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ProtoDUNE-DP
PROTOtype for the Deep Underground Neutrino
Experiment - Dual Phase detector

Electrostatic Simulations and Performance Studies

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Abstract

In search of answers to the biggest missing puzzle in the field of neutrino physics, large-scale Liquid Argon Time Projection Chambers (LAr-TPCs) have been postulated to be the most attractive instruments for next generation neutrino observations. A state-of-the-art experiment, the Deep Underground Neutrino Experiment (DUNE), which will utilize this LAr-TPC technology for the studies of neutrino science and proton decay, is currently in the stage of design and prototyping.

This thesis reports on the behavior studies of a $6 \times 6 \times 6 \text{ m}^3$ prototype, ProtoDUNE, in the context of DUNE from the electrostatic's point of view. Electrostatic simulations had been performed on the whole detector in order to verify the uniformity of the electric field, and to assure that all local electric fields within the detector are below a certain value to avoid any electrical breakdown phenomena. Additionally, to characterize the performance of the 2D anode used for charge readout in the experiment, some simulations and measurements had been conducted.

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Chapter 1

Introduction

Over the past half-century, researches and discoveries have pushed neutrinos, the most bountiful matter particles in the universe, onto the stage for further studies of several fundamental questions about the nature of matter and the evolution of the universe [1]. Physicists are interested in searching for the missing puzzles within the Standard Model (SM) of particle physics through neutrino studies, including the origin of neutrino masses, CP-violation in the leptonic sector, or the reasons of the preponderance of matter over antimatter in the universe [2].

Aiming for the studies of neutrino science and proton decay, a cutting-edge, international experiment, the *Deep Underground Neutrino Experiment (DUNE)*, has been carried out, which will enable physicists to search for new subatomic phenomena [1], measure unknown parameters in the SM [3], and potentially achieve a revolutionary level of the knowledge for neutrinos and their role in the universe.

To carry out these neutrino researches, neutrino beams are typically designed with energies in the range of GeV or below; therefore, massive detectors are necessary as the cross-sections of interactions are approximately linear with the beam energy [4]. The *Long-Baseline Neutrino Facility (LBNF)* hosted by *Fermi National Accelerator Laboratory (Fermilab)* is the required facility to support the experiment. LBNF and DUNE will together comprise the world's most intense neutrino beam at Fermilab, in *Batavia, Illinois*, a high-precision near detector on the Fermilab site which will record particle interactions close to the source of the beam, a second, much larger *Liquid Argon Time Projection Chamber (LAr-TPC)* far detector installed more than a kilometer underground at the *Sanford Underground Research Laboratory (Sanford Lab)*, in *Lead, South Dakota*, 1300 km downstream of the source, and all other conventional and technical facilities to support the detector systems [1, 3].

In this chapter, to stress the motivation of neutrino studies, a brief introduction on the biggest missing piece of neutrino physics will first be elaborated. Next, as the subject of this thesis is based on a study simulating the dual-phase LAr-TPC prototype for the DUNE far detector, the concept of LAr-TPC as well as the dual-phase technology and performance will be introduced.

1.1 Big Question for Neutrino Physics

The concept of neutrino, which is an electrically neutral fermion with a mass much smaller than those of the other known elementary particles in the SM [5], was first postulated by W. Pauli in 1930 to ensure energy, momentum and angular momentum conservation in beta decay [2]. Since then, physicists around the world have engaged in the studies of these particles.

Neutrinos are produced from weak interactions in a well-defined weak eigenstate, possessing one of the three flavors: electronic (ν_e), muonic (ν_μ) or tauonic (ν_τ), but propagate through mass eigenstates [6, 7]. Recently, neutrino oscillations, whereby neutrinos of different generations can transform into another flavor, have been observed by many experiments of solar, atmospheric, accelerator and reactor neutrinos, which require nonzero neutrino masses and neutrino mixing [8]. The idea of neutrino mixing, first proposed by B. Pontecorvo [9] and by Z. Maki, M. Nakagawa and S. Sakata [10] independently, indicating a relation between the flavor eigenstates and the mass eigenstates of neutrinos, denotes that the flavor eigenstates are each a superposition of the three mass eigenstates, namely

$$\nu_{lL}(x) = \sum_{j=1}^3 U_{lj} \nu_{jL}(x) \quad , \quad l = e, \mu, \tau, \quad (1.1)$$

where $\nu_{jL}(x)$ is a left-handed mass eigenstate possessing a mass m_j , and U_{lj} is the neutrino mixing matrix, often called the *Pontecorvo-Maki-Nakagawa-Sakata* (PMNS) mixing matrix. The PMNS matrix is usually parameterized as:

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \quad (1.2)$$

where $s_{12} = \sin \theta_{12}$, $c_{12} = \cos \theta_{12}$, etc, consisting of the three mixing angles θ_{12} , θ_{23} , θ_{13} and the Dirac phase δ .

To complete the whole PMNS matrix, all the elements need to be precisely defined; the recent measurement of the θ_{13} angle, indicating non-zero values of the three mixing angles, has opened a new way towards the study of neutrino oscillation [11]. The next milestone lies in the observation of the phase factor δ . By studying the $\nu_\mu \rightarrow \nu_e$ oscillation, information on the unknown element in the PMNS matrix can be feasible, providing a way to observe CP violation in the leptonic sector [4], which is our best explanation of the matter-antimatter asymmetry in the universe [11].

Since neutrinos only interact through weak interactions and the weak force has a very short range, neutrinos are typically difficult to detect as they pass through normal matters unimpeded [6], leaving no traces of their passages. To observe the rare interactions of neutrinos with matter, neutrino detectors must be large enough, containing massive amount of target material, being operated for a long enough of time, for detection of a significant number of neutrinos [1]. In addition, these detectors are often built underground to avoid the effects of cosmic rays or other background radiations. To achieve the goal of this challenging experiment, new large-scale neutrino detectors are indispensable, resulting in the introduction of large LAr-TPC detectors.

1.2 Liquid Argon Time Projection Chamber

In the 1970's, D. Nygren first proposed an idea of a new type of particle detector [12], the Time Projection Chamber (TPC), which would provide a brand new way for studies on particle collisions. A TPC features its ability in three dimensional analyses for particle collisions, allowing greater accuracy for event reconstruction.

A TPC consists of a detection volume filled with a certain material. The original technology of a TPC is to fill the detector with a material of one single phase, whereas later on, an advanced technique by exploiting materials in two different phases, with the gas phase located on top of the liquid phase, characterizes its ability in charge multiplication, which provides an excellent signal-to-noise ratio [2, 4, 13, 14, 15, 16, 17]. In the following lines, we will give a detailed description of the principle of a dual-phase TPC.

When an incoming particle travels through the active volume of the detector and strikes the target material in the liquid phase, it ionizes the atoms and frees their electrons. The basic working principle of a dual-phase TPC is to exploit a uniform electric field to transport the tracks of ionized charged particles over a distance until the liquid-vapor interface. With a larger electric field in the gas phase, electrons can be extracted efficiently from the liquid to the gas phase, and thereby triggers the Townsend mechanism for signal amplifications [2, 4, 13, 14, 15, 16, 17, 18]. Figure 1.1 displays a schematic diagram of a dual-phase TPC from where one can see the basic principle of the technology; with different electric field stages, significantly amplified signals allow a good background suppression.

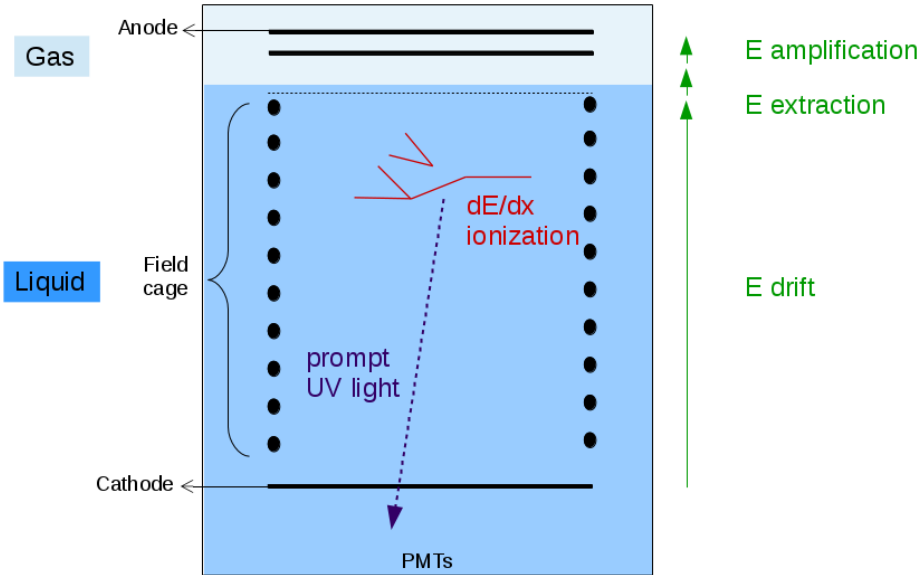


Figure 1.1: Schematic diagram of a dual-phase TPC.

The body of a typical TPC is composed of three parts. At the bottom of the TPC, the drift field is generated by a metallic structure, cathode, to where a bias voltage will be applied. The middle part is a field cage constructed on top of the cathode, and it consists of a series of electrodes surrounding the detector. Each electrode possessing a

graded electric potential produces a uniform electric field within the active volume. The uniformity of the electric field in the TPC provides straight tracks for the ionized charged particles. With as little as possible deviations of the trajectories, the interaction positions can be reconstructed unbiasedly. On top of the TPC, a two-dimensional multi-electrode array, anode, installed at the end of the drift path, is used for readout of the whole electron image of an event. Under this concept, the three-dimensional image (x, y, z) of the event can then be reconstructed from the transverse (x, y) information, recorded directly from the signals induced by the drifted electrons, and the calculation of z -coordinate by the drift time of the ionized electrons and their drift velocity.

Among different ideas of using liquid noble gases as the target material, liquid argon (LAr) appeared to represent one of the most appealing designs [2]. The technology of LAr-TPC was first introduced by C. Rubbia in 1977 [19] for neutrino studies, serving as a potential device which would be able to combine the advantage of both the high resolution but relatively small sensitive mass bubble chambers and the electron detectors with a much more massive target volume but weaker capability in event's global features observation. The aim of this proposal was to incorporate the great amount of specific information on the topology of events from a bubble chamber into a much larger mass, timing, and geometrical flexibility of a counter experiment [20].

The reasons of selecting pure LAr as the target material for these TPCs are listed in the following [19, 20]:

1. it is dense (1.4 g/cm^3) – more neutrino collisions per unit volume can be achieved;
2. it is a byproduct from air liquefaction process – cheaper than other noble gases;
3. it can be easily obtained and purified – many of the organic impurities are frozen out from its liquid form;
4. it is inert and can be easily liquefied with liquid nitrogen;
5. it does not attach free electrons – permits long electron drift time;
6. high ionization density in LAr provides enough electron-ion pairs per unit volume to be detected;
7. diffusion in LAr is small – gives a high spatial resolution.

Some important properties of Ar are summarized in Table 1.1.

Table 1.1: Physical and chemical properties of argon (Ar) [14].

Atomic number	18
Molecular weight	39.948 [g/mol]
Concentration in air	0.934 %
Melting point under 1 atm	83.8 [K]
Boiling point under 1 atm	87.3 [K]
Ionization energy (W_{ion}) in GAr	26.4 [eV]
Ionization energy (W_{ion}) in LAr	23.6 [eV]
Excitation energy (W_{γ}) in LAr	19.5 [eV]
Radiation length (X_0)	14 [cm]
Average energy loss (dE/dx) for MIP	2.12 [MeV/cm]

With LAr appearing to be the best choice for the target material used in the TPC, it is of great importance that the LAr should be “pure”, as its purity affects the collection efficiency of charged particles by the anode. If electronegative molecules (e.g. O_2) are at presence, electrons will be captured instead of contributing to the readout signal. These

molecules becoming electrically-negative will be drifted towards the anode in much slower velocities owing to their larger masses and cross-sections with the LAr atoms. As a result, the purity of the LAr is a basic condition; possible contamination must be kept at a minimum level [14].

By assuring the purity of the LAr, electrons can be drifted to the anode without attaching to other contaminants. To determine the nominal value of the homogeneous electric field in order to drift the electrons efficiently to the anode over a long drift distance, a measurement on the drift velocity V_d of free electrons in LAr under various values of electric field had been carried out [21]. In the study, the electron drift velocity is given as a function of the electric field strength in the range of $0.5 \text{ kV/cm} \leq |\mathbf{E}| \leq 12.6 \text{ kV/cm}$ and the temperature in the range of $87 \text{ K} \leq T \leq 94 \text{ K}$ by fitting the data to an empirical function

$$V_d(T, |\mathbf{E}|) = (P_1(T - T_0) + 1) \left(P_3 |\mathbf{E}| \ln \left(1 + \frac{P_4}{|\mathbf{E}|} \right) + P_5 |\mathbf{E}|^{P_6} \right) + P_2(T - T_0) \quad (1.3)$$

with the parameters listed in Table 1.2. The reference temperature T_0 is set to the mean value of the temperatures used for all data points.

Table 1.2: Global fit parameters of Equation 1.3.

Parameter	Value
P_1	$-0.01481 \pm 0.00095 \text{ [K}^{-1}\text{]}$
P_2	$-0.0075 \pm 0.0028 \text{ [K}^{-1}\text{]}$
P_3	$0.141 \pm 0.023 \text{ [(kV/cm)}^{-1}\text{]}$
P_4	$12.4 \pm 2.7 \text{ [(kV/cm)]}$
P_5	$1.627 \pm 0.078 \text{ [(kV/cm)}^{-P_6}\text{]}$
P_6	0.317 ± 0.021
T_0	90.371 K

Systematic uncertainties on the measurements of electron drift time as well as the inaccurate determinations of the drift distances dominate the total systematic errors of this experiment, while the uncertainties of the temperature determination and the knowledge of the electric field strength are considered to be negligible. As a result, the relative error on the drift velocity V_d resulted from systematic uncertainties is equivalent to around $\pm 0.8 \%$ ($\pm 5 \%$) for $|\mathbf{E}| \geq 2.5 \text{ kV/cm}$ (7.9 kV/cm), and about $\pm 2.1 \%$ ($\pm 32 \%$) for $|\mathbf{E}| = 0.5 \text{ kV/cm}$ (1.6 kV/cm) [21]. Figure 1.2 displays the results of the drift velocity as a function of the electric field strength from the measurement, with the fit results superimposed. As a result, the optimal value of the drift field for a LAr-TPC to efficiently drift the electrons in the LAr over a long drift distance is in the range of $0.25 - 1 \text{ kV/cm}$ [14, 21, 22].

In large detectors, the drift distances are of orders of a few meters. In order to provide a uniform electric field at a nominal value of 0.5 kV/cm in the active volume, very high voltages need to be applied at the cathode so as to drift the electrons efficiently to the anode; the longer the drift distances, the higher the voltages demanded for the cathode. This task represent a challenge in terms of generations and safe transmissions of the voltage. To provide such high voltages to the cathode, a dedicated system is needed in this kind of detectors. All the elements need to be carefully designed to guarantee a safe operation of the detector.

With the cathode operating at such high voltages immersed in a dielectric material,

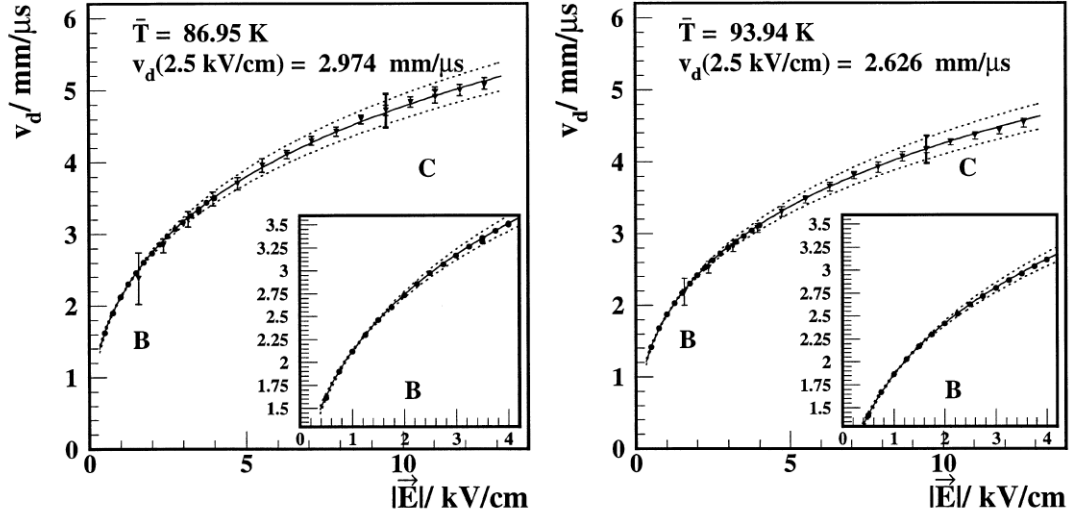


Figure 1.2: Electron drift velocities in liquid argon under different electric field strengths between 0.5 kV/cm and 12.6 kV/cm at 87 K and 94 K. [21]

influences from generated electric field nearby might result in modifications of the material properties. For instance, electrical breakdown, a phenomenon of the loss of dielectric characteristic of an insulator (in solid, liquid or gas phases) is caused by the presence of a strong electric field exceeding a certain threshold magnitude. This critical value at which the breakdown takes place is a physical property of a material and is called the dielectric strength. In pure liquids and gases, the current carriers, the free electrons and ions generated by external radiation, are accelerated by the surrounding electric field. With the presence of a strong electric field, large enough kinetic energies acquired by the accelerated particles are transformed into potential energies by ionizing further molecules or atoms, potentially initiating the process of avalanche [14, 18]. With much larger densities compared to gases, liquids are expected to have higher dielectric strengths than gases.

