6.2. MEASUREMENTS IN DOUBLE PHASE

Figure 6.7: Event display of two cosmic muon tracks recorded with amplification fields of 32 kV/cm (top) and 35.5 kV/cm (bottom). Each event is associated to two figures, one showing the signal waveforms of each channel (different colors refer to different strips) and the other showing on the X-axis the channel number, on the Y-axis the drift time and in grey scale the amplitude of the pulses. The X- and Y-views are shown on the left and on the right respectively.

6.2.3 Three-dimensional track reconstruction

A quantitative analysis of the cosmic muons requires the three-dimensional reconstruction of straight tracks. The algorithms for the treatment of the raw data are collected in a C++ library package called fullReco, used by the analysis software and event display Qscan [122].
Figure 6.8: Left: a typical PMT signal due to primary scintillation induced by a cosmic muon. The fast and the slow components of the scintillation light are clearly distinguishable. The fast component saturates the ADC of the oscilloscope. Right: two signals of the charge readout fitted by the preamplifier response function. The two waveforms refer to two non-adjacent channels of the same view.

A digital filter is applied to the raw data in order to subtract the coherent noise affecting all the channels due to a non-optimized configuration of the ground connections (also applied in the events displayed in Figure 6.7). At a given time the filter compares the values of the digital samples of all the waveforms of the same board in order to find the most probable value of the baseline. The most probable value is subtracted from all the signals, resulting in the suppression of the signals in common (common noise) to all the channels of the same board. A filter on the Fourier transform, though available and tested, is not applied because the residual noise is at the level of 3 ADC counts only.

Signals are discriminated from the noise by means of a peak finding algorithm, able to distinguish multiple peaks in the same waveform. The response of the preamplifier (see Section 5.3) convoluted with a flat pulse function (to take into account the extended charge distribution) is fitted to each peak, correctly taking into account the overlap. An example of a signal with the fitting function is shown in Figure 6.8 (right). The output of the fit is the initial time of the peak, the width of the pulse and the integral of the preamplifier response function. This defines the so called hit.

Each hit is associated to a Z-coordinate given by the drift velocity multiplied by the drift time, i.e. the difference between the initial time of the peak and the trigger time from the primary scintillation light. The strip number gives the coordinate of the corresponding view. In order to obtain the three-dimensional location of the hit a link between the two views is needed.

Adjacent hits of each view are clustered together and fitted by a straight line, namely $x(z)$ and $y(z)$. Considering that the two clusters on each view belong to the same ionizing event and that the charge induces the signals on both views at the same time, one can extract the
third coordinate ($y$ for the X-view and $x$ for the Y-view) of each hit matching the common Z-coordinates (drift time). For example, the Y-coordinate associated to a hit of a X-view cluster is $\tilde{y} = y(\tilde{z})$, where $\tilde{z}$ is the Z-coordinate of the considered hit, and $y(z)$ is the linear fit to the Y-view cluster. Figure 6.9 represents schematically the three-dimensional reconstruction process. Each hit is associated also to the charge $\Delta Q$ collected on the corresponding strip, proportional to the signal integral, and to the three-dimensional track length below the strip $\Delta l$. The ratio $\Delta Q/\Delta l$ is proportional to the energy loss per unit path length, and this quantity is at the base of the quantitative analysis.

The quantities associated to the cluster are the $\chi^2$ of the linear fits, the track length, the angle $\theta$ with respect to the vertical axis, the start position and the end position. Cuts on these parameter are used to choose well reconstructed tracks. In Figure 6.10 we show some consistency plots. On top the track length and the angular distributions of the well reconstructed tracks are displayed. The lack of vertical tracks ($\theta = 0$) is due to the requirement of
Figure 6.10: Top: track length and azimuthal angle distributions of the well reconstructed muon tracks. Bottom: scatter plot of the signal integral divided by its amplitude for the two views (see text).

having at least five channels per view involved (needed for the linear fit of the cluster). The maximum track length is about 22.5 cm when the muon enters from one of the top corners and exits from the opposite one. The short tracks are given by the muons entering (or exiting) from the side of the drift volume, without crossing the entire drift volume (the event reported in Figure 6.9 is an example). The two scatter plots on the bottom of Figure 6.10 show for each cluster the sum of the peak integrals divided by the sum of the peak amplitudes as a function of $\theta$. The increase of this ratio at small $\theta$ in both views is due to the response of the preamplifier to extended current pulses (see Section 5.3). By design, for an infinitely short pulse, approximated in this case by a horizontal muon, the ratio equals 4.4 $\mu$s, very close to what is shown in the figures.

The algorithms used are able to reconstruct three-dimensional straight tracks, but no effort was made to reconstruct $\delta$ rays, pileup events or more complicated geometries. The single straight muon is the only event topology used to characterize the response of the detector. It is worth noting that in this way of treating the events the charge freed in the
6.2. MEASUREMENTS IN DOUBLE PHASE

liquid argon due to the $\delta$ rays is not fully considered. This is done in order to obtain a measurement of the energy loss per unit path independent of the muon energy. The energy spectrum of cosmic muons is almost flat below 1 GeV, it is roughly proportional to $E^{-2.7}$ for energies above 10 GeV, and the average muon energy is 4 GeV. A significant fraction of cosmic muons have energies above the minimum ionizing energy (about 300 MeV). As pointed out in Section 2.1, $\delta$ rays contribute to the rise of the stopping power after the minimum, that is limited cutting the energetic $\delta$ rays, as shown in Figure 2.3. Considering the strip width of 3 mm, the cutoff energy is estimated to be about 4 MeV, corresponding to a 7 mm of CSDA range\textsuperscript{2} for electrons. In this way, the restricted stopping power reaches a Fermi plateau that is comparable with the stopping power of a minimum ionizing muon. We can then approximate the average energy loss on the entire cosmic muon spectrum with a constant equal to 2.1 MeV/cm.

6.2.4 Performance of the two views anode

The imaging capabilities of the detector reflect the two views anode performance, which therefore must be benchmarked. For doing this, the total charge in the X- and Y-clusters from cosmic muon data was compared. We recall that by design the charge is equally shared between the two sets of orthogonal strips (see Section 4.2). The results are displayed in Figure 6.11. The scatter plot (left) shows a very good correlation between the charge collected on the two views. The deviation from the perfect charge sharing is 2.5 %, as shown in the histogram (right) of the difference between the charge collected on the two views normalized to their sum. In order to evaluate the spatial resolution on the X-Y plane, a point-like charge distribution is needed, but it was not available at the moment of the data taking. Such a measurement is left for future tests.

Though the vertical muons are not used for the analysis, they are properly recorded on both views, proving that the anode works well and as expected also with a considerable amount of charge extended along the drift direction. This is in general not the case for standard TPC readouts due to the signal cancellation on the induction view (for more details see Section 2.6). In addition, the total sample of the events visually-scanned, that includes cosmic muon events with $\delta$ rays, electromagnetic showers and events with difficult topologies, showed consistent charge clusters in the two views. The performance of the anode was stable with time, and no degradation after discharges was observed. We conclude that the design and the production of the two views anode completely satisfy the detector requirements.