The dielectric strength of LAr runs over a wide range of values depending on its purity and cryogenic conditions [22]. If impurities are found within LAr, formations of ellipsoids from these impure drops by the electric field merge and form a high-conductive channel between the electrodes, resulting in the occurrences of electrical breakdown [23]. Several measurements for LAr breakdown has been reported in literature. A first measurement of the LAr dielectric strength provided a reference value of 1.4 MV/cm [24]. Later on, dielectric strengths with much lower values have been observed in various tests [25]. It is believed that the strength of LAr would be much less than this reference value in large spacing [26]. Recently, an examination used to test the dielectric strength of LAr had been performed, showing a sustainable steady field of 100 kV/cm at equilibrium. Nevertheless, a lower breakdown value of 40 kV/cm was observed as the LAr boiled. As argon gas has a much lower dielectric strength compared to the liquid, we interpret the presence of this behavior as being triggered by the formation of bubbles [27, 28], which is believed to be due to the fact that the geometries of the bubbles are changed and they can reform and merge into larger high-conductive channels prone to discharges [14]. As a result, in order to maintain the stability of LAr and to prevent the occurrences of electrical breakdown, all local electric fields inside the LAr should be minimized, keeping a guideline for the upper boundary as 40 kV/cm [14].

For a better understanding on the avant-guard technology of a dual-phase LAr-TPC, a prototype detector *ProtoDUNE-DP* will be built in the context of DUNE. The aim of this thesis is to study the behavior of this prototype from the electrostatic's point of view. We will perform electrostatic simulations of the whole detector at the nominal voltage selected for the ProtoDUNE-DP detector to verify the uniformity of the electric field within the field cage, and to guarantee that the electric field distribution inside the liquid argon satisfies our guideline. The second part of this work is based on the 2D anode capacitance simulations and its comparison with measurements performed in a stand-alone anode.

Chapter 2

Design Concept of the ProtoDUNE-DP Detector

The DUNE far detector planned at the Sanford Lab site will be as yet the largest LAr-TPC (68,000 tons of LAr in total for four cryostats) ever built in the world, preceding the two largest LAr-TPC that have been built up to date, the *ICARUS* detector (760 tons) and the *MicroBooNE* detector (170 tons), in the amount of target material by around a factor of hundred [1].

In order to test the detector components and have a closer insight into the technologies used for the construction of the far detector, two large prototype detectors (*ProtoDUNE*) at *CERN (European Organization for Nuclear Research) Neutrino Platform* will be built. The Single-Phase ProtoDUNE detector (*ProtoDUNE-SP*) will be built using the full-scale single-phase LAr-TPC detector technology based on the techniques established for detectors used in ICARUS and MicroBooNE. The Dual-Phase ProtoDUNE detector (*ProtoDUNE-DP*) will on the other hand test a revolutionary alteration of the LAr-TPC technology, whose state-of-the-art technology features amplifiers in a relatively small volume of GAR above a greater volume of LAr, assuring a 20-fold amplification of signals produced by ionized electrons drifting from the LAr volume [1].

As mentioned in Section 1.2, the fundamental working principle of a LAr-TPC demands the presence of a homogeneous electric field in order to prevent any distortions of particle trajectories for event reconstructions. In the ProtoDUNE-DP detector, the nominal value of the electric field will be set to 0.5 kV/cm. With a long drift distance of about 6 m, in order to generate the drift field at a nominal value of 0.5 kV/cm, a bias voltage of 300 kV is required at the cathode.

In this chapter, detailed elaborations on the configuration of the ProtoDUNE-DP detector, including the design of the TPC and the high voltage (HV) system required to support the experiment will be unveiled.

2.1 Time Projection Chamber

Figure 2.1 is the schematic diagram of the ProtoDUNE-DP detector. The detector has a vertically standing cubic structure consisting of a cryogenic vessel with an inner volume

of about $7.9(\text{H}) \times 8.5(\text{L}) \times 8.5(\text{W}) \text{ m}^3$, and an inner detector with a volume of around $6 \times 6 \times 6 \text{ m}^3$ suspended within the vessel [14]. The main parameters are summarized in Table 2.1 and a vertical cross-section view can be found in Figure 2.2.

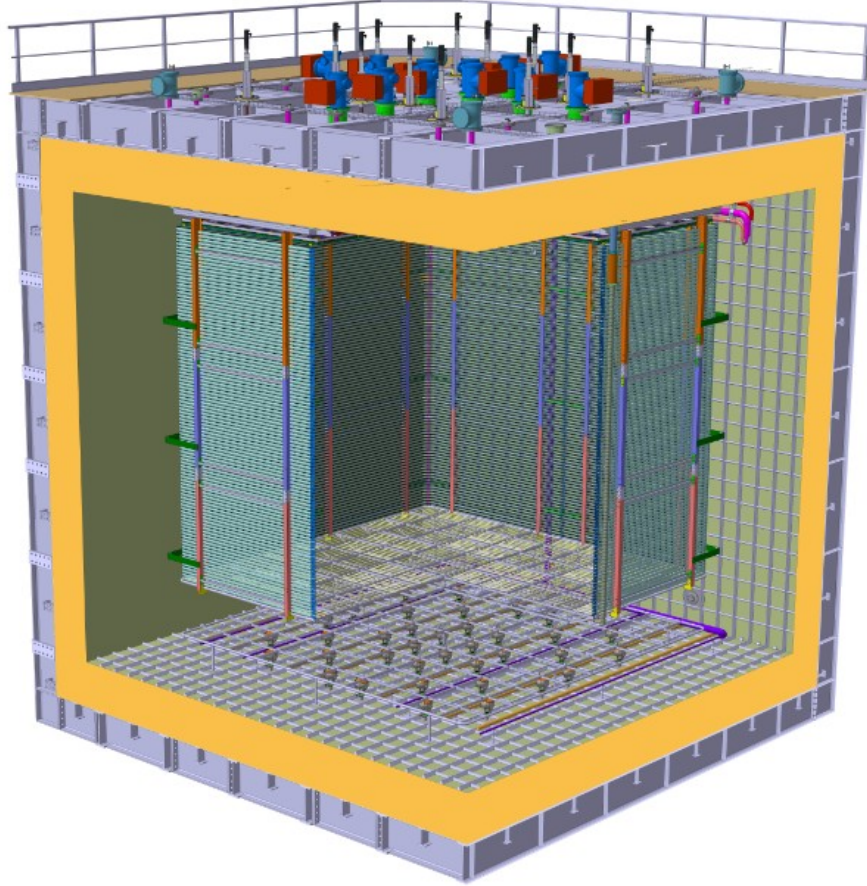


Figure 2.1: Schematic diagram of the ProtoDUNE-DP detector, including the cryogenic vessel and the inner detector, with some boundaries partially hidden for a perspective view.

Table 2.1: Main parameters of the ProtoDUNE-DP detector.

Section	Volume (H $\times$ L $\times$ W)
Total inner volume	7900 [mm] $\times$ 8548 [mm] $\times$ 8548 [mm]
LAr volume	7385 [mm] $\times$ 8548 [mm] $\times$ 8548 [mm]
GAr volume	515 [mm] $\times$ 8548 [mm] $\times$ 8548 [mm]
Panel	Thickness
Cryostat plate	10 [mm]
Insulation	0.8 [m]
Membrane	2 [mm]

The whole volume is filled with argon as the target material, with the gas phase (*GAr*) on top of the liquid phase (*LAr*). The inner detector provides a uniform electric field pointing downward, in order to drift the electrons vertically to the liquid-vapor interface

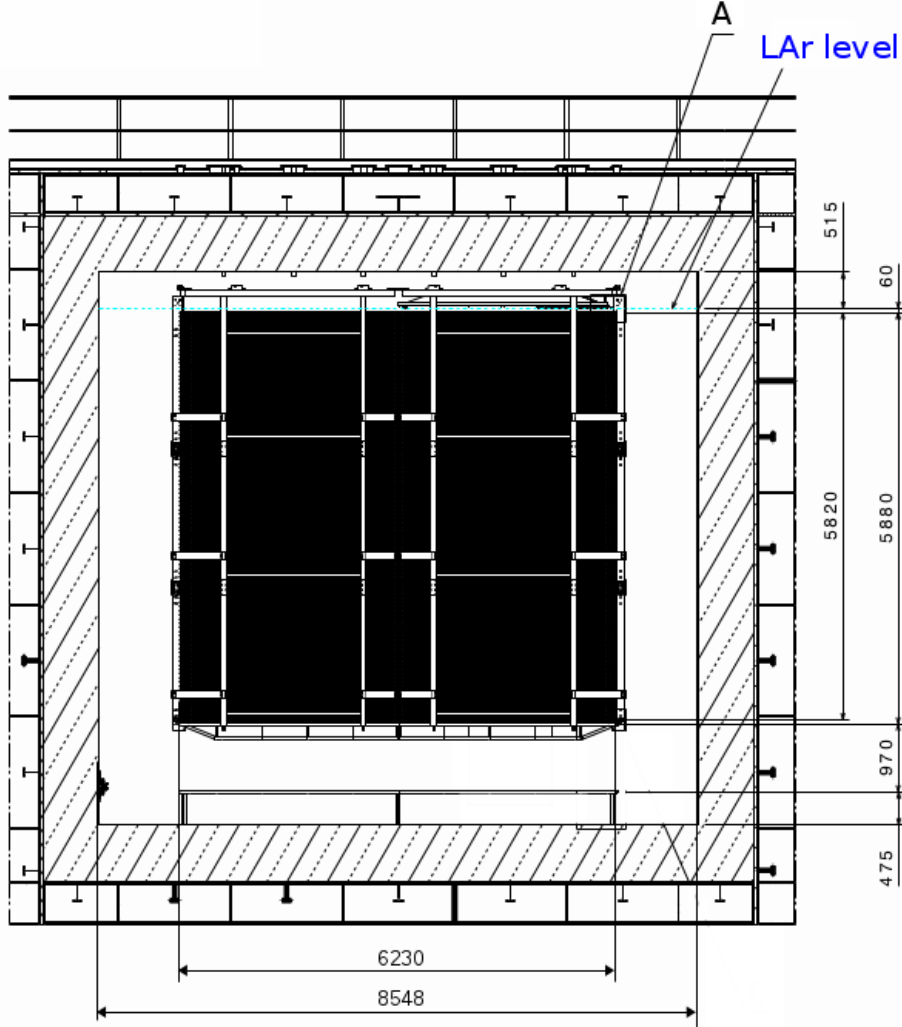


Figure 2.2: Vertical cross-section of the ProtoDUNE-TP detector; all dimensions in the unit of mm.

(denoted as *LAr level* henceforth). This uniform drift field is generated by a *field cage*, composed of 98 equally-spaced aluminum profiles (round tubes along a square path with rounded corners [14]) named as *field shapers*. Another metallic structure, *cathode*, assembled 60 mm below the last field shaper, is applied with a high voltage designed to reach up to 300 kV, and R & D towards 600 kV will be considered after feasible operation for 300 kV. With well-designed *voltage divider boards* consisting of resistors and varistors attached to the cathode and the field shapers, a discrete electric potential difference of 3 kV between two adjacent stages creates a uniform drift field of 0.5 kV/cm from the cathode to the LAr level.

The cathode placed 60 mm below the last field shaper closes the drift field at the bottom of the detector. It consists of a stainless steel gridded structure, named as support structure, and a number of 1-cm-radius, 63-cm-long tubes inserted between each grid. A close-up view of the cathode structure can be found in Figure 3.18. An array of photomultipliers (PMTs) uniformly distributed around 1 m below are used for scintillation

light detection. The grid-like geometry of the cathode enables the transparency to light. In between the cathode and the PMTs is a grounded grid-like stainless steel framework, *ground grid*, serving as the electrostatic shielding for the PMTs.

The *charge readout plane (CRP)* consisting of three sandwiched layers: the *anode*, the *large electron multiplier (LEM)* and the *extraction grid* (in a sequence from top to the bottom) with precisely defined inter-stage distances and inter alignment, is suspended above the field cage. The CRP module used in the ProtoDUNE-DP detector with an active area approximately as large as $6 \times 6 \text{ m}^2$ is a direct extrapolation of the successful $10 \times 10 \text{ cm}^2$ prototypes [15, 16, 17]. To demonstrate a uniform gain and the detector response on the readout plane at a multi-square-meter scale, the designs and the quality controls of the anode, the LEM and the extraction grid ought to be carefully studied and sustained. For example, different patterns on the anode were investigated, and was finally optimized to promise an exact 50:50 charge sharing between both views and the best resolution on the particle energy loss per unit length dE/dx [13, 16]. Similarly, LEMs of varying hole diameters, hole pitches and rim thicknesses had been operated to determine the best structure which provided the most stable gain under dual-phase circumstances [13, 17]. Following many years of tests with prototyping on smaller-scale LAr detectors, all layouts have matured and are ready for utilization in a larger-scale detector.

The anode consists of two sets of perpendicular 3-mm-pitch copper strips (denoted as *views*), which provide 2D (x, y) coordinate detection of the events. The LEM is made up of a 1-mm-thick FR4 substrate with thin copper layers laminated on both sides, and is perforated with 800- μm -spaced, 500- μm -diameter circular holes. Both the anodes and the LEMs come in individual units with an area of $50 \times 50 \text{ cm}^2$, and are printed circuit boards (PCBs) that can be simply mass-produced in the industry at affordable costs [13]. The extraction grid is composed of a series of 100- μm -diameter wires matching the readout pitch of 3 mm in both directions, and is tensed across the whole $6 \times 6 \text{ m}^2$ area. Figure 2.3 are photos of a piece of LEM (the two on the left) and a piece of anode (the two on the right) with sizes of $50 \times 50 \text{ cm}^2$. Upper left is the LEM with the holes displayed in the zoomed figure and lower left shows the HV connections to the two electrodes of the LEM. Upper right is the front side of the anode module with a total of 160 readout strips for each view, and lower right is the back side including 20 KEL connectors with each linking a group of 32 strips.

Figure 2.4a is a zoom around the top part of the detector (part A in Figure 2.2) containing the first three field shapers and the CRP; Figure 2.4b is a zoomed diagram of the part denoted as DETAIL D, used additionally to display the sandwiched layers of the CRP. The working principle of the CPR is as the following. First, the extraction grid placed 5 mm below the LAr level efficiently extracts the electrons from the LAr into the GAR. Later, the LEM at 10 mm above the extraction grid amplifies the signal by triggering Townsend avalanche [2, 4, 13, 14, 15, 16, 17, 18] in the holes with a large electric field of around 35 kV/cm. Finally, the electrons are collected by the 2D anode located 2 mm above the LEM.