6.2.5 Drifting electron lifetime correction

As described in Section 2.4, when the liquid argon is polluted with electronegative impurities, the drifting charge is attenuated by a factor $e^{-t/\tau}$, where $t$ is the time since the ionization

\textsuperscript{2}The Continuous Slowing Down Approximation (CSDA) range is computed integrating $(dE/dx)^{-1}$. 
and $\tau_e$ is the so called drifting electron lifetime, proportional to the inverse of the impurity contaminations. In order to drift 20 cm with a field of 500 V/cm, the liquid argon purity must be enough to ensure at least $\tau_e \approx 120 \, \mu s$, and also with such a purity the attenuation along the drift must be taken into account to correct the collected charge as a function of the drift time (interaction depth). The purity can decrease because of the material outgassing or leaks to the atmosphere, and it can improve thanks to the gas purification. These changes are slow, and during few hours (typical data acquisition time) one can consider the purity as constant.

The correction is based on the variation with the drift time of the $\Delta Q/\Delta l$ associated to each hit belonging to a straight cosmic muon track. Ideally the drift is subdivided into slices of the same thickness along the Z direction. For each slice a Landau function convoluted with a Gaussian fits the distribution of the $\Delta Q/\Delta l$. The convolution with a Gaussian takes into account the finite energy resolution of the detector and the variation of the Landau shape due to the change of the thickness of the absorber (for details see Section 2.1). In fact, the thickness in this case is the track length below each strip $\Delta l$, and it depends on the muon direction. The Landau most probable value already takes into account the normalization for the track length, and for this reason it is referred with $\Delta p/\Delta l$.

The fitted most probable value is plotted as a function of the drift time\(^3\) and fitted by an exponential function. The most probable value is used instead of the average because it is less sensitive to the statistics, and this correction requires only a relative measurement of the collected charge. An example of the result is reported in Figure 6.12 showing on top the $\Delta Q/\Delta l$ distributions for three different slices and at the bottom the most probable value.

\(^3\)In this case the reference to define the drift time is the beginning of the slice, but the measurement of the lifetime is independent of the reference choice.
Figure 6.12: Top: $\Delta Q/\Delta l$ distributions for three drift slices fitted with a Landau function convoluted with a Gaussian. Bottom: Landau most probable value as a function of the drift time fitted with an exponential function. The plots on the left and on the right refer to the X-view and Y-view respectively.

$\Delta p/\Delta l$ versus the drift time. In the particular example the electron lifetime measured is $\tau_e = 145 \pm 5 \mu s$, that corresponds to an oxygen equivalent contamination of 2 ppb according to what is described in Section 2.4. Note the agreement between the two measurements from the two views. The exponential is used to correct the signals at different drift times dividing the charge collected at time $t$ from the trigger with $e^{-t/\tau_e}$. From now on this correction is applied to all the data.

### 6.2.6 Effective gain

The output signal amplitude depends on the primary ionization charge and on a number of effects that can be ideally factorized. In details, it depends on the amount of charge that arrives at the liquid surface, on the efficiency to extract the charge to the vapor phase, on the transparency of the grids, on the gain of the LEM, on the transparency of the LEM and finally on the response of the electronics. The first effect is taken into account by the electron...
lifetime correction, the last effect is well known from the study of the preamplifier described in Section 5.3. All the other effects are in practice impossible to disentangle, and they can be summarized into a single parameter called effective gain of the device, that depends on the details of the entire field configuration.

The effective gain can be measured knowing the initial charge from the ionizing event. From what is described in Section 2.1, with a cutoff energy on the $\delta$ ray energy of 4 MeV, the restricted average energy loss per unit path is 2.1 MeV/cm and approximately independent of the muon energy. The average energy to produce an electron-ion pair in liquid argon is 23.6 eV (see Section 2.2). The charge recombination factor in an electric field of 500 V/cm for a minimum ionizing particle is 0.7 (see Section 2.4). This results in a charge per unit length drifting towards the liquid-vapor interface of $dQ_0/dl = 10$ fC/cm. The effective gain is then defined as the average charge per unit muon track length collected on both the views of the anode divided by $dQ_0/dl$. The collected charge is extracted from the $\Delta Q/\Delta l$ distribution corrected for the electron drift time.

### 6.2.7 Electric field scans

As described in Chapter 4, the configuration of the electric fields must satisfy some requirements:

1. the drift field must guarantee that the maximum drift time is compatible with the liquid argon purity,

2. the extraction field must be larger than 2.5 kV/cm in order to extract the charge into the vapor phase efficiently and fast (see Sections 2.5 and 4.3),

3. the transfer field is defined by the trade-off between the grid transparency and the deformation of the initial charge distribution (see Section 4.3),

4. in order to multiply the charge in the LEM, the amplification field must be larger than 25 kV/cm,

5. to effectively collect the charge leaving the LEM holes the induction field must be as large as possible, compatible with a stable operation (see Section 4.2).

In order to increase the potential difference between the grids and the anode, in the design phase, it was chosen not to fix any electrode to ground, so that the anode can be at positive voltage and the grids at negative voltage. The maximum voltage difference is not the only limit in defining the optimal field configuration, in fact discharges towards ground may occur due to failures of the high voltage coaxial cables/connections and of the high voltage decoupling capacitors of the anode. In other words, also the absolute potential is relevant and can be tuned shifting all the potentials, maintaining the field configuration unchanged.
### 6.2. MEASUREMENTS IN DOUBLE PHASE

**Table 6.2: Typical electric field configuration.**

<table>
<thead>
<tr>
<th>electric field</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>induction</td>
<td>3 kV/cm</td>
</tr>
<tr>
<td>amplification</td>
<td>30–35.5 kV/cm</td>
</tr>
<tr>
<td>transfer</td>
<td>1.5 kV/cm</td>
</tr>
<tr>
<td>extraction</td>
<td>3 kV/cm</td>
</tr>
<tr>
<td>drift</td>
<td>0.5 kV/cm</td>
</tr>
</tbody>
</table>

All the electric fields must be considered as *nominal* fields, defined as the ratio of the potential difference and the distance between the electrodes in question. The nominal extraction field is defined as $E_{\text{ext}} = \Delta V / (x + (d - x)\epsilon_{\text{liq}}/\epsilon_{\text{vap}})$, with $\Delta V$ the voltage across the grids, $d = 1$ cm their distance, $x \approx 0.5$ cm the distance between the liquid level and the grid in liquid (with a precision of 1 mm) and $\epsilon_{\text{liq}} = 1.5$ and $\epsilon_{\text{vap}} = 1$ the relative permittivity of the liquid and of the argon vapor. Table 6.2 summarizes the typical electric field configuration. With such fields the charge produced in the liquid drifts through several regions with different electric fields and eventually it is collected on the anode. Starting from this configuration, we can change one electric field at the time and measure the effect on the response of the detector.

Increasing the drift field the signal amplitude improves slightly due to the reduced electron-ion recombination, and the maximum drift time decreases due to the drift velocity, as shown in Figure 6.5. In the following we report the details of the extraction field, the transfer field and the induction field scans. The results are summarized in Figure 6.13, that shows the average charge per unit length normalized to the maximum value as a function of the nominal fields. The amplification field is kept at 30 kV/cm, that guarantees the charge to enter and be amplified in the LEM, and at the same time it guarantees enough safety margin to the maximum possible potential (breakdown potential).

The collected charge increases with the extraction field until it saturates between 3 kV/cm and 3.5 kV/cm. This behavior is expected recalling that the probability of the electron to transit from the liquid to the vapor phase depends on the electric field, as described in Section 2.5. The top left plot of Figure 6.13 can be compared with the right plot of Figure 2.6. In the latter the saturation appears at a lower electric field, but this is due to the fact that the nominal electric field is an overestimation of the actual extraction field. 3 kV/cm nominal field is sufficient to basically extract the total charge arriving at the liquid vapor interface. This is the standard value used in the detector operation.

Varying the transfer field between the grid in gas and the LEM, the collected charge reaches a maximum. This behavior is associated to two competing effects: (1) the transparency of the grids improves increasing the transfer fields, because less charge is collected on the grid in gas, as explained in Section 4.3, and (2) the transparency of the LEM decreases, because more charge is collected on the bottom electrode of the LEM, as explained...
Figure 6.13: Electric field scans. The average charge per muon track length is shown varying the extraction field (top left), the transfer field (top right) and the induction field (bottom left). The normalization is such that the maximum value is the unity.

in Section 4.1. According to this explanation the position of the maximum is expected to depend on the amplification field in the LEM holes, but no measurement of this effect was made, because there is another constraint to be taken into account when optimizing the induction field. As already pointed out in Section 4.3, the charge coming from the drift volume is focalized between the grids and de-focalized in the transfer region to restore the charge distribution. The de-focalization depends on the transfer field, and this means that the optimal choice of this field is a compromise between effective gain and image deformation. In Figure 6.14 we report the effect on the collected charge changing the transfer field. $\Delta Q/\Delta l$ distributions for each channel are fitted with the usual Gaussian convoluted Landau function and the Landau most probable value $\Delta_p/\Delta l$ is displayed as a function of the strip position. The charge collected on the X-view strips, since they are parallel to the wires of the extraction grids, is subject to the deformation that increases with the transfer field. A sinusoidal function with period 5 mm, that is the wire pitch of the extraction grids, fits the data. On the Y-view the effect is averaged and, as already mentioned, only the total charge is slightly
Figure 6.14: Most probable value of the Gaussian convoluted Landau fit as a function of the strip position for the X-view (left) and the Y-view (right) with a transfer field of 1.5 kV/cm (top) and 4 kV/cm (bottom). On the X-view a sinusoidal function with a period of 5 mm, corresponding to the wire pitch of the grids, is superimposed.

affected by the transfer field. From these considerations we defined the optimal transfer field to be in the range 1–1.5 kV/cm. Figure 6.14 (right) shows also that the LEM amplification is rather uniform, without any significant trend.

Increasing the induction field the transparency of the LEM increases, similarly to what happens to the transparency of the grids increasing the transfer field. The signal amplitude is expected to saturate as soon as no charge is collected on the top electrode of the LEM, but this condition was not reached to avoid discharges across the decoupling capacitors between the anode and the signal plane. A stable operational point was found with an induction field of 3 kV/cm.

We finally describe the effect of changing the amplification field in the LEM holes. The signal amplitude increases exponentially\(^4\) due to the dependence of the Townsend coefficient on the electric field. The \(\Delta Q/\Delta l\) distributions at different amplification fields for both

\(^4\)The increment in gain is apparently exponential in this range of electric field. In general the gain is described by equation 3.2.
CHAPTER 6. RESULTS FROM THE 3 LITER SETUP

Table 6.3: Summary of the results of the Gauss convoluted Landau function fitted to the \( \Delta Q/\Delta l \) distributions at different voltages across the LEM.

<table>
<thead>
<tr>
<th>( \Delta V ) (kV)</th>
<th>( \Delta p/\Delta l ) (fC/cm)</th>
<th>Landau FWHM (fC/cm)</th>
<th>Gauss ( \sigma ) (fC/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-view</td>
<td>Y-view</td>
<td>X-view</td>
</tr>
<tr>
<td>3.0</td>
<td>11.28 ± 0.05</td>
<td>11.03 ± 0.03</td>
<td>1.12 ± 0.03</td>
</tr>
<tr>
<td>3.1</td>
<td>16.27 ± 0.08</td>
<td>15.74 ± 0.05</td>
<td>1.55 ± 0.05</td>
</tr>
<tr>
<td>3.2</td>
<td>24.2 ± 0.1</td>
<td>23.3 ± 0.1</td>
<td>1.98 ± 0.03</td>
</tr>
<tr>
<td>3.3</td>
<td>35.9 ± 0.1</td>
<td>35.2 ± 0.1</td>
<td>3.46 ± 0.07</td>
</tr>
<tr>
<td>3.4</td>
<td>54.5 ± 0.4</td>
<td>52.7 ± 0.2</td>
<td>5.6 ± 0.3</td>
</tr>
<tr>
<td>3.5</td>
<td>83.5 ± 0.4</td>
<td>82.4 ± 0.3</td>
<td>8.5 ± 0.4</td>
</tr>
<tr>
<td>3.55</td>
<td>103 ± 0.5</td>
<td>99 ± 0.3</td>
<td>11.3 ± 0.4</td>
</tr>
</tbody>
</table>

Figure 6.15: \( \Delta Q/\Delta l \) distributions for the X-view (left) and the Y-view (right) at different voltages across the LEM, fitted by a Gauss convoluted Landau function.

views are shown in Figure 6.15, and in Table 6.3 we report the fitting parameters of the Gauss-convoluted Landau functions. Comparing the two views one can note that at a given amplification field the most probable values \( \Delta p/\Delta l \) are compatible, but the width of the distributions on the X-view is constantly larger. This is due to the deformation of the charge distribution introduced by the extraction grids. Note also that at different voltage on the LEM the Landau FWHM stays around 10 % and 7.5 % of \( \Delta p/\Delta l \) for the X- and Y-views respectively, and the Gaussian \( \sigma \) decreases from 18 % to 11 % for the X-view and from 13 % to 8 % for the Y-view. This reflects the good uniformity of the LEM, in fact the difference in gain due to significant thickness variations is accentuated at larger gains, worsening the energy resolution.

In Figure 6.16 we report the effective gain, defined as the sum of the average collected charge per unit track length in the X- and Y-views divided by \( dQ_0/dl = 10 \) fC/cm, versus the applied voltage across the LEM. The largest effective gain is 27, that results in a signal to noise ratio for minimum ionizing muons of more than 200. Since the amplitude of the signal depends on the inclination of the track, the signal to noise ratio is defined for horizontal
6.3. SUMMARY

The maximum amplification in stable conditions is reached with 3.55 kV, equivalent to a nominal amplification field of 35.5 kV/cm. Beyond this point discharges across the LEM occurred. The discharges appear violent and audible analogous to the one in high pressure gas at room temperature. The current of the power supply exceeded the trip threshold and the voltage is ramped down. Optically checking the LEM and the anode after the experiment, no trace of the discharges was found.