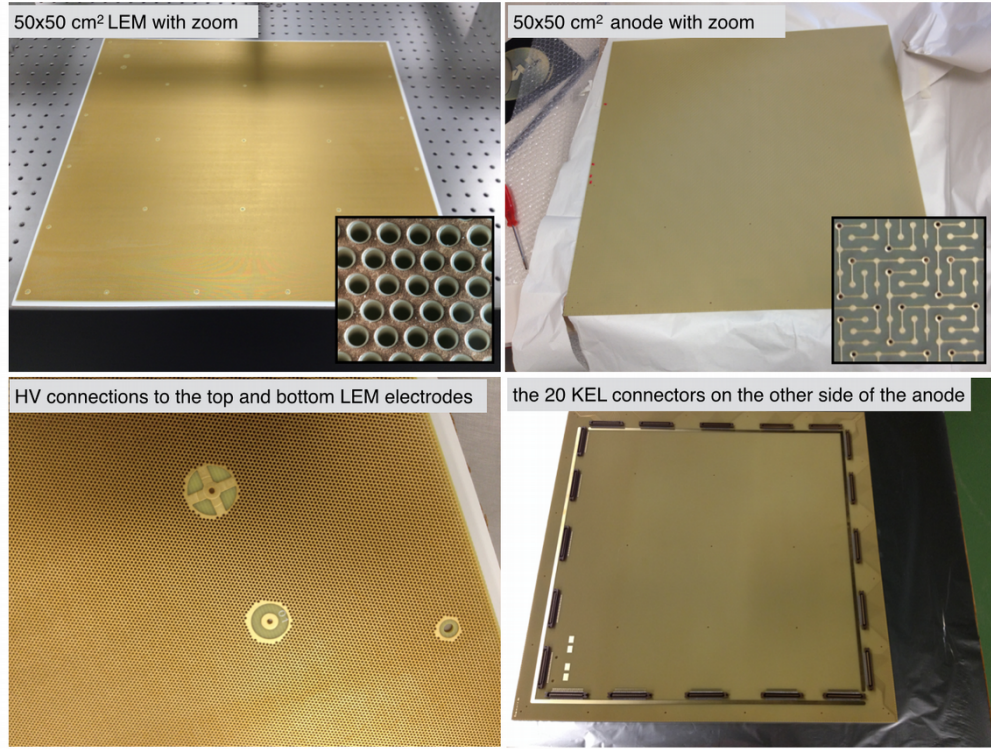


Figure 2.3: Photos of a piece of $50 \times 50 \text{ cm}^2$ LEM (shown on the left) and anode (shown on the right) module.

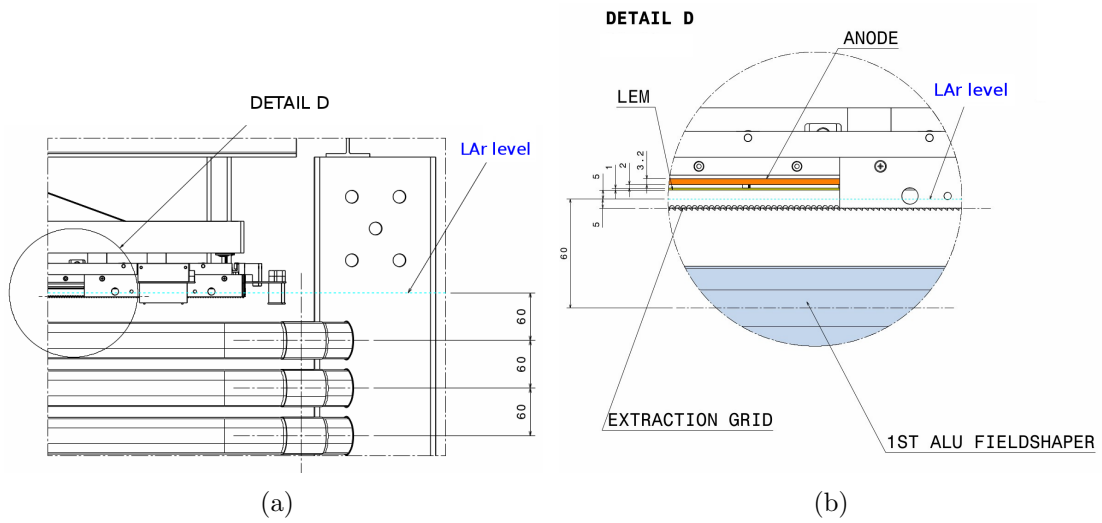


Figure 2.4: (a) Schematic diagram around the top part of the detector, comprising the first few field shapers and the CRP. (b) Zoom of DETAIL D to provide a closer look for the sandwiched layers within the CRP. All dimensions are in the unit of mm.

2.2 High Voltage System

First of all, to provide the required voltage to the cathode, we need to generate it. In the ProtoDUNE-DP detector, an external HV power supply *PNChp 300000-05-neg* provided by *Heinzinger[®] electronic GmbH* [29] will be used. The second step is to transmit the voltage from the power supply located outside the cryostat to the cathode, which is immersed inside the LAr. Several components develop this task:

- HV cable: It connects the power supply to a feedthrough. HV cables up to 300 kV with the required specifications in terms of stability, safety, noise and low residual ripple, are commercially available. In the case of the ProtoDUNE-DP detector, Heinzinger provides also the rated cable.
- High voltage feedthrough (HVFT): It is the most delicate component as its role is to safely deliver the very high voltage to the cathode through the thick insulating walls of the cryostat without compromising the purity of the Ar inside. It is a custom-made feedthrough of 2.4 m long to traverse the insulator and should be carefully designed to be vacuum tight and have small heat input. Furthermore, it brings the high voltage from warm temperatures (outside the cryostat) to LAr temperatures; thus, chosen ought to be capable of executions under cryogenic circumstances and possesses low heat conductivity.

Figure 2.5 shows the pilot design of the HVFT, already installed in the $3 \times 1 \times 1$ m³ dual-phase prototype detector[13], which will be used by the ProtoDUNE-DP feedthrough after minor modifications. The feedthrough is a scaled up version of the one used in the ICARUS detector designed to sustain 150 kV and operated at -75 kV for several years [30]. The design has a coaxial configuration with an outer and an inner conductor separated by a High Molecular Density Polyethylene (HMDPE) insulator. The outer conductor consists of a 2-mm-thick tube with a CF250 Ultra High Vacuum flange welded on one end and an elliptical edge ring welded on the other. The inner conductor is a 1-mm-thick stainless steel tube filled with FR4 to guarantee the vacuum tightness. One end of it is a female receptacle to accept the plug from the cable and the other end is a male contact to provide the high voltage connection into the LAr volume. More details on the feedthrough and the test performed at -295 kV can be found in Reference [22].

- Connection between the HVFT and the cathode: Because of the long drift distance of the detector with the cathode assembled around 6 m below the LAr level, a connecting component is also needed, serving as the link between the HVFT and the cathode. Figure 2.6 is the schematic diagram of a preliminary layout for the custom-designed connecting component (denoted as *connection* in the figure). Figure 2.6a shows the connection between the feedthrough and the component connected to the cathode. The connecting component is composed of three ~ 1.8 m-long pieces providing a total length more than 5 m. A certain thickness of HMDPE is covered on the surface for the insulating protection. Besides, the first few field shapers and *degraders* attached on the HMDPE surface of the connecting component can be seen. The degraders are an array of stainless steel rings surrounding the connecting component with the same electric potential as the corresponding field shaper located at the same height. The connection between the corresponding field shaper and the degrader is done through a copper wire which can be seen from the perspective view of Figure 2.6b.

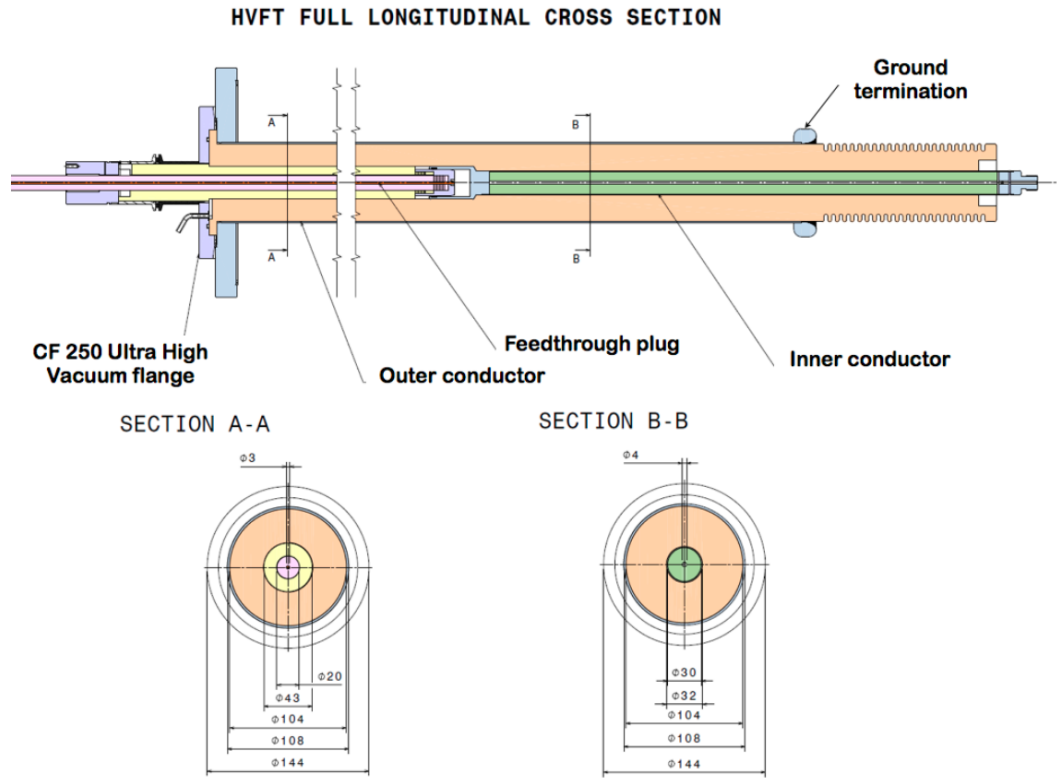


Figure 2.5: The top figure is a schematic diagram of the HVFT design longitudinal cross-section. The two figures at the bottom are cross-sections in the transverse direction from two positions; all dimensions in the unit of mm.

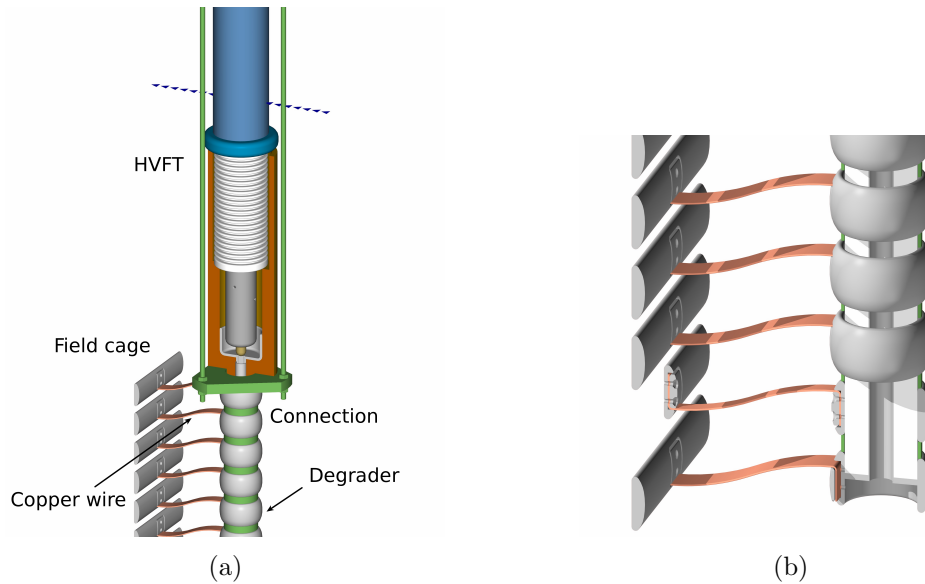


Figure 2.6: Schematic diagram of the design for the connecting component serving as the connection between the HVFT and the cathode. The blue dashed line in (a) denotes the LAr level.

Finally, apart from feeding the nominal voltage to the cathode, we need to guarantee a safe operation avoiding reaching very high electric fields inside the LAr. This means that all different parts of the TPC (field cage, cathode,...) and the HVFT should be carefully designed to minimize the electric fields which can cause sparks that can damage parts of the detector. The goal of this work is to perform electrostatic simulations of the whole detector, including all the elements of the TPC and the HVFT, to verify that all electric fields inside the LAr are minimized. These simulation results will be displayed in the following chapters.

Chapter 3

Electrostatic Simulation

The purpose of building the ProtoDUNE-DP detector is to fully illustrate the technologies that will be used for a future larger dual-phase LAr-TPC installation. Before pragmatically building up a detector, the designs of the detector components require lots of studies in order to reach the requirements in terms of functionality, but also of manufacturing capability, with some of them in large quantities. Within this framework, electrostatic simulations of all the different components of the detector each exposed to a certain voltage were performed. The two goals of these simulations are the following: first, verify the existence of a uniform electric field within the target volume, and second, avoid any local electric field inside the LAr volume higher than our guideline of 40 kV/cm, explained in Chapter 1.

All the simulations in this thesis were performed using the COMSOL *Multiphysics*[®] modeling software with the Electrical AC/DC Module which aims at simulating electric, magnetic, and electromagnetic fields in static and low-frequency applications [31]. In electromagnetic analyses on a macroscopic level, the problem is that of solving *Maxwell's equations* subjected to certain boundary conditions [32]. For an electrostatic study which is the aim of this work, the *constitutive relation* which describes the macroscopic properties of the medium is given as

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E} = \varepsilon \mathbf{E} \quad (3.1)$$

where $\mathbf{E}$ and $\mathbf{D}$ are the electric field and the electric displacement field respectively. ε_0 is the permittivity of vacuum which is a physical constant with a defined value of

$$\varepsilon_0 \approx 8.854 \cdot 10^{-12} F/m \quad (3.2)$$

describing the ability of vacuum to permit electric field lines; on the other hand, ε is the permittivity of the medium which gives particular values for different materials under various conditions. The relative permittivity or sometimes called dielectric constant ε_r defined as the ratio of the material's own permittivity over the permittivity of vacuum

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \quad (3.3)$$

plays an important role in specifying the boundary conditions at material interfaces and physical boundaries [32].

This chapter summarizes the results of the electrostatic simulations performed on the whole experimental setup, including the TPC and the HV system as represented in Figure

3.1. Simulations on different parts of the TPC, including the field cage, the cathode, the ground grid, the CRP, as well as the HVFT and its connection to the cathode, will be displayed separately in different sections. The materials and their corresponding relative permittivities used in the simulations are summarized in Table 3.1.

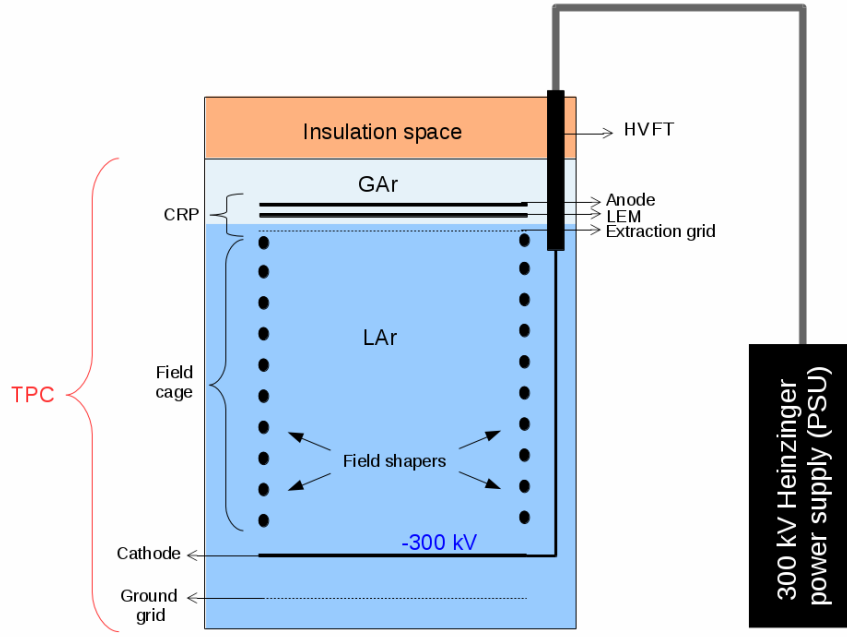


Figure 3.1: Schematic diagram of the experimental setup: CRP, field cage, cathode, ground grid, HVFT and its connection to the cathode.

Table 3.1: Material properties of the detector components used in the simulations.

	Component	Material	ϵ_r
Target material	GAr	argon	1.1
	LAr	argon	1.5
TPC	CRP	stainless steel	—
	Field cage	aluminum	—
	Cathode	stainless steel	—
	Ground grid	stainless steel	—
HVFT	Outer conductor	stainless steel	—
	Insulator	HMDPE	2.3
	Inner conductor	stainless steel	—
Connection	Degraders	aluminum	—
	Wires	copper	—

3.1 Time Projection Chamber

The TPC consists of separate components: the field cage, the cathode, the ground grid and the CRP. The purpose of the electrostatic simulations on the TPC is to verify the uniformity of the electric field inside the active volume, and to guarantee that there are no critical field regions inside the LAr.

The TPC structure is quite complex as we had shown in the previous chapter, and a whole 3D simulation will be very difficult to perform and very time consuming. Instead, taking advantage of the symmetry of the detector, a simplified 2D model can be used to analyze the uniformity of the electric field in different parts of the detector. Figure 3.2 displays the 2D cross-section of one corner of the TPC, with an area of $3 \times 3 \text{ m}^2$ used to perform the simulations. All the relevant distances are illustrated in the figure in mm.

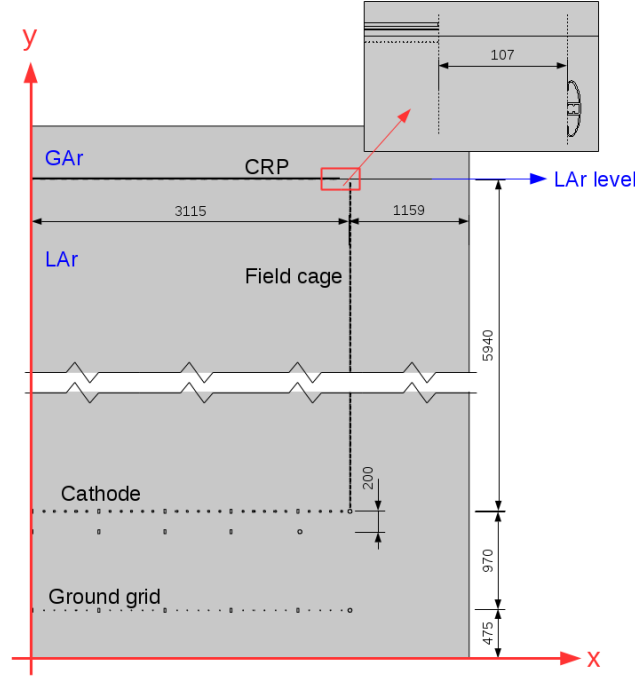


Figure 3.2: 2D simulation model of the TPC; all dimensions in the unit of mm.

According to the electric fields needed for different stages during operation, the electrostatic configuration of the TPC is summarized in Table 3.2.

3.1.1 Field Cage

The field cage is composed of 98 profiles, named as field shapers, and separated by 60 mm. Each field shaper is electrically connected to its neighboring ones through a voltage divider board in order to provide a graded potential from -9.5 kV to -300.5 kV. The potential difference of 3 kV between two of them guarantees a uniform field at the nominal value of 0.5 kV/cm, and results in a drift velocity of 1.6 mm/ μs for the electrons [14].

Table 3.2: Electrostatic configuration of the TPC.

	Distance to the stage above [mm]	Nominal potential [kV]	Field to the stage above [kV/cm]
Anode	-	0	-
LEM(upper electrode)	2	-1	5
LEM(lower electrode)	1	-4	30
LAr level	5	-	-
Extraction grid	5	-6.5	2.5
First field shaper	60	-9.5	0.5
Last field shaper	60	-300.5	0.5
Cathode	60	-303.5	0.5

In a detector, the *Fiducial Volume* is defined to be the active volume within which the contributions from the edge effect is negligible. In our detector, the fiducial volume is defined as the active volume in where an electric field of negligible deviations from the nominal value of 0.5 kV/cm is found, in order to reconstruct the exact interaction position of an incoming particle with the argon molecule unbiasedly. Through electrostatic simulations, the uniformity of the electric field within a certain region can be verified.

To study the homogeneity of the electric field, Figure 3.3 displays the electric potential and the electric field lines distribution within the field cage. Electric field line deviation from a straight track can be seen at the periphery of the field cage, including the bottom part close to the cathode, and the top side area between the end of the CRP and the field shapers.

Figure 3.4 zooms at the bottom part of the field cage which is the region above the cathode. The cathode is not a continuous plane and has a segmented geometry coming from the grid-like support structure and the tubes inserted in between. Because of this, the electric field is perturbed near the surface of the tubes as shown in Figure 3.4b. Local electric fields around the structure are higher than 1 kV/cm while those between tubes are around 0.3 kV/cm.

To evaluate at which distance this deviation starts to be negligible, electric fields along horizontal parallel lines with different distances away from the cathode were simulated and the result is exhibited in Figure 3.5. The plot shows the results with distances in steps of 10 mm between 0 and 70 mm. The light blue line denoted as “Distance = 0” displays the electric field along a cut line right above the cathode which runs from 0.1 kV/cm to 1.5 kV/cm. By moving away from the cathode, the perturbation of electric field on the cut line reduces as expected. At 70 mm above the cathode, a perturbation of the drift field below 0.02 kV/cm can be obtained.

Figure 3.6 zooms at the upper part of the field cage that is the region between the end of the CRP and the surface of the field shapers. Because of the presence of a gap between the end of the CRP and the first field shaper, the electric field lines deviate in this region. Figure 3.6b zooms in the scale for a better view on the values of the normalized electric field; at the edge of the CRP, local electric field higher than 1 kV/cm can take place.

To estimate at which distance this effect disappear, in search of the horizontal boundary of the fiducial volume, electric fields in the normalized value (E_{norm}), the value in horizontal direction (E_x) and the value in vertical direction (E_y) along a vertical cut line

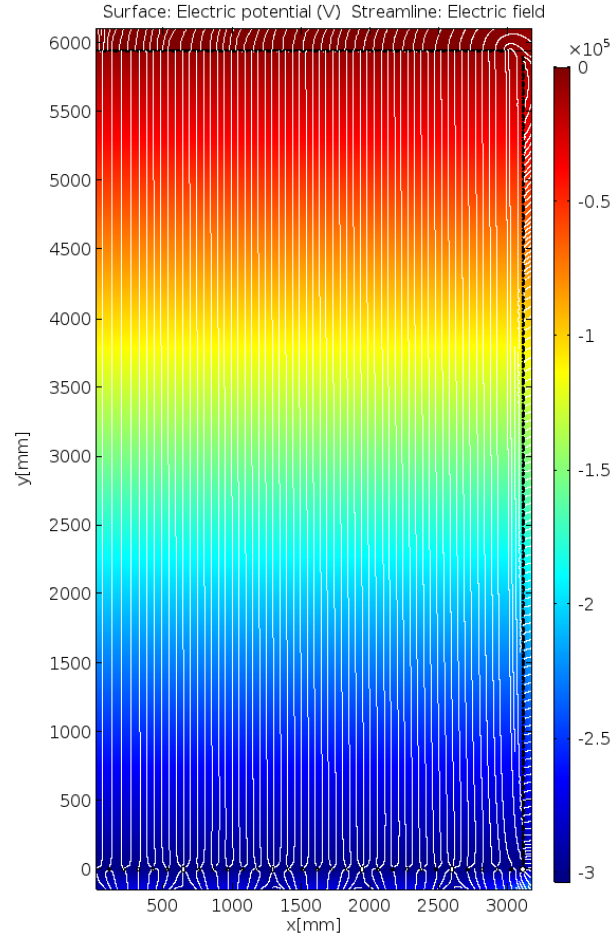


Figure 3.3: Electric potential and field lines distribution in the whole field cage.

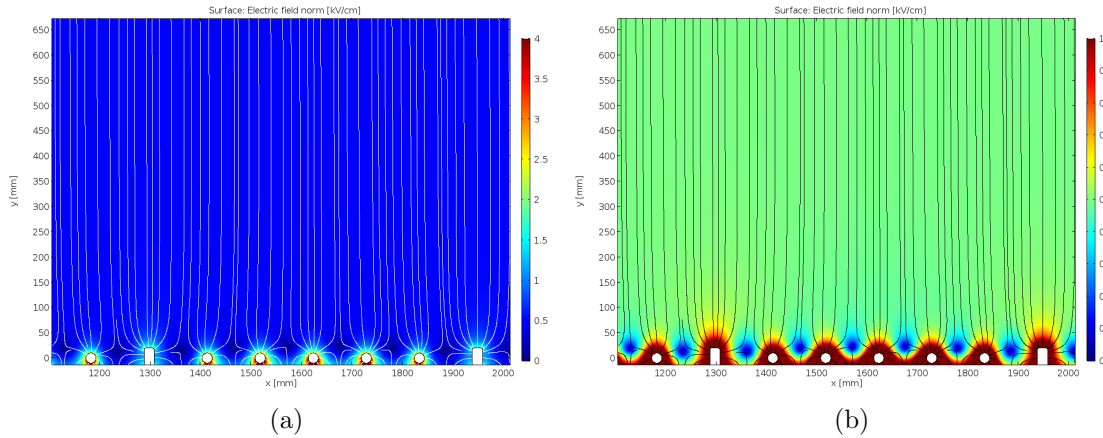


Figure 3.4: Normalized electric field and field lines distribution in the vicinity of the cathode in two different electric field scales.

starting from the cathode and ending 1 mm below the extraction grid at the end of the CRP are displayed in Figure 3.7. The direction of the electric field was studied since a nonzero E_x can cause a horizontal displacement between the primary ionization positions and the anode strip positions, bringing about incorrect reconstruction positions, while E_y

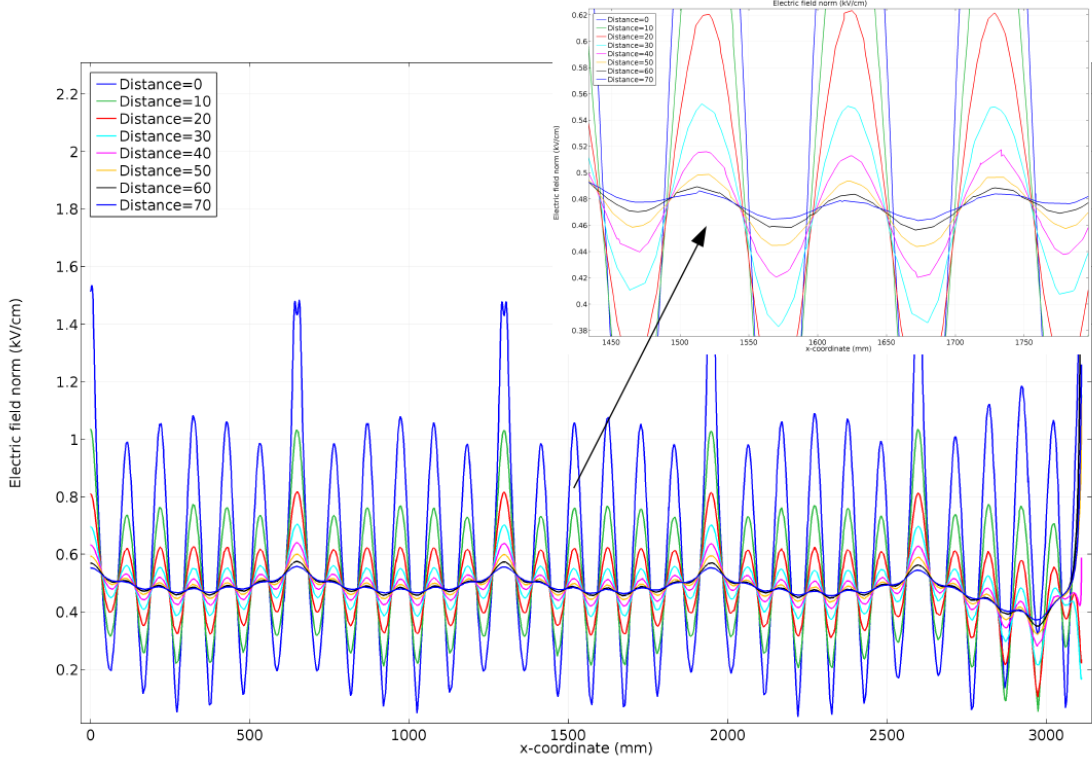


Figure 3.5: Electric fields along horizontal parallel cut lines with different distances from the cathode. “Distance = 0” denotes the cut line right above the cathode and “Distance = 70” denotes the cut line at 70 mm above the former one.

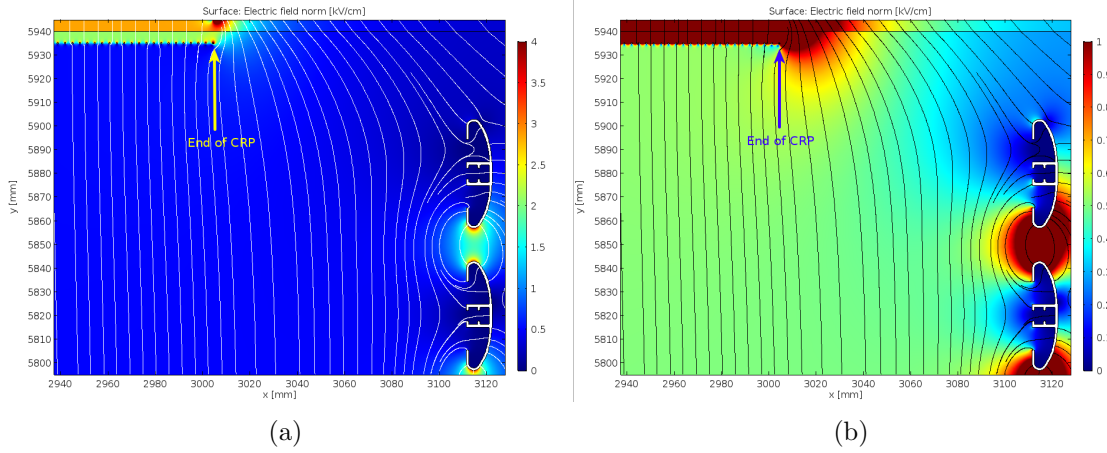


Figure 3.6: Normalized electric field and field lines distribution in the vicinity of the end of the CRP in two different electric field scales.

mainly results in a change in the electron drift velocity. One can see from the figure that the normalized electric field E_{norm} has a value of around 1 kV/cm in the vicinity of the cathode because of its special structure as mentioned earlier. As approaching the CRP, another peak on E_{norm} which reaches 0.63 kV/cm appears, resulting from the sharp edge existing at the end of the CRP. As one can see in the figure, in this area, E_y reaches a value of 0.62 kV/cm while E_x is around 0.04 kV/cm; namely, the deviation of E_{norm} from the

nominal value of 0.5 kV/cm is generated mostly by E_y , which is the electric field strength in the drift direction. While the impact of E_x is negligible, according to a well-known fact where the electric field is higher if the potential difference between the cathode and the last field shaper has a same value as that between each field shapers, the increment in E_y can be compensated by adjusting the potential difference between the cathode and the last field shaper to have a uniform field in the region. This voltage can be regulated by changing the resistors between the cathode and the last field shaper, and those between each field shaper.

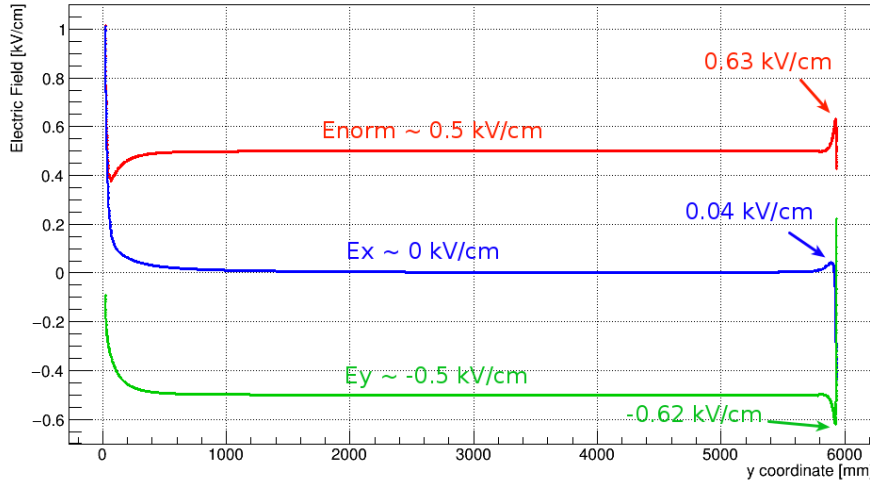


Figure 3.7: Normalized electric field (E_{norm}) and electric field in horizontal (E_x)/vertical (E_y) directions along a vertical cut line at the end of the CRP.

As mentioned earlier, the electron drift velocity as a function of the electric field strength and the temperature had been studied (shown in Equation 1.3). In our simulations, the temperature was set as a constant; therefore, Equation 1.3 can be simplified as

$$V_d(|\mathbf{E}|) = \left(P_3 |\mathbf{E}| \ln \left(1 + \frac{P_4}{|\mathbf{E}|} \right) + P_5 |\mathbf{E}|^{P_6} \right) . \quad (3.4)$$

By varying the electric field strength in steps of 0.25 kV/cm in the range of $0.5 \text{ kV/cm} \leq |\mathbf{E}| < 12.6 \text{ kV/cm}$, the drift velocity as a function of the electric field strength is plotted in Figure 3.8. One can see that with an electric field rising from 0.5 kV/cm to 0.63 kV/cm, the electron drift velocity will increase from $1.55 \text{ mm}/\mu\text{s}$ to $1.67 \text{ mm}/\mu\text{s}$.