6.3 Summary

In this chapter we presented the operation of the double phase argon LEM-TPC as a tracking device, reconstructing straight muon tracks, and as calorimetric device, measuring the \( \frac{dE}{dx} \) of the muons. The detector response is well understood both in terms of the liquid argon TPC and in terms of the charge amplification device in gas.

This is the first time a double phase TPC with imaging capabilities and charge amplification is successful operated. Increasing the gain, we observe a considerable improvement of the signal to noise ratio in the cosmic muon tracks. The gain extends the potentiality of the TPC to lower energy thresholds and it can compensate for the charge loss due to liquid argon impurities in very long drifts.

This provides the proof of principle of the LEM-TPC and a well defined workable design of the charge readout.
CHAPTER 6. RESULTS FROM THE 3 LITER SETUP
Chapter 7

Further development of the LEM-TPC

The proof of principle of the double phase argon LEM-TPC is established by the successful operation of the so called 3 L detector. We can consider the design parameters of the LEM and the two views anode as fixed. We focus now on the necessary steps in order to make this technology attractive and accessible for neutrino and Dark Matter experiments.

Due to the very low energy thresholds required for the direct Dark Matter experiments\(^1\), the most crucial issue is the effective gain. We will discuss what are the possibilities, in our opinion, to extend it beyond 100.

Neutrino experiments need a very large sensitive mass, and hence large instrumented surfaces, that can be achieved with a modular approach. It consists in covering the large surface with a collection of charge readout systems, comprising the extraction grids, the LEM and the two views anode, operating independently. The dimensions of the fundamental brick are limited by production issues to order of 1 m\(^2\). The proof of scalability of this technology is given in this chapter, describing the operation of the first prototype LEM and two views anode with an active area of about 40 × 80 cm\(^2\).

7.1 Towards larger gain

Considering the electronics used in the 3 L detector, an RMS noise of 3 ADC counts (typical after the coherent noise subtraction) and a minimum signal to noise ratio of 10 as analysis threshold, we define the minimum effective gain required in order to perform a direct Dark Matter search with the double phase argon LEM-TPC. The relevant events can be categorized as electron recoils, for instance β rays or electrons ejected due to photon interactions, and nuclear recoils, induced by neutrons or WIMPs. We consider the two separate cases.

\(^1\)Weakly Interacting Massive Particles (WIMPs), a Dark Matter candidate, are expected to interact via elastic collisions with ordinary matter, giving rise to nuclear recoils with energies in the range of 1–100 keV. See Chapter 1.
CHAPTER 7. FURTHER DEVELOPMENT OF THE LEM-TPC

The stopping power in liquid argon for a 10 keV electron is about 21 MeV/cm (see Figure 2.2), about ten times more than for a minimum ionizing muon. The charge recombination factor at an electric field of 1 kV/cm for such an ionization density is about 45% (see the left plot in Figure 2.4 and the text of the paragraph). Since the $dE/dx$ increases while the electron is slowing down, the effective (average) recombination factor can be estimated to about 35%. Recalling that the average energy to produce an electron-ion pair in liquid argon is 23.6 eV, about 150 electrons are freed by a 10 keV electron, and this implies the need of an effective gain of at least 80.

Concerning the nuclear recoils the estimations are more difficult since no comprehensive data exists in the literature. From the data published by the WArP collaboration [16], we can estimate (from the scatter plot of $S_2/S_1$ versus the pulse shape discrimination parameter) the ratio between the proportional scintillation and the primary scintillation for electrons ($S_e^2/S_e^1$) and nuclear recoils ($S_r^2/S_r^1$). The ratio $S_e^2/S_e^1$ is of the order of 10 with an electric field of 1 kV/cm and in the energy range of 40–60 keV$_{re}$. The subscript stays for recoil equivalent, and it means that the energy calibration, performed using the primary scintillation $S_1$, refers to the nuclear recoils. This means that $S_e^1$ and $S_r^1$ are the same for a given recoil equivalent energy, and it turns out that $S_e^2 \approx 10 \times S_r^2$. In other words, the charge freed by an electron is ten times more than the charge freed by a nuclear recoils when they emit the same amount of light. We recall that the amount of photons per unit energy ($Y_e$) produced by electrons differs from the light yield ($Y_r$) of nuclear recoils due to quenching processes (see Section 2.3). For recoil energies above 20 keV$_{re}$ and in absence of an electric field, $Y_r/Y_e \approx 0.25$ [50, 134]. The introduction of an electric field tends to increase $Y_r/Y_e$, since $Y_r$ is almost not affected, while $Y_e$ decreases due to the missing recombination. We can roughly evaluate the ratio $Y_r/Y_e$ in presence of an electric field, recalling that, in case of a minimum ionizing electron, 30% of the scintillation is due to self trapped excitons (limit at infinite electric field), and the rest is due to charge recombination (see the right plot of Figure 2.4). Due to the missing recombination of about the 45% of the charge, $Y_e$ is reduced to 70%, and therefore $Y_r/Y_e \approx 0.35$. It follows that an electron recoil of 10 keV produces the same amount of light as a 28 keV nuclear recoil, and from the values of $S_2/S_1$ from WArP the freed charge is about 15 electrons. This requires a minimum gain of 830, and it becomes 1250 if the threshold is set to 10 electrons. This must be considered as an estimation of the order of magnitude, rather than the calculation of the real amount of ionization charge.

The single amplification stage seems not to be enough to reach these gains. One possibility is to stack two LEMs one on top of the other, in such a way that the charge amplified by the first LEM undergoes a further multiplication in the second one. The advantage is that the charge is spread on different LEM holes, such that the amount of charge in each hole is far form the spark limit (Raether limit). The extrapolation of the effective gain of a double stage LEM-TPC in symmetric operation, where the transparency and the multiplication for
7.1. TOWARDS LARGER GAIN

<table>
<thead>
<tr>
<th>stage</th>
<th>gain</th>
<th>0.5 mm</th>
<th>1 mm</th>
<th>1.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>87 K, 1 bar</td>
<td>single</td>
<td>≈ 30</td>
<td>2.54 kV</td>
<td>3.95 kV</td>
</tr>
<tr>
<td></td>
<td>double</td>
<td>≈ 1200</td>
<td>5.48 kV</td>
<td>8.30 kV</td>
</tr>
<tr>
<td>84 K, 0.7 bar</td>
<td>single</td>
<td>≈ 30</td>
<td>1.97 kV</td>
<td>2.92 kV</td>
</tr>
<tr>
<td></td>
<td>double</td>
<td>≈ 1200</td>
<td>5.14 kV</td>
<td>7.04 kV</td>
</tr>
</tbody>
</table>

Table 7.1: Extrapolation of the gain and of the required voltage for different configurations of the LEM-TPC. The given voltages are taken between the bottom electrode of the first LEM and the anode.

the two LEMs are the same, is:

\[ G_{\text{eff}}^d = T_{\text{ex}} (G_{\text{eff}}^s / T_{\text{ex}})^2, \]

where \( G_{\text{eff}}^s \approx 30 \) is the effective gain (see the definition of effective gain in Section 6.1) of the single stage LEM-TPC, and \( T_{\text{ex}} \approx 0.75 \) (see Section 4.3) takes into account the efficiency of the electron extraction to the vapor phase and the transparency of the extraction grids.