3.1.2 Field Shapers

As described previously, the different elements of the detector should be carefully designed to minimize locally the magnitudes of the electric field. First of all, we performed the simulations considering the exact shape of the field shapers to guarantee that all the fields are under control. Later on, as the field shapers are made in pieces of 3 m, to connect all of them together and make a 6 m ring, a clip is used. Figure 3.9 illustrates the two different pieces designed; one is used to connect the middle part of the modules, i.e. the blue part, and the other one is made to connect the corners, i.e. the purple part in the figure. To study the effect of these clips, some 2D and 3D simulations were carried out at the different places where the clips are installed.

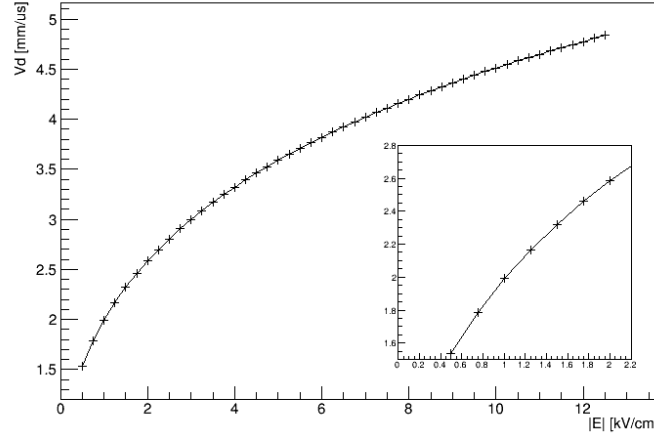


Figure 3.8: Electron drift velocities in LAr under different electric field strengths between 0.5 kV/cm and 12.6 kV/cm. [21]

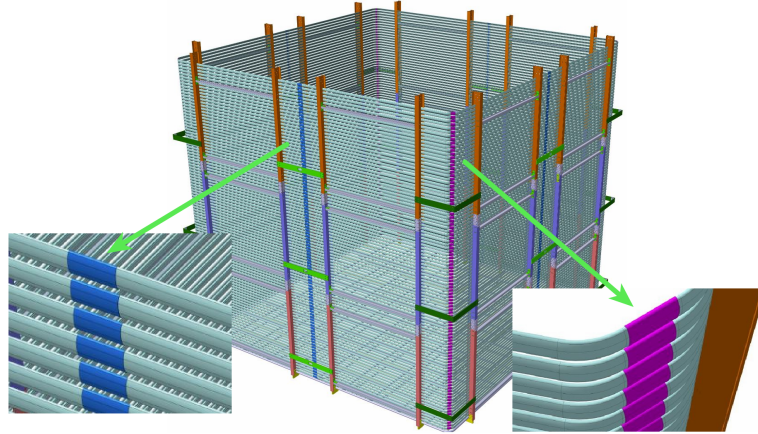


Figure 3.9: Illustration of clip positions on the field shapers. The blue pieces are attached at the centers of the four side edges while the purple ones are assembled on the four corners.

Initially, we compared directly the cross-sections of one field shaper with and without clip (see Figure 3.10). Each field shaper has a width of 11.1 mm and a height of 46 mm. However, with the clips attached to the field shapers, the profiles are 0.7 mm thicker, resulting in an extended height up to 47.4 mm. To understand how this difference can be reflected on computed electric field on the surface of the field shapers and inside the active volume, we performed 2D simulations on a simplified geometry with only 6 field shapers in two 2D cut views: the side and the front views of the field shapers. The former is used to study the effect of its shape, while the goal of the latter is to study the region between the field shapers.

Figure 3.11 is the side view of this simplified simulation model. With only 6 field shapers applied, a plate (denoted as anode) whose end has a 107 mm horizontal distance from the surface of the field shapers and a vertical distance of 60 mm from the first field shaper is added on top to maintain the uniformity of the electric field. The potential differences

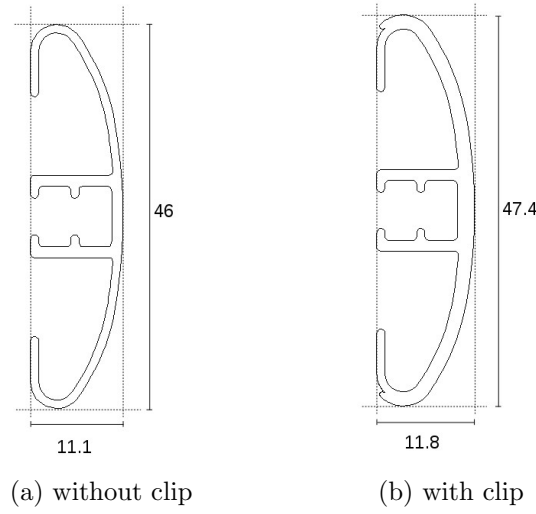


Figure 3.10: cross-section on the side view of one field shaper (a) without clip and (b) with clip; all dimensions in the unit of mm.

between the cathode and the last field shaper, between two adjacent field shapers, and between the anode and the first field shaper are all kept at 3 kV to guarantee a uniform drift field of 0.5 kV/cm. The field shapers with the shapes displayed in Figure 3.10 for both cases without and with clips were added into the model shown in Figure 3.11 respectively, and the electric field in the vicinity of the field shapers of both cases were studied.

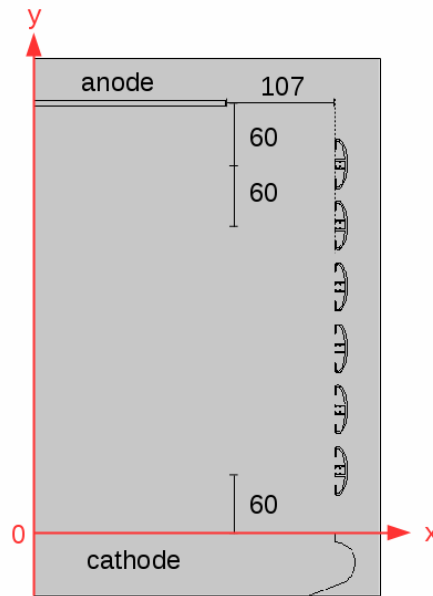


Figure 3.11: 2D simplified simulation model with only 6 field shapers from the side view; all dimensions in the unit of mm.

In Figure 3.12 the electric field on the surface of the field shaper facing the active volume of the TPC is displayed for both cases. The black lines represent the case without clips while the red ones are that with clips. Figure 3.12b is a zoom of the region inside the blue rectangle of Figure 3.12a, where we see a rise in the electric field from 4.9 kV/cm to

5.5 kV/cm in the vicinity of the upper part of the clip, and from 2 kV/cm to 3.6 kV/cm in the region around the lower part of the clip. To understand if this effect can introduce additional deviations in the tracks starting from the cathode, electric fields along vertical parallel lines starting from the surface of the field shapers in steps of 5 mm between 0 and 30 mm are plotted in Figure 3.13a (Figure 3.13b and 3.13c shows the schematic representation of the cut lines). The dashed lines show the electric fields considering the case without clips under different distances, while the solid lines display the results of the case with clips. One can see from the blue lines, which show the electric field on the surface of the field shapers, an electric field discrepancy of 0.2 – 0.4 kV/cm between both cases; nevertheless, as we go further away from the field shapers, the difference between the both reduces. The black lines indicate that starting from 30 mm away from the surface of the field shapers, both follow identical distributions. As there is an horizontal distance of 107 mm between the CRP, where we read the signal, and the first field shaper, the proposed clip design does not represent any additional loss of fiducial volume from the simulation's point of view.

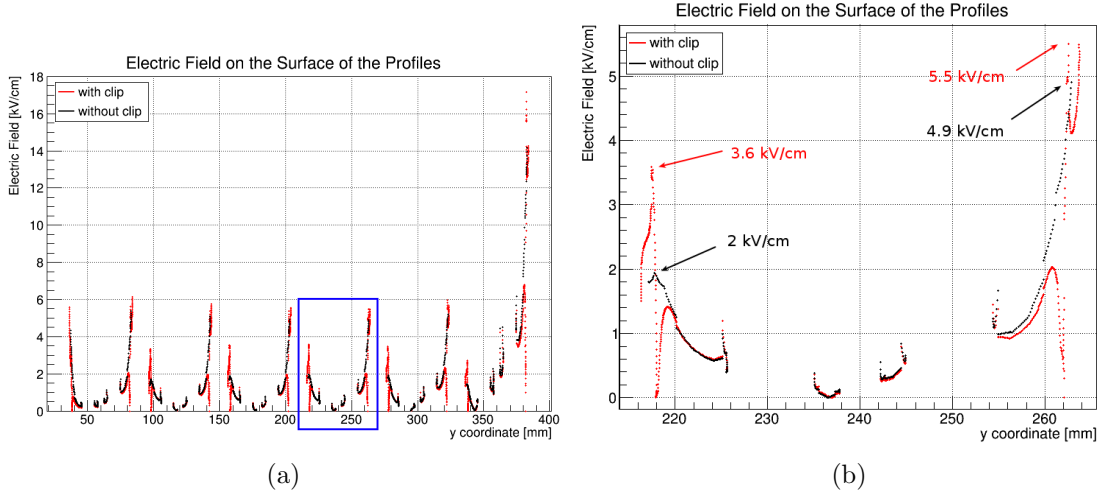


Figure 3.12: Electric field on the surface of the field shapers facing the active volume of the cases with and without clips. (a) is the surface electric field on all 6 field shapers, while (b) zooms around the fourth field shaper counting from the bottom.

On the other hand, as the clips locate just at the junctions between modules, we need to guarantee that this does not represent discontinuities in the field between parallel field shapers. To address this point, a 2D simplified model considering a front view of the detector as representative was used for the simulations (see Figure 3.14). As previously, only 6 field shapers were considered in this model for simplicity. The height of the field shapers is 1.4 mm greater with clips attached. Therefore, as the distance between field shapers is fixed to 60 mm, in the regions where the clips are at present this distance is reduced. Color distributions in Figure 3.15 show the normalized electric field in the region between parallel field shapers. For the case without clips, the regions between two parallel field shapers have a fixed distance of 14 mm; hence, the field is uniform at 2 kV/cm between two different field shapers (orange region in Figure 3.15a). On the contrary, with clips attached, in the regions where the clips take place, the distance is reduced to 12.6 mm (length of the clip piece is 20 mm) whereas the remains have the original 14 mm distances if they are not at present. Thus, the electric field in the space between two parallel field shapers raises from 2 kV/cm (green region in the figure) to 2.5 kV/cm (yellow region in

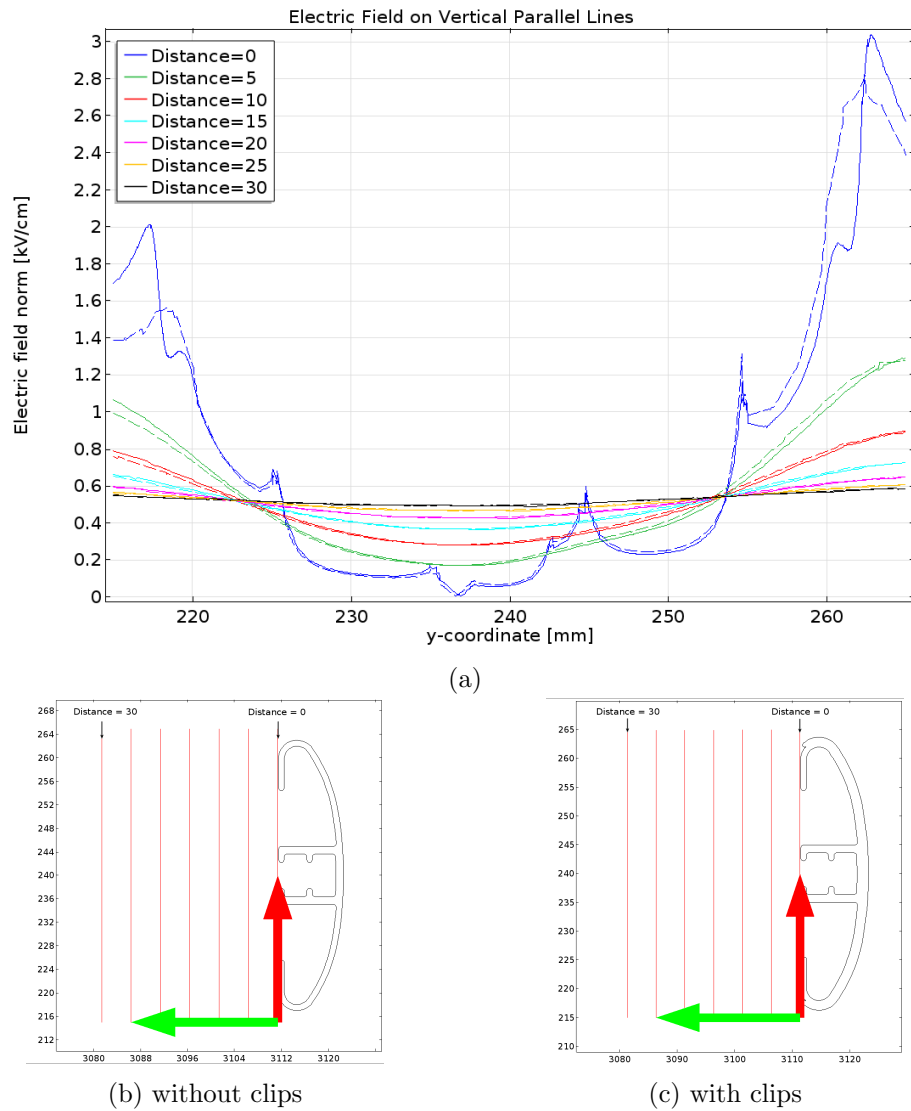


Figure 3.13: (a) Electric fields along vertical parallel lines in the vicinity of the field shapers. The dashed lines are the results of the case without clips, and the solid lines are those with clips. The vertical parallel lines starting from the surface of the field shapers with 5 mm distance in between in the case (b) without and (c) with clips. The lines closest to the field shapers are denoted as “Distance = 0” and the farthest as “Distance = 30”.

the figure).

Besides, to study the effect of the clips at the corners, 3D simulations are required. For simplicity in a preliminary study, a simplified model was carried out whose geometry can be seen in Figure 3.16. In this model, two pieces of perpendicular field shapers at the same height are connected by the clip at the corner into a set and only 3 sets of field shapers were built. Instead of constructing the whole CRP, only the grounded anode which is 8 mm above the LAr level was used. To maintain the uniform electric field of 0.5 kV/cm, the cathode in this model is set to -18.5 kV as only 3 field shapers are included. The line below the anode represents the interface between LAr volume and the GAR volume. Figure 3.16b zooms in the area where the clips are attached (blue square) to connect two

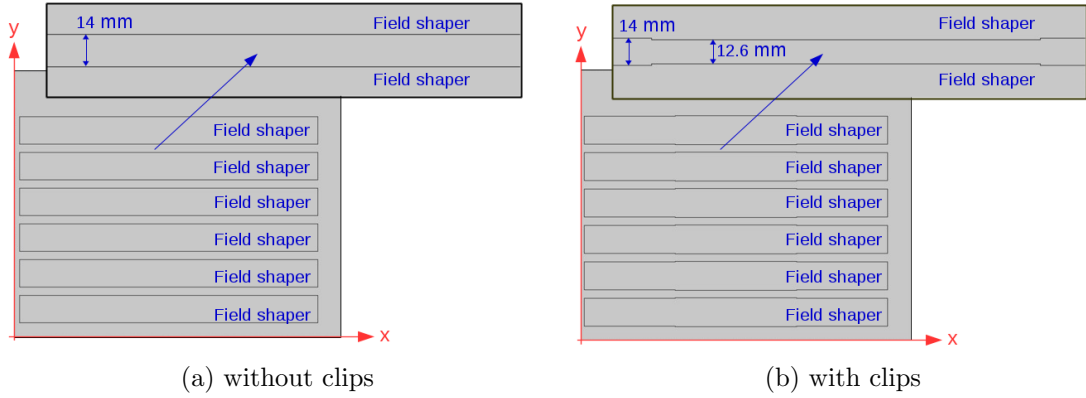


Figure 3.14: 2D simplified simulation model with only 6 field shapers from the front view. (a) is the case without clips with a vertical distance of 14 mm between two parallel field shapers, while (b) is the case with clips introduced, possessing a smaller distance of 12.6 mm at the positions with clips attached.