In Table 7.1 we report a tentative extrapolation of the voltage to be applied on the LEM in different conditions. For the extrapolation we used the first Townsend coefficient computed with Magboltz 8.4 [86] at 87 K and 1 bar and the parallel plate approximation for the LEM gain (see equation 3.3). The required voltage is defined as the potential difference between the bottom electrode of the first LEM and the anode. In case of a single amplification stage, we assume an induction field of 2 kV/cm and 2 mm spacing between the anode and the LEM.

In case of a double amplification stage, we assume a transfer field between the LEMs of 2 kV/cm and 2 mm spacing between them, and the induction field of 4 kV/cm always over a distance of 2 mm. At such high gains, events with considerable ionization charge like muons might trigger a breakdown \(^2\), and this might require to perform these tests underground.

Note that for the double amplification stage the required voltage exceeds 8 kV for the 1 mm and the 1.5 mm thick LEMs. A way to reduce it is to lower the density of the vapor cooling the liquid argon. For instance, keeping the temperature at 84 K, the vapor pressure drops to 0.7 bar. The required voltage in this condition is shown in the last rows of Table 7.1.

Another possibility to extend the maximum achievable gain might be to dope the argon with methane, because it acts as a quenching gas, easing the amplification. It was shown [135] that electrons can drift in a liquified mixture of Ar/CH\(_4\) with methane concentrations up to 50 %. The drawback is that the 128 nm scintillation light would be completely quenched (see Section 2.3). Naturally, the purification system must be designed to be non-effective on the methane.

In order to reduce the consequences of a discharge, the electrodes of the LEM can be made

\(^2\) The maximum gain decreases with increasing the charge entering the LEM holes (see Section 4.1).
out of a resistive layer \[136\], in analogy to the Resistive Plate Chambers (RPCs) that, unlike the LEM, operate in streamer mode\(^3\). Such a device is usually called resistive thick GEM (RETGEM). During a discharge the voltage drops only locally, so that the spark is quenched before the whole electrode is discharged, therefore the charge involved and, consequently, the energy are considerably reduced. The resistive electrodes do not avoid the discharge, but it appears a promising technique to make the LEM operation spark tolerant.

### 7.2 Towards larger surface

In order to avoid the divergence of the number of readout modules needed to instrument large surfaces, one has to produce a readout system of the order of \(1 \text{ m}^2\) active area. The problems arise from the required precision on the PCB thickness, on the dielectric rim size and on the smoothness of the hole surfaces. Moreover, the probability for the presence of a defective hole that triggers a premature discharge increases with the active surface, implying that the precision requirements become even more stringent. The larger the readout, the larger the number of the parts that can fail during long operation is, a reason why a simplification of the system is preferable.

Once that not only the geometry parameters, but also the operational conditions are defined, one can intervene, for instance, removing the high voltage decoupling capacitors and directly connect the preamplifier to the strips. This would ward off the failure of a capacitor and ensure that all the charge is fed to the input of the preamplifier\(^4\). This would also greatly simplify the layout of the signal routing plane.

A further simplification can be the removal of the extraction grid in gas, as long as the grid pitch is smaller than the readout pitch, so that the image deformation is irrelevant. The grid in gas serves not only to re-establish the spacial charge distribution after the electron extraction, but also to decrease the electric field before the LEM, easing the focussing of the charge into the LEM holes. The absence of the grid in gas might worsen the transparency of the LEM. It is a matter of carefully evaluating the trade off between the simplification and amplification.

Since the operation point of the LEM-TPC is not yet defined, these simplifications are postponed, and a prototype of charge readout with active area of \(40 \times 76 \text{ cm}^2\) was built as a replica of the \(10 \times 10 \text{ cm}^2\) system of the 3 L detector. The design parameters of the amplification and readout stages are maintained the same, as far as limitations in the production allow. In fact, one of the challenges of building such a detector is to overcome the production issues due to the large surface. The whole readout system is referred to as readout sandwich, and it consists of the two views anode, the LEM and the extraction grids.

---

\(^{3}\)The signals are induced by the streamer locally triggered by the ionizing event.

\(^{4}\)A capacitive coupling to the preamplifier implies that a fraction of signal is lost towards ground through stray capacitances like the cables or the strips themselves. The fraction of charge lost is negligible as long as the decoupling capacitor is much larger than the stray capacitance.
7.2. TOWARDS LARGER SURFACE

piled on top of each other. It is a standalone structure that can be considered as the basic
module to cover larger surfaces.

The readout stage was designed to be compatible with an upgrade of the liquid argon
TPC of the T32 experiment [11], a low momentum charged particle test beam experiment
at the Japan Proton Accelerator Research Complex (J-PARC), proposed to study the par-
ticle identification potentialities of liquid argon TPCs. This new readout was produced and
successfully operated in autumn 2011 in the cryostat of the ArDM experiment [18], a direct
Dark Matter search experiment with a kiloton size double phase argon TPC. In the following
we describe the detector and its operation in the ArDM dewar.

7.2.1 The detector in the ArDM cryostat

The ArDM cryogenic infrastructure consists of two main parts (see Figure 7.1): the detector
vessel and the liquid argon purification circuit. They are both surrounded by a separate
volume that acts as external bath. The ArDM vessel is a vacuum tight cylindrical container
(1 m in diameter and 2 m high) connected to the liquid recirculation. Due to the large
amount of liquid argon, both liquid and gas purification are foreseen. The liquid recirculation,
consisting of a liquid pump and a purification cartridge (filled with copper grains), is custom
made, while the gas recirculation employs commercial solutions for the pump and the getter.
The thermodynamic conditions are controlled by two Gifford-McMahon cryocoolers\textsuperscript{5},
that re-condense the evaporated argon from the external bath. The cryocoolers are managed by
a Programmable Logic Control (PLC) unit, that also monitors all the slow control processes
related to the pressures and temperatures of the system.

The detector is hanging from the top flange of the vessel, as shown in Figure 7.2 (left).
Two 3 inch cryogenic PMTs\textsuperscript{6} are installed below the cathode, protected by a metallic mesh
kept at ground. This kind of mesh, shown in Figure 7.4, is also used as cathode and as
extraction grids, and it will be described later in the text. The windows of the PMTs are
coated with TPB in a polymer matrix in order to convert the scintillation light into visible
light. The primary scintillation signals are used as trigger for the charge readout.

The drift cage is made out of PCB plates. It is limited at the bottom by the cathode
mesh and on the top by the extraction grids. It is 60 cm high and 40 $\times$ 76 cm$^2$ in cross
section to match the dimensions of the readout sandwich. Thirty field shaping electrodes
spaced 2 cm are printed with PCB techniques on the internal surfaces of the plates. They
ensure the uniformity of the drift field along the entire volume.

The high voltage is provided by a 30 stages Greinacher circuit [137], also known as
Cockroft-Walton voltage multiplier. It consists of a series of diodes and capacitors arranged
as Figure 7.3 displays. The components are directly mounted on the external PCB wall of
the drift cage, completely immersed in the liquid. The first stage is connected to the ex-

\textsuperscript{5}Air-cooled Cryomech AL 300.

\textsuperscript{6}Hamamatsu R11065.
Figure 7.1: CAD drawing of the system. The ArDM vessel (1) with the LEM-TPC detector (2) installed, the liquid argon recirculation column (3) containing the custom made pump and filter, the gas recirculation system (4), the re-condenser with the two cryocoolers (5).

traction grid in liquid, the last stage to the cathode and all the others to the corresponding field shaping electrodes. The last stages are connected to the respective electrodes through 200 MΩ resistors that limit the current in case of a discharge (see the picture in Figure 7.3). When an alternating voltage is fed to the input of the circuit the capacitors are charged up. In an ideally steady state, the potential difference across each stage equals the peak to peak voltage of the input AC voltage, and there is no need to provide any current to maintain the potential. In reality the capacities discharge through the reverse current of the diodes and due to the current generated by cosmic muons in the drift volume. This is in fact a very slow process, and during the operation the circuit was charged up about once per day. The way to turn off the drift field is to connect the last stage of the Greinacher circuit to ground through a large resistance to limit the current. This is implemented with a rotary switch installed in liquid argon, that directly touches the cathode. By design the maximum voltage difference between two stages is 2 kV, defining the maximum achievable drift field to be 1 kV/cm. The potential of all the stages can be globally shifted by a DC voltage, in order to match the needed voltage on the grid in liquid without affecting the drift field.

Four capacitive level meters, shown in Figure 7.4, are installed around the extraction grids outside the active volume. The measurement of the liquid level in different positions allows to adjust the planarity of the detector with respect the liquid level, a required feature for large area devices. In fact, the entire vessel can be tilted by means of screw driven movable
7.2. TOWARDS LARGER SURFACE

Figure 7.2: Pictures of the detector. Top right: detector during the assemblage phase. Left: fully assembled detector hanging from the top flange of the ArDM vessel. Bottom right: detector half in the ArDM vessel during the closing procedure.

stands.

7.2.2 The readout sandwich

The readout sandwich, shown schematically in Figure 7.5, consists of the two extraction grids, the LEM, the two views anode, the spacers and the signal routing PCBs. The design parameters of the LEM are the same as for the $10 \times 10 \text{ cm}^2$ prototype operated in the 3 L detector, and the same applies for the two views anode. The 1 mm thick LEM has an active area of $40 \times 76 \text{ cm}^2$ with about of $5 \times 10^5$ holes drilled. To limit the charge involved during a discharge, the LEM electrodes are divided in eight sectors along the long side and powered through 500 MΩ resistors. When a spark occurs only the affected sector is discharged, because the distance between the electrodes of two sectors (1.6 mm) is enough to avoid the propagation of the discharge from one sector to the other.

The LEM was produced by an Italian company\textsuperscript{7} since its dimensions are incompatible with the drilling machines of the CERN TS/DEM workshop. This introduced changes in the production of the dielectric rims, compared to the $10 \times 10 \text{ cm}^2$ LEM. As described already with Figure 5.9, there are two ways to produce the rims. One, used in the case of the $10 \times 10 \text{ cm}^2$ LEM, requires the coating with a resistive layer and slow drilling velocities. The other is simpler, since it involves only chemical etching, but has the drawback that the

\textsuperscript{7}Eltos S.p.A., San Zeno (AR) Italy.
CHAPTER 7. FURTHER DEVELOPMENT OF THE LEM-TPC

Figure 7.3: Top: scheme of the Greinacher circuit composed of the AC power source (a), the shifting voltage source (b) and the field shapers (1, 2, 3, ...). Bottom: picture of the Greinacher circuit mounted on an outer wall of the drift box. Note the 200 MΩ protecting resistors installed on the last twelve stages.

dimension of the rim is limited by the thickness of the electrode. Since the company could not ensure the adequate drilling care, the second method was chosen. The outcome is a 40 μm rim perfectly centered. To avoid further reduction of the dielectric rim, the metal electrodes were passivated\(^8\) instead of being gold plated, as in the case of the 10 × 10 cm\(^2\) LEM. Photos of the LEM and of the holes are reported in Figure 7.6.

To maintain a uniform distance from the anode, a 2 mm thick spacer is installed in between the top LEM face and the anode strips. Its shape matches the division in sectors of the LEM in order not to introduce more dead space. The same structure is installed below the LEM to reduce the sagging due to the weight.

The anode, produced at the CERN TS/DEM workshop, has the same active area as the LEM and 256 strips per view. In view of a test beam, in order not to have any strip parallel to the incoming particles, the strips are rotated by 45° with respect to the anode length. Pictures of the anode and a close view of the strips are shown in Figure 7.6.

The components to feed the voltages, to decouple the signal from the high voltage and to protect the electronics from discharges are equivalent to the one used for the 10 × 10 cm\(^2\) readout system. The 512 (one per channel) 500 MΩ resistors to feed the voltage to the anode strips are mounted on a first signal routing plane. The 270 pF HV decoupling capacitors connects this first plane to a second one, where the 33 Ω resistors, the surge arrestors and

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\(^8\)Passivation is a controlled oxidation of the metal surface to protect it from corrosion.
The two extraction grids, with a distance of 1 cm from each other, are mounted 1.2 cm below the LEM. Built with the same technique as the cathode and the PMT protecting grid, they are made out of 150 µm thick stainless steel foils chemically etched, to leave a square mesh with a pitch of 3 mm and wires 150 µm thick. A picture of the mesh is shown in Figure 7.4. They are glued to 1 cm thick PCB frames, that provide the right tension to keep them flat. For construction constraints, instead of stretching the mesh, the frame was compressed during the gluing phase. The alignment between the two grids is within a wire diameter in the center, but it becomes worse at the edges, because the two grids are inevitably stretched slightly differently. Potentially, this can compromise the grid transparency, that can be restored increasing the transfer field. As described in Section 6.2, image distortions can be caused by the field configuration around the extraction grids, and for this reason the pitch of the meshes was chosen to be equal to the readout strip pitch.

The signal feedthrough, shown in Figure 7.4, is produced in analogy to the 3 L detector, but with sixteen cables passing through the same CF100 flange. The Kapton cables were re-designed to use a spring locked connector, more stable than the ZIF connectors. This allows to extend the Kapton cables, 40 cm long, with ribbon cables. Copper shields against pickup noise are used for the outer extensions.

Each cable connects 32 channels to a CAEN A2792 board (see Section 5.3). Two complete
Figure 7.5: Drawing of the readout sandwich. From bottom to top in the enlarged circle, one can notice the extraction grid in liquid glued on a PCB frame (1), the similar structure for the grid in gas (2), the LEM and the two views anode separate by a spacer (3), and the support of the first signal plane (4). Four level meters (5) are screwed to the grid in liquid, 500 MΩ HV resistors (6) feed the voltage to the anode strips, 270 pF HV capacitors (7) decouple the signal from the HV, surge arresters (8) and 33 Ω resistors (9) protect the electronics from discharges, and the HV connectors (10) bring the power to the LEM and to the anode. The readout sandwich is fixed to the drift cage by means of the structure marked with (11).