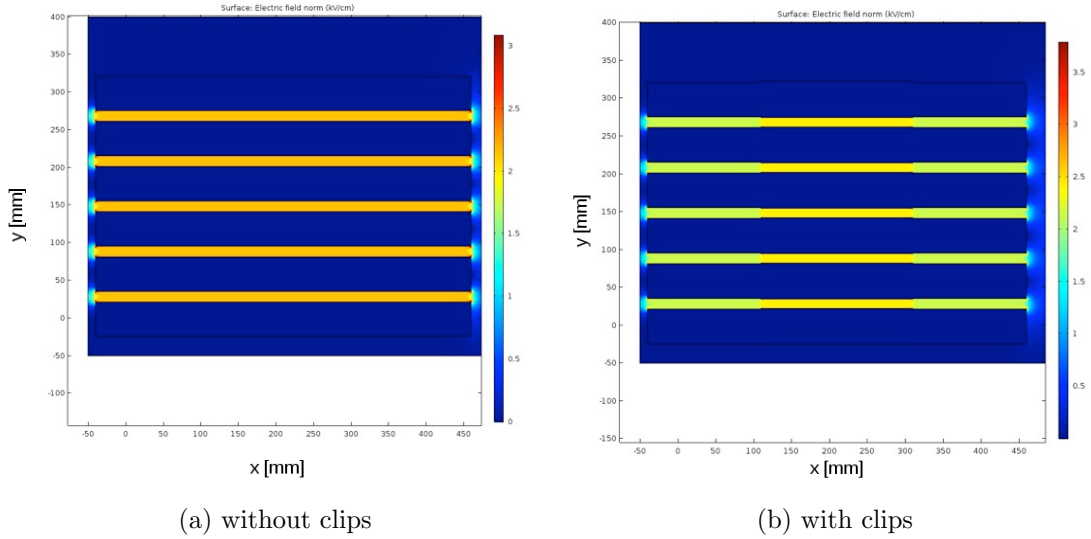


Figure 3.15: Normalized electric field from the front view of the simplified model with only 6 field shapers in the case (a) without clips and (b) with clips.

perpendicular field shapers at the corner. Because of the bend at the corner, the horizontal distance between the edge of the anode and the surface of the field shaper decreases from its original 107 mm at the side edge to 71.5 mm at the corner. Figure 3.17 is the electric field on the cross-section of the diagonal cut plane of the detector. This cut plane has a local coordinate of (u, v, w) as can be seen in Figure 3.16a. The highest field is obtained at the end of the anode, 7 kV/cm, owing to the edge effect.

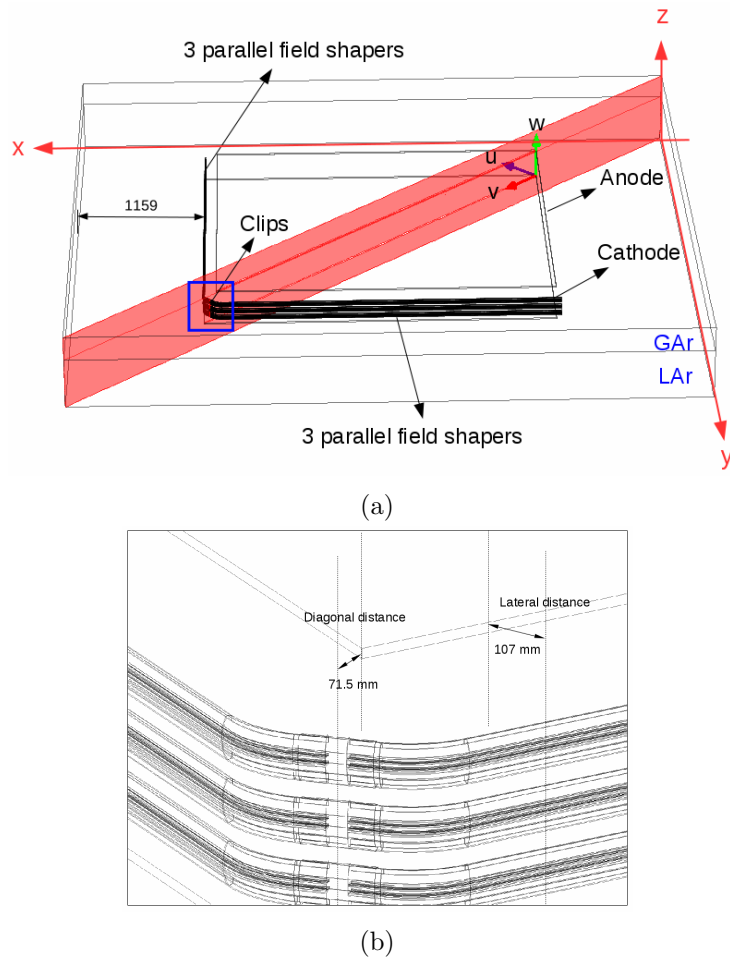


Figure 3.16: (a) 3D simplified simulation model of a corner of the detector with only 3 sets of field shapers. (b) Zoom in the region with clips connecting two perpendicular field shapers. All dimensions included are in the unit of mm.

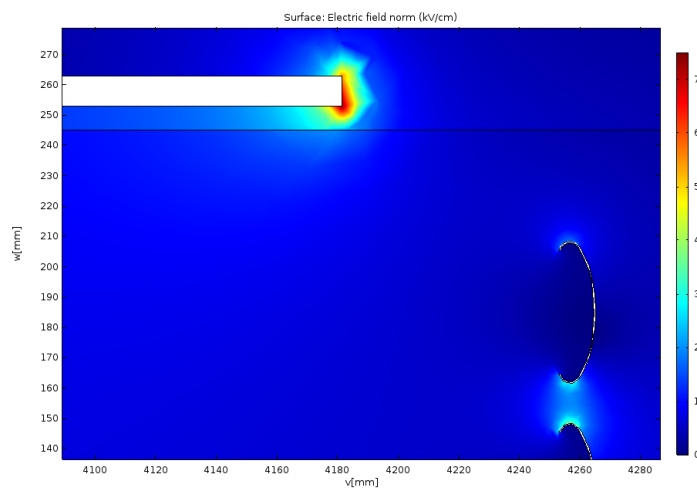


Figure 3.17: Electric field distribution on the cross-section of the diagonal cut plane.

3.1.3 Cathode

The cathode situating 60 mm below the last field shaper consists of a grid-like stainless steel support structure with tubes inserted between the spaces within each grid. The total $6 \times 6 \text{ m}^2$ structure comprises four $3 \times 3 \text{ m}^2$ pieces as can be seen in Figure 3.18. The blue grid-like part is the support structure, while the yellow cylindrical structures inserted within the grids are the tubes.

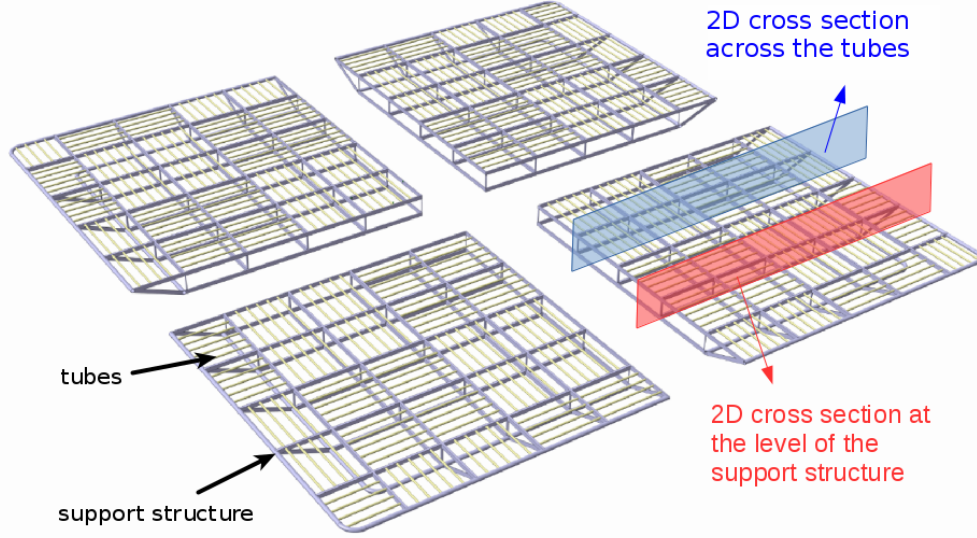


Figure 3.18: 3D geometry of the cathode with two different possible cross-sections included.

Owing to its grid-like structure, two different types of cross-sections were made to perform the simulations in 2D. In one of the cases, the cross-sectional cut is made across the tubes, which is the blue surface displayed in Figure 3.18; on the other hand, the red surface represents a cross-section at the level of the support structure. Simulation results for the two cases will be presented separately in the following.

Starting from the first case, the cross-section cutting across the tubes, Figure 3.19 shows the area at the bottom part of the TPC including the last few field shapers, the cathode and the ground grid. All dimensions are specified in mm. Figure 3.20 shows the electric potential and electric field lines distribution in the vicinity of the cathode, where deviations of the field lines can be seen owing to its segmented composition. Figure 3.21 shows the electric field distribution on the surface of the cathode. Due to the potential difference between the cathode ($\sim -300 \text{ kV}$) and the ground grid (0 kV), the highest electric field is reached on the lower boundary of the support structure facing the ground grid. Electric fields on the surface of the tubes and the support structure are plotted separately in Figure 3.22 and the indication of the different boundaries is specified in Figure 3.21. The blue line represents the electric field on the lower boundary of the tubes. As these edges have a distance of about 970 mm from the ground grid, the electric field is the lowest among the three cases. The green line shows the electric field on the upper boundary of the support structure, around 200 mm below the tubes. The electric field on these boundaries is higher than that in the previous case as the distance to the ground grid is smaller. Finally, the red line shows the highest electric field among the three cases, reached in the lower boundary of the support structure, which has the shortest distance from the ground

grid. From all the cases, one can see that the electric field along the whole structure of the cathode is below 30 kV/cm.

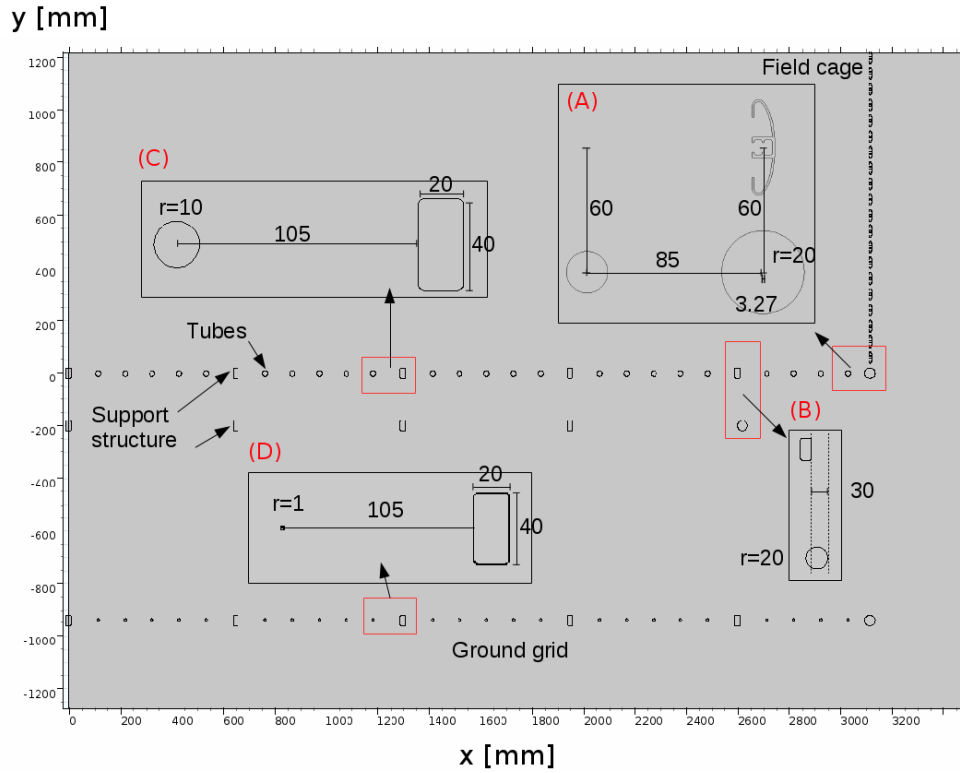


Figure 3.19: First case of 2D cross-section around the cathode which cuts across the tubes. The dimensions of the structure are included in the graph with all units in mm.

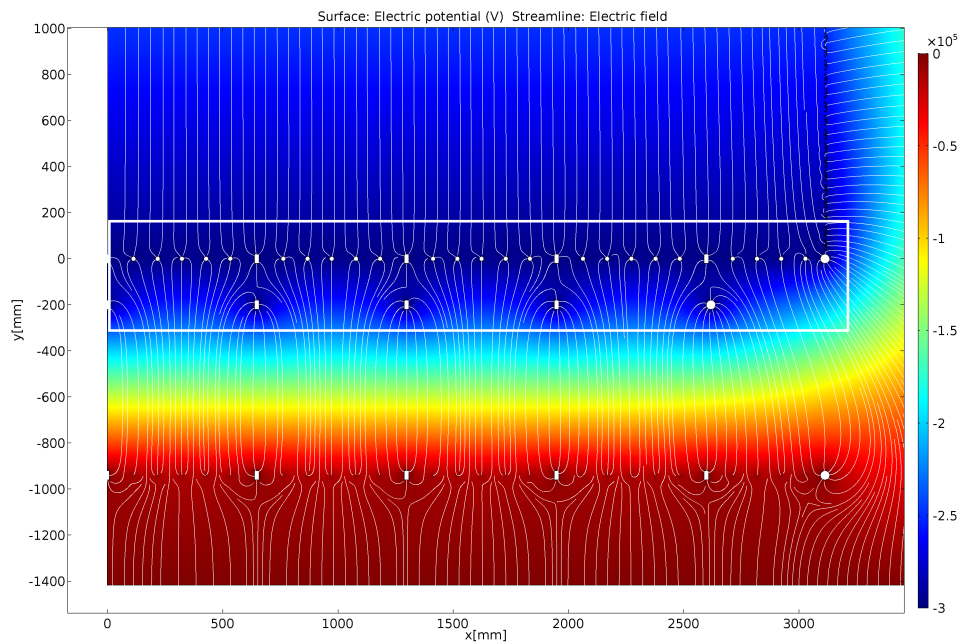


Figure 3.20: Electric potential and field lines distribution around the cathode.

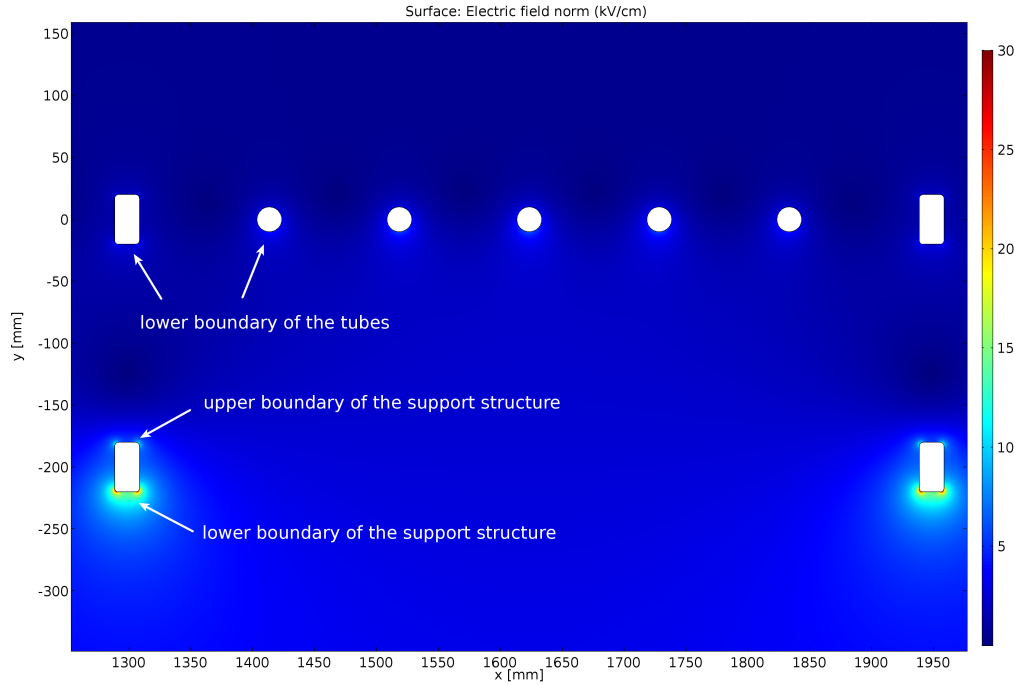


Figure 3.21: Electric field distribution around the cathode.