CAEN SY2791 crates are used to record the signals from the 512 channels. The acquisition trigger is provided by a threshold discriminator on the signal of the PMTs.

7.2.3 The detector operation

The liquid argon filling procedure is the same as the one used for the 3 L detector. Before the filling, the detector is evacuated to about $10^{-5}$ mbar for about one week in order to let the materials composing the detector outgas. Next, the vessel is filled with pure argon gas recirculated through the gas purification system. This guarantees that the molecules outgassed from the detector, still warm and no longer under vacuum, are trapped in the getter. At the same time the detector is cooled down, condensing argon in the external bath by means of the cryocoolers. Once the system is cold and in thermal equilibrium, the detector is filled with liquid argon passed through the input cartridge used for the 3 L detector. The filling is stopped when the level stabilizes in the middle of the extraction grids. At this point the detector can be leveled with respect to the liquid surface.

The detector was operated for more than four weeks. Several tests were performed concerning the high voltage system, the purification systems and the cryogenics. Stable operation of the charge readout was reached with the nominal electric fields reported in Table 7.2. The
7.2. TOWARDS LARGER SURFACE

Figure 7.6: Top: picture of the $80 \times 40 \text{ cm}^2$ LEM (left) and close-up of its holes (right). Bottom: picture of the two views anode (right) and close-up of its strips (left).

<table>
<thead>
<tr>
<th>electric field</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>induction</td>
<td>2 kV/cm</td>
</tr>
<tr>
<td>amplification</td>
<td>30–35 kV/cm</td>
</tr>
<tr>
<td>transfer</td>
<td>0.6 kV/cm</td>
</tr>
<tr>
<td>extraction</td>
<td>2 kV/cm</td>
</tr>
<tr>
<td>drift</td>
<td>0.4 kV/cm</td>
</tr>
</tbody>
</table>

Table 7.2: Typical electric field configuration.

tests proved not only the functioning of the charge readout, but also the establishment of the liquid argon purity in the ArDM vessel and the effectiveness of the purification systems. The free electron lifetime at the beginning of the experiment was 150 $\mu$s, and at the end it exceeded 500 $\mu$s.

In the following we present some events recorded at the maximum effective gain. As usual, the event display shows on the X-axis and Y-axis the channel number and the drift time respectively, the grey scale represents the signal amplitude. The two views are displayed in the two columns of Figure 7.7. Similarly to the 3 L detector, the common noise of the board is suppressed by a digital filter, described in Section 6.2. The Figure 7.7 presents remarkably clear events showing straight muons, a muon emitting $\delta$ rays, an electromagnetic shower and a nuclear breakup, presumably due to a high energetic neutron. The regularly spaced missing signals along the tracks are due to the dead space between the LEM sectors. The second event shows an extended portion of the track missing, presumably due to the wetting of the
LEM caused by the liquid argon recirculation system. In fact, the region affected by this loss faces the exhaust of the purification circuit, and the effect is correlated with the speed of the liquid argon pump. The purified liquid argon either drips on the readout sandwich, cooling it and favoring the condensation of argon on its surfaces, or it causes some drops from the liquid argon surface to wet the LEM. Though this issue is certainly related to the liquid argon recirculation, further investigations are required to understand it in details.

7.3 Summary

In this chapter we tried to address issues concerning the next development steps of the LEM-TPC technology to make it accessible to neutrino experiments and direct Dark Matter search experiments. The key issue of direct Dark Matter experiments is the required gain of the order of 1000. In order to achieve this, a double amplification stage is needed, though the doping of the argon with methane and the LEM with resistive electrode (RETGEM) are appealing solutions to assist the high gain operation.

The large dimensions are the main concern for a (cost-effective) liquid argon TPC for neutrino physics. The scaling up of the fundamental unit to cover the active area is mandatory, and we believe that a 1 m$^2$ readout sandwich can be produced and operated.

We described and we showed the first operation of a 40×80 cm$^2$ readout system prototype. A detailed analysis of the acquired data and a quantitative evaluation of its performance go beyond the scope of this work. The evaluation of the effective gain of the device must follow a detailed study of the preamplifier response for large input capacitance. At the highest amplification the signal to noise ratio, neglecting the extremely noisy channels, for minimum ionizing particles is about 30. This test demonstrated also the establishment and the maintaining of the liquid argon purity in the ArDM vessel, a basic requirement for the proper operation of the ArDM experiment, and the effectiveness of the Greinacher circuit as a high voltage generator in liquid argon.
Figure 7.7: Display of some events recorded at the maximum amplification field. Left and right columns refer to the two views. From top to bottom: a straight muon, a muon crossing a dead region, a muon which emits $\delta$ rays, an electromagnetic shower and a nuclear breakup.
Chapter 8

Conclusions

The focus of my research activities was the development of a liquid argon Time Projection Chamber (TPC) with amplification of the ionization charge with a dedicated readout system. A liquid argon TPC with an active volume of 3 L was designed, built and operated in several tests. The detector design is based on the double phase TPC concept, and the charge amplification and readout systems rely on the Large Electron Multiplier (LEM) and the two views projective anode installed in the argon vapor.

The behavior of a discharge in the LEM was understood through a numerical study, described in Chapter 4, giving the possibility to improve the design of the charge readout and to interpret the experimental results. The model of streamer formation and propagation relies on the electron diffusion in gas and on the electric field distortion due to space charge. The computation was carried out with a Finite Element Analysis program, and in the same context we designed the extraction grids and the two views projective anode.

We developed and built an experimental setup that performed well in terms of the parameters relevant for TPC operation, i.e. liquid argon purity, stability of thermodynamic conditions, high voltage reliability. A detailed description of the setup was given in Chapter 5.

We built the charge readout system and tested it in pure argon gas at room temperature and at different pressures, characterizing quantitatively the detector response with radioactive sources. Several tests of the double phase argon LEM-TPC, fully operational in double phase conditions, were also performed taking cosmic muon data. The uniformity and the accuracy of the drift field and the effectiveness of the electron extraction were tested measuring the electron drift velocity at different electric fields. The charge amplification and readout systems were benchmarked using cosmic ray muons, three-dimensionally reconstructing the straight tracks and evaluating the charge released per unit length. In this way we could prove that the design parameters of the anode were properly chosen and that it behaved as expected, sharing the charge equally between the two views. We measured the effective gain of the double phase argon LEM-TPC with different field configurations, obtaining a maximum gain
of about 30 for a single stage LEM. The response of the detector was fully understood, and all the observed effects could be explained. These results, described in Chapter 6 and also published in [128], constitute an important milestone in a R&D program for large mass double phase argon TPCs.