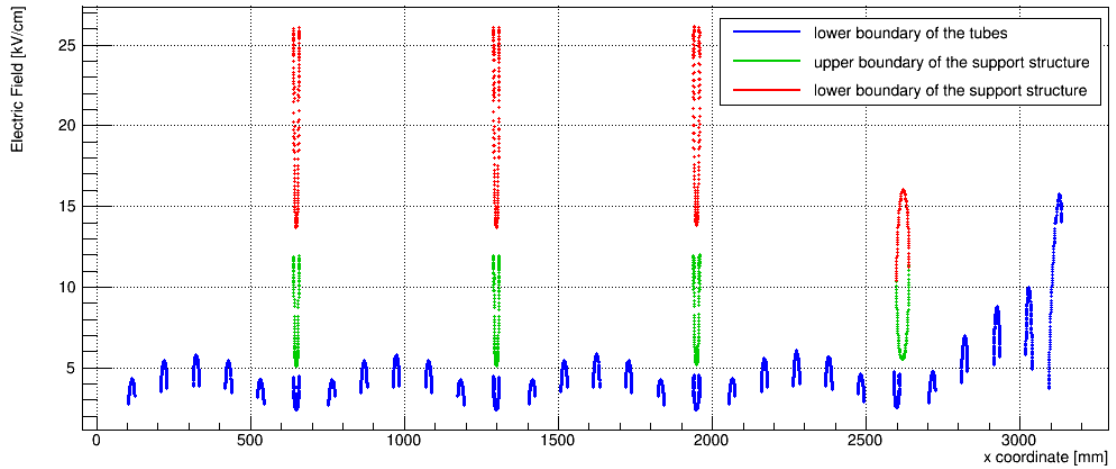


Figure 3.22: Electric fields on three distinct boundaries around the cathode. Indication of different sections can be found in Figure 3.21

The geometry of the second case, the cross-section at the level of the support structure, is shown in Figure 3.23. In this case, the cathode is represented as a whole conductor piece. Figure 3.24 shows the electric field distribution around the cathode. Because of the potential difference between the support structure (~ -300 kV) and the ground grid (0 kV), the electric field on the lower-half boundary of the support structure facing the ground grid is higher than that on the upper-half. Electric fields on the upper and lower halves boundaries are plotted separately in Figure 3.25 and the denotations of different parts are shown in Figure 3.24. The blue line is the electric field on the lower-half boundary of the support structure which has a value of around 4 kV/cm and two peaks at about 7 kV/cm

and 14 kV/cm at the two edges. By contrast, the green line which shows the electric field on the upper-half of the support structure demonstrates a uniform value of 0.5 kV/cm before reaching the boundary which has a value of about 3 kV/cm. From simulations, all local electric fields are below 15 kV/cm in this region.

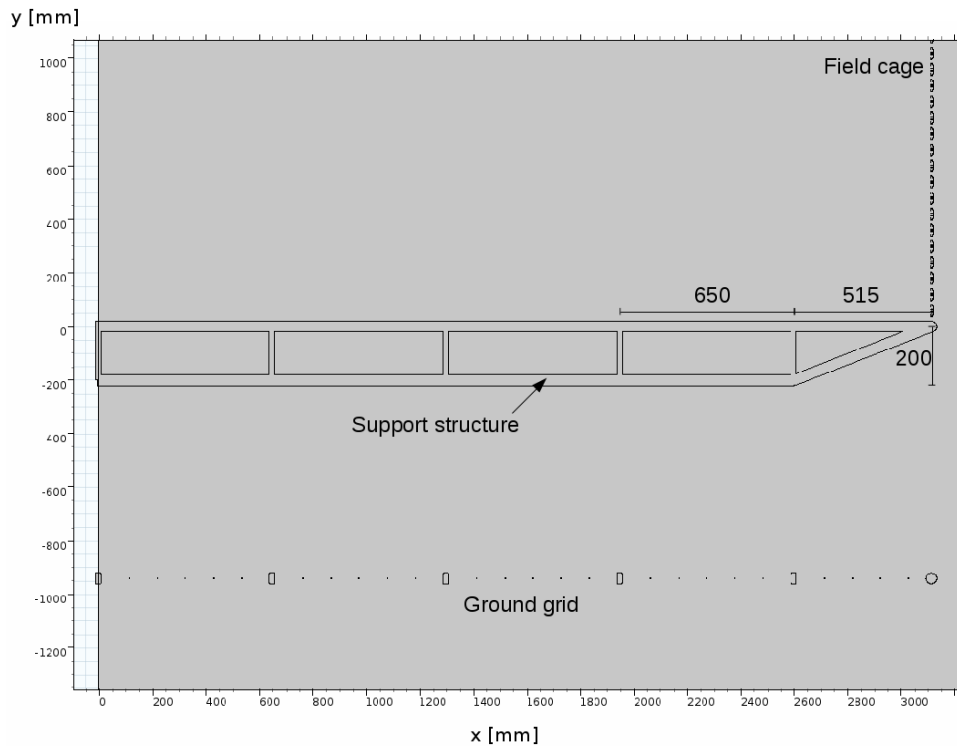


Figure 3.23: Second case of 2D cross-section around the cathode which cuts at the level of the support structure. The dimensions of the structure are included in the graph with all units in mm.

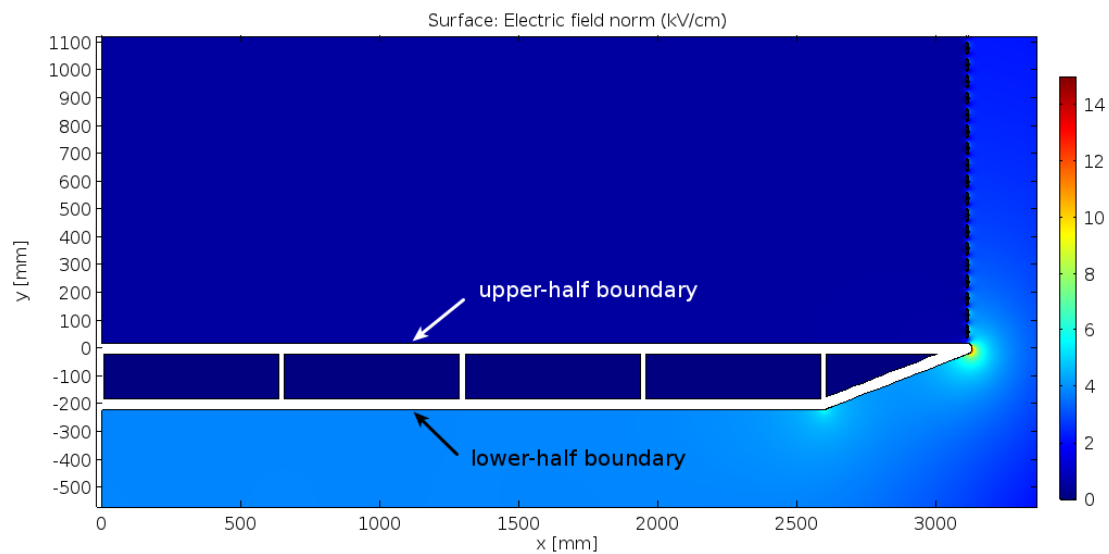


Figure 3.24: Electric field distribution around the cathode.

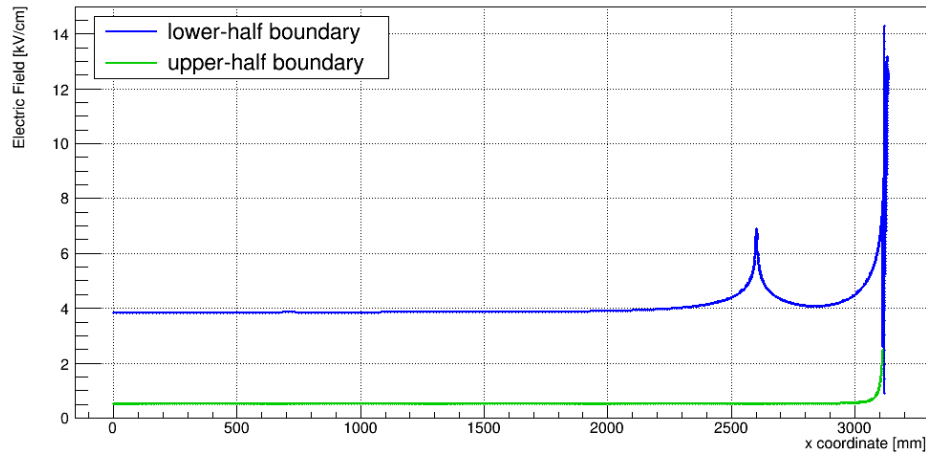


Figure 3.25: Electric fields on two distinct halves of the boundaries around the cathode. Indication of different sections can be seen in Figure 3.24.

In addition, with a great potential difference of 300 kV applied between the cathode and the ground grid over a distance of 77 cm, the cathode and the ground grid together act like a capacitor where a certain amount of energy can be stored in the space between them. Thus, we conducted a 3D simulation on a corner of the cathode with the simulation model shown in Figure 3.26 to calculate this stored energy. In this simplified model, only the cathode, the ground grid and a cube filled with LAr were included. For simplicity, the small tubes inserted between the cathode grids were not taken into account. The capacitance calculated from this model with only one fourth of the real structure is 0.25 nF, and the total energy stored within the capacitor equals to 11.4 J in the case with a nominal voltage of 300 kV at the cathode. For the whole structure of the cathode and the ground grid, these values will be around four times of the magnitudes. The energy density distributions on the surfaces of the cathode and the ground grid are displayed separately in Figure 3.27.

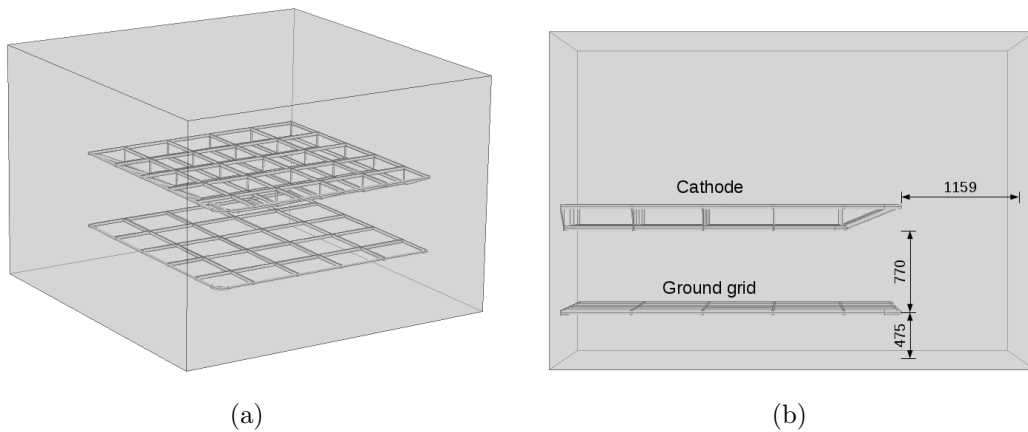
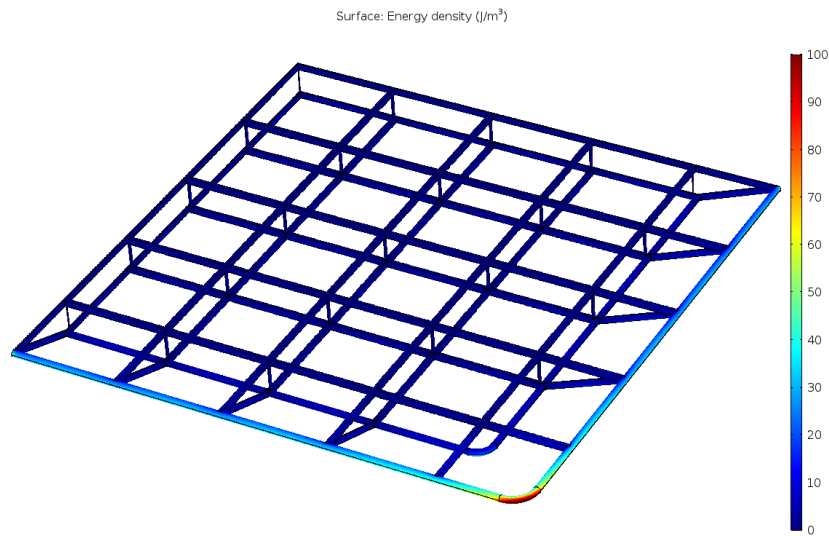
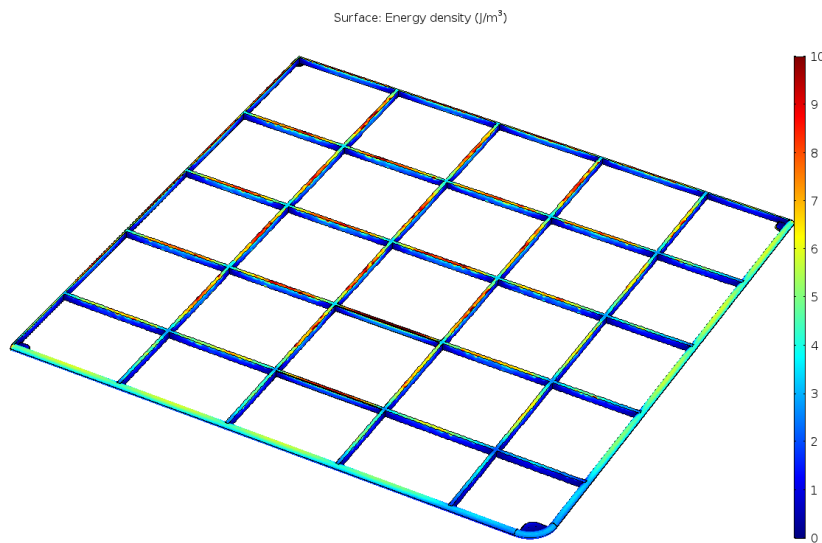


Figure 3.26: (a) 3D model of one corner of the cathode and the ground grid. (b) 2D cross-section of this model with all dimensions in the unit of mm.



(a) cathode



(b) ground grid

Figure 3.27: Energy density distribution on (a) the cathode and (b) the ground grid.

3.1.4 Ground Grid

The ground grid placed around 1 m below the cathode serves as the electrostatic shielding for the PMTs, preventing the PMTs from any possible damage caused by a discharge. The geometry of the ground grid made up of wires with a radius of 1 mm and a pitch of 105 mm can be found in Figure 3.19. The electric field around the ground grid is displayed in Figure 3.28 in the case of 1-mm-radius wires, where electric fields larger than 50 kV/cm can be reached on the surface of the wires. Simulations considering different radius values were performed in order to find a compromise between transparency and lower fields. Figure 3.29 displays the electric fields on the surface of the ground grid wires

with different radii ranging from 1 – 5 mm. With wires of 2 mm radius, the electric field on the surface of the wires with a value below 30 kV/cm can be obtained.

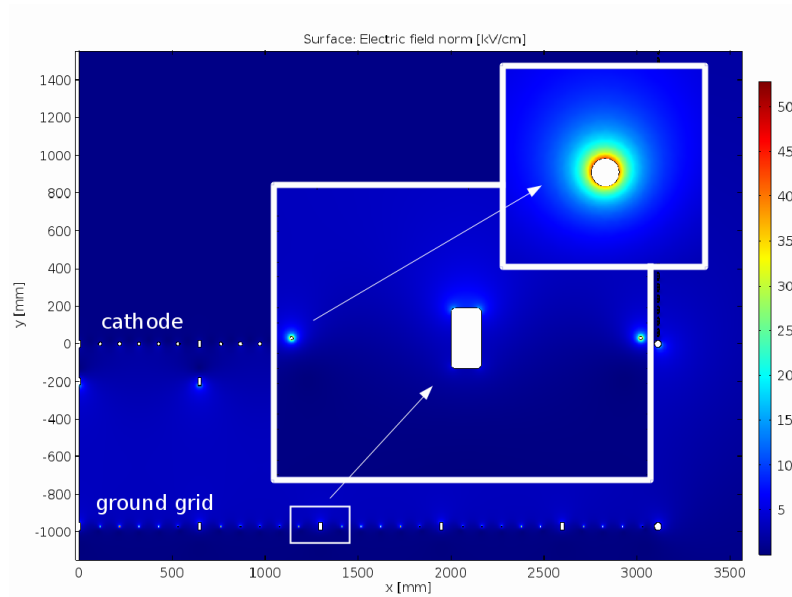


Figure 3.28: Electric field distribution around the ground grid.