In Chapter 7 we reported the possible next steps to increase the maximum gain and the readout area, important in order to make the double phase argon LEM-TPC an attractive technology for neutrino physics, proton decay and direct Dark Matter search experiments. Most importantly, we described the construction and the first operation of a double phase argon LEM-TPC with an active area of 40×80 cm$^2$. The detector was tested during a run that lasted more than four weeks, recording events from cosmic ray muons. The successful test of the large area device marks a critical step towards the completion of the R&D program.
Appendix A

Tests for the optimization of the LEM design

The design of the charge readout that gave the results described in Chapter 6 was preceded by several different tests of other charge readout systems, described in the following paragraphs and published in [125, 126, 127]. The approach of reading two orthogonal sets of electrodes was completely different from what was described in this thesis. In the following, the anode is segmented in sixteen strips 6 mm wide along one direction, and the top electrode of the LEM is segmented in sixteen strips 6 mm wide oriented orthogonally with respect to the anode strips. In this case, the amplification and the readout stages are not independent. The LEM and the anode were fabricated by a German company\(^1\), and the main difference with the one produced at CERN is the dielectric rim production. In fact, in this case the metal is etched away before the drilling. It turns out that the rim is not automatically centered around the holes, and the alignment precision is limited by the machine capabilities to some tens of micrometer. The high voltage is fed on the LEM and anode strips through 500 MΩ resistors, and the signals are decoupled from the high voltage via the usual HV capacitors. Pictures of the segmented LEM, of the anode and of the signal electronic chain are shown in Figure A.1. The mechanical layout allows to mount the LEM and the anode on the 3 L detector without the need of any modification.

The segmentation of the top LEM electrode is supposed to make the device more prone to discharges. This is inferred because during discharge tests in air the sparks happened in the border region of the strips, in the vicinity of the sharpening of the electrode (see Figure A.1), where the electric field is large and distorted by the metal discontinuities. In the case of a spark, the voltage between the affected strip and the bottom electrode drops, increasing the potential difference between the neighboring strips. This initiates a chain reaction that propagates the discharge to all the strips, and possibly this leads to the damage of the electrode at several points.

\(^1\)Multi PCB ltd., Brunnthal, Bayern, Germany.
The design discussed in Chapter 4 was developed because it avoids the segmentation of the LEM electrode. In that case, the decoupling capacitors connected to the LEM are not needed, and this has the beneficial effect to reduce the charge involved in a spark. In contrast to the segmented LEM and single view anode configuration, the signals on the two views projective anode have the same shape for the both views, since the two sets of strips are very close. In addition, the charge sharing is defined by the geometry of the two views anode, and it is independent of the electric field details in the LEM holes and between the anode and the top LEM electrode. This means that design allows to develop the amplification stage and the readout stage independently.

Nevertheless, single and double amplification stage with the segmented LEM were operated in pure gas argon and in double phase conditions. X-ray sources and cosmic muons were used to characterize the detector with an analysis analogous to the one described in Chapter 6. For details refer to that chapter.

**Single stage operation**

Tests of a 1.6 mm thick LEM were performed in double phase conditions reaching an effective maximum gain, limited by the occurrence of discharges in the LEM holes, of about 6 [127]. The effective gain of the device as a function of the potential applied to the LEM is shown on the right plot of Figure A.2. During the experiment, lasting for more than three weeks,
Figure A.2: Left: fitted most probable value of the Gauss convoluted Landau function as a function of time. The steps are due to the change of the amplification field, while the slow decrease is addressed to the charging up of the hole walls. X and Y refer to the anode and LEM views respectively. Right: effective gain versus the applied voltage across the 1.6 mm segmented LEM.

different field configurations were used. This is shown on the left of Figure A.2, where the fitted most probable value of the Gauss convoluted Landau function to the $dQ/dx$ distribution is plotted as a function of time. The two sets of data refer to the charge collected on the anode and on the top LEM strips. In the period highlighted the detector was off because the gas purification system was on and the liquid level was not properly set in between the extraction grids. The steps in gain are due to the change of the amplification field, while the slowly decrease might be due to charging up of the holes.

The amount of charge collected on the anode and on the LEM depends on the induction field and so does the induced signal. When the induction field between the top LEM electrode and the anode is below $\approx 6$ kV/cm, part of the electrons produced in the LEM holes are collected on the top LEM electrode. The fraction diminishes increasing the induction field, until all the charge is collected on the anode. The shape of the signals induced on the LEM strips is supposed to become bipolar, and finally the polarity is inverted with respect to the signal induced on the anode, since the charge is moving away from the LEM and approaching the anode. This behavior is shown in the waveforms of Figure A.3 recorded at three induction fields. The anode signals (left) maintain the same shape, while the LEM signals (right) become bipolar and finally negative. The operation at very large induction fields required a considerable voltage across the decoupling capacitors, making this configuration more difficult to reach in stable conditions, due to discharges across the capacitors.
Double stage operation

Two 1.6 mm thick LEMs, stacked on top of each other to form a double amplification stage, were operated in pure argon gas at STP [125]. The bottom LEM has no segmentation, since it is not read out, while the top one is the same as the one shown in Figure A.1. In Figure A.4 we report an example of energy spectrum of $^{55}$Fe and $^{109}$Cd X-rays sources installed inside the detector at the height of the cathode. Three peaks are clearly visible: the $^{55}$Fe escape peak at around 2.8 keV, the $^{55}$Fe full energy peak at around 5.9 keV and the $^{109}$Cd full energy peak at around 22 keV. In the plots below we show the gain of the device as a function of the applied voltage on each stage and the peak amplitude as a function of the X-ray energy, showing a good linearity.

The double amplification stage was also tested in double phase conditions, recording an effective maximum gain of the order of 10, limited by the occurrence of discharges. During the operation it was impossible to identify in which device the sparks occurred, because all the power supplies quenched simultaneously. Due to the very large voltage difference required between the extraction grids and the anode, the cause of the rather low gain can also be attributed to the failure of the HV decoupling capacitors or of the high voltage cables. The difficulty in operating the detector due to the large absolute voltage with respect to ground suggests that the use of thinner LEMs (or GEMs) for this purpose is preferable. An example of cosmic muon event recorded in double phase condition with a gain of about 10 is shown in Figure A.5.

The use of multi amplification stages is the path to follow when gains larger than 100 are required. In fact, each LEM can operate far from the Raether limit (the charge density that triggers the streamer spark), because the multiplied charge in the bottom LEM is spread on different holes of the top LEM. To enhance this feature, the LEMs can be operated asymmetrically, i.e. the bottom LEM amplifying more than the top one.
Figure A.3: Example of cosmic muon events at different induction fields, namely 10 kV/cm (top), 12 kV/cm (middle) and 14 kV/cm (bottom). The left and the right columns refer to the anode and to the LEM views respectively.
Figure A.4: Double stage of amplification with two 1.6 mm LEMs operated in pure argon gas at STP. Top: signal amplitude distribution when a $^{55}$Fe and a $^{109}$Cd X-ray sources are installed in the detector. Bottom: effective gain of the device versus the voltage applied across each LEM (left) and peak amplitude versus X-ray energy (right).
Figure A.5: Typical cosmic muon signal recorded at the maximum gain of the double amplification stage charge readout. The left and the right columns refer to the anode and to the LEM views respectively.
Bibliography


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