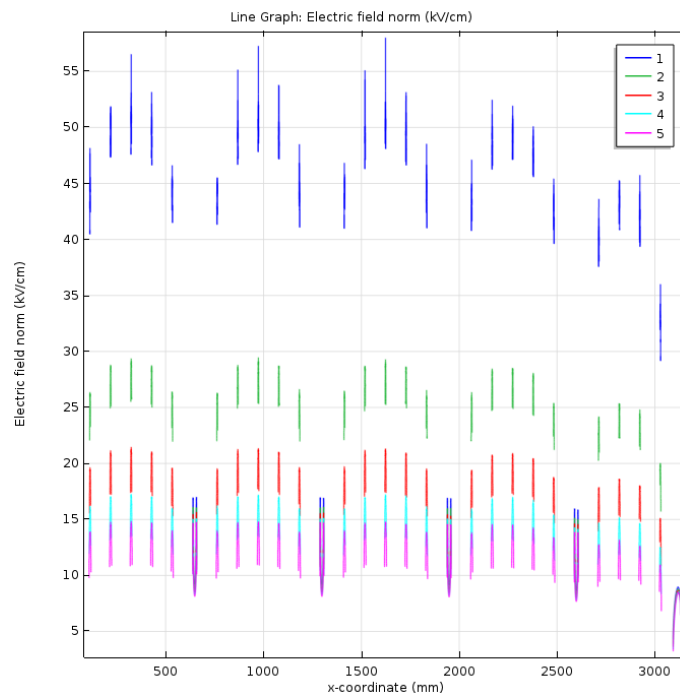


Figure 3.29: Electric field on the surface of the ground grid wires with different radii ranging from 1 – 5 mm. The legend on the upper right corner denotes the radius of the wires.

3.1.5 Charge Readout Plane

Figure 3.30 shows the simplified 2D model built to simulate the CRP. In this case, the anode is simplified as a 3-m-long plate with a thickness of 3.2 mm and the LEM as two extremely thin plates of 5 μm thick separated by a distance of 1 mm representing the upper and the lower electrodes. The charge extraction grid consists of a series of circles with a pitch of 3.125 mm. In the experiment, the diameter of these wires is 100 μm while in the case of the simulation, we consider a 600 μm diameter owing to the tolerated resolution of the simulation program.

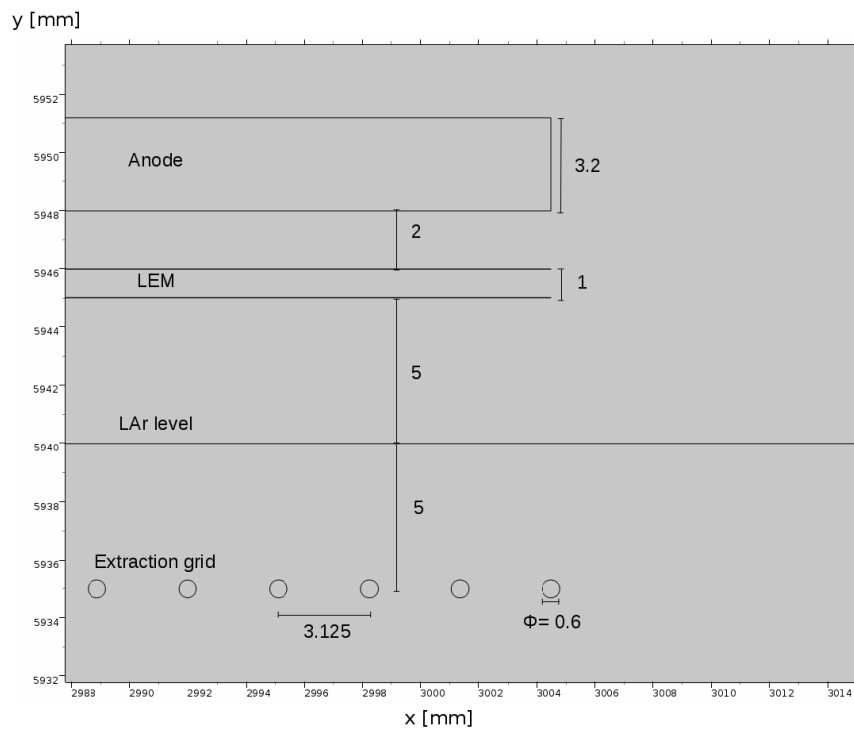


Figure 3.30: 2D cross-section of the simplified model used for the CRP simulations with all the dimensions of the structure included in the units of mm.

We computed the electric field between each stage. Figure 3.32 displays the electric field along a vertical cut line (shown as the yellow lines in Figures 3.31 which lie 25 mm inner from the end of the CRP to avoid the edge effect) from the LAr volume to the bottom of the anode. As one can see from these figures, the electric field is around 0.5 kV/cm below the extraction grid which is the nominal value of the drift field provided by the drift cage. The electric field in the vicinity of the extraction grid, possessing a value around 2 – 3 kV/cm, is used for the extraction of electrons. In the region between the two plates of the LEM, the electric field reaching about 30 kV/cm is expected to provide the trigger for electron multiplication.

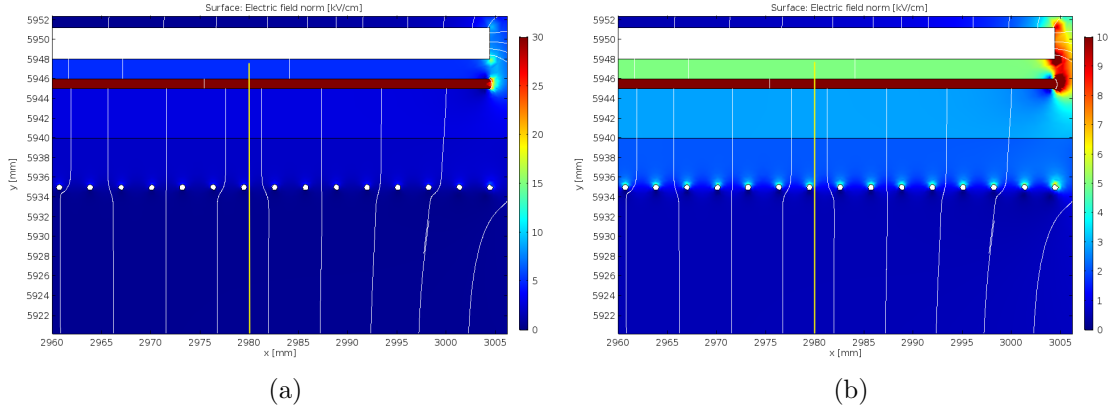


Figure 3.31: Normalized electric field and field lines distribution in the vicinity of the CRP in two different electric field scales.

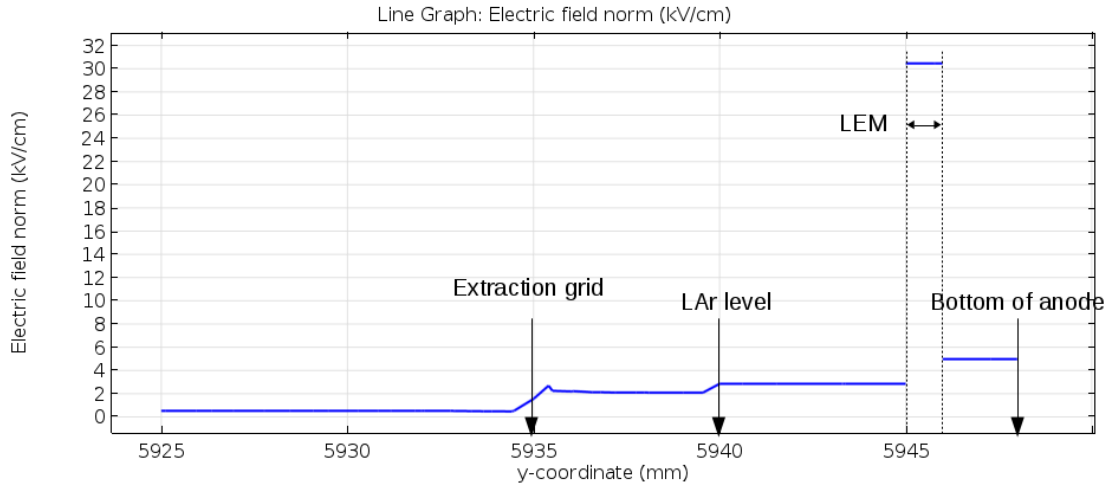


Figure 3.32: Normalized electric field along the vertical cut line from the LAr volume to the bottom of the anode at 25 mm away from the end of the CRP.

3.2 High Voltage Feedthrough and Connection to Cathode

To provide a bias voltage of -300 kV to the cathode, a HVFT and a connecting component linking the HVFT and the cathode are required to safely transmit the high voltage into the LAr volume. Simulations on the HVFT as well as its connection with the cathode were conducted to assure the absence of any critical electric field values.

Figure 3.33 represents the 2D model used in the simulations. Part (A) displays the overall structure of the TPC (as shown in Figure 3.2) as well as the HVFT inserted into the detector, and the element connecting the HVFT and the cathode, denoted as *connection* in the figure. Part (B) is a zoom around the HVFT, where the outer conductor and the HMDPE insulator are illustrated. In this model, the feedthrough plug is replaced by a simplified conductor which carries the -300 kV high voltage, penetrates the LAr level from the GAr phase and joins the inner conductor in the LAr phase. Part (C) zooms in the

vicinity of the LAr level, displaying the geometry of the HVFT and the connection, and their dimensions with respect to the field cage. Part (D) displays the region at the end of the connecting component, zooming in the area to where the cathode is connected. In addition, the degraders assembled along the connecting component can be observed in the figure.

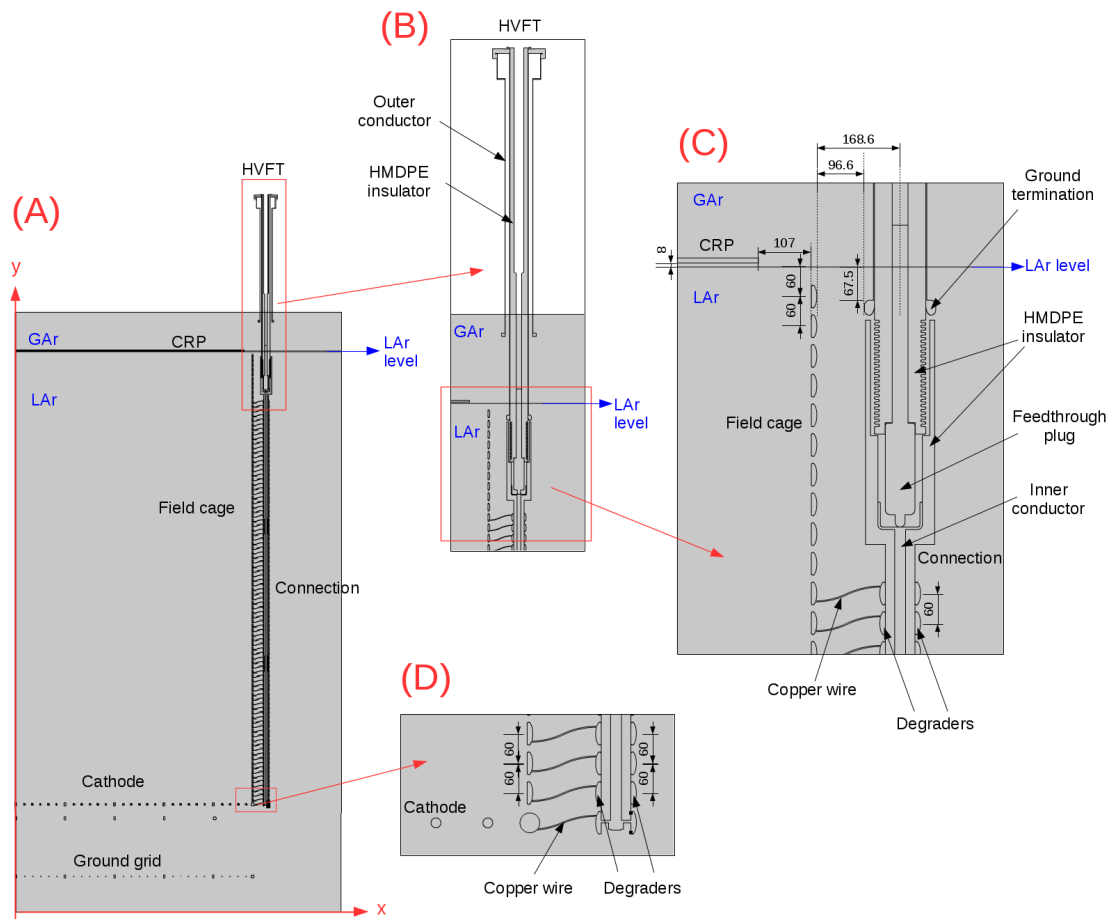


Figure 3.33: 2D simulation model of the TPC with the HVFT and its connecting component added; all dimensions in the unit of mm.

3.2.1 High Voltage Feedthrough

First of all, we studied the local electric field along the surface of the HVFT. The colored surface in Figure 3.34 represents the normalized electric field distribution along the HVFT at the interface between the liquid and the gas phase. As illustrated in the figure, the highest field is reached at the end of the ground termination of the outer conductor. In this particular point, electric field lines deviate because of the change of the dielectric constant from the HMDPE to LAr, and owing to the edge effect caused by the ground termination. In high voltage literature, this kind of points are defined as *triple point*, where the boundary condition can be described as:

$$\varepsilon_1 \mathbf{E}_1 = \varepsilon_2 \mathbf{E}_2 \quad (3.5)$$

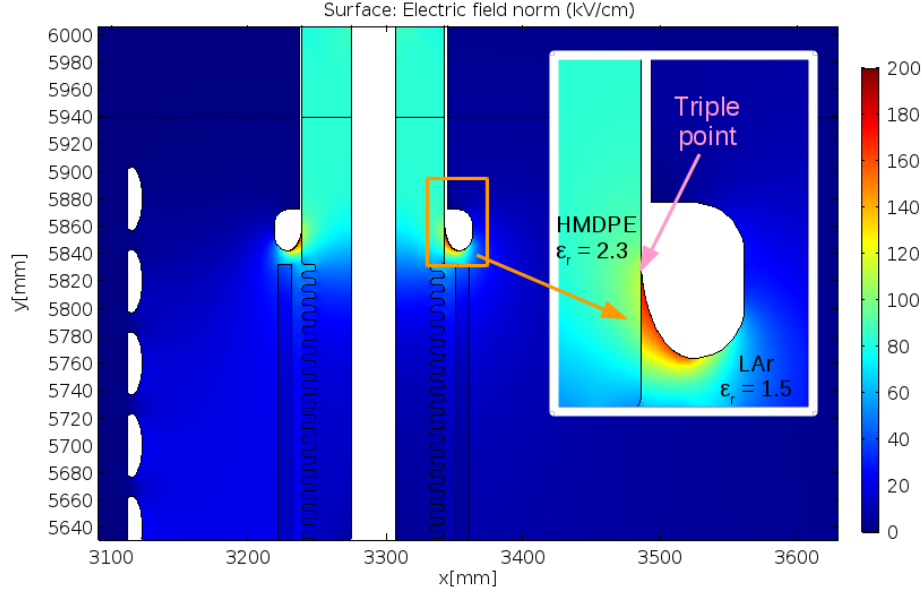


Figure 3.34: Electric field distribution around the HVFT at the LAr level. The zoomed part provides a detailed view around the triple point.

To minimize the field at this point, two different solutions can be applied. The first one is to change the geometry of the ground termination. The ICARUS feedthrough ground termination follows a circular shape; however, for the new feedthrough, an elliptical shape was selected to reduce the field for a 30 % value at this point [22]. The other possibility is to minimize the dielectric transition. We tried to simulate a different design where we allow a LAr gap between the outer conductor and the HMDPE insulator, providing a region around the outer conductor ground termination with a uniform material. In these studies, thanks to the axial-symmetric geometry of the HVFT, a simplified axial-symmetric model on the HVFT itself was used. Figure 3.35 shows the schematic of the model where only the inner conductor, the HMDPE insulator and the ground termination are considered. Figure 3.35a corresponds to the original design with a 36-mm-thick HMDPE insulator, and Figure 3.35b and 3.35c are the first and the second modified designs with each having a 5 and 15-mm-thick LAr gap added between the ground termination and the insulator respectively.

The electric field distributions in the gap between the HMDPE insulator and the ground termination for the three configurations are displayed in Figure 3.36. In the original model, shown in Figure 3.36a, the electric field in this region reaches a critical value larger than 100 kV/cm. One can see from Figure 3.36b and 3.36c that with a 5 and 15-mm-thick LAr gap inserted, the field decreases in the gap region whereas on the surface of the ground termination a local electric field higher than 100 kV/cm can still be reached. This effect is better represented in Figure 3.37 where the field strength along the surface of the ground termination facing the HMDPE insulator is computed. The blue line is the result for the original design, and the green and red lines are those for the two modified designs. As one can see from the three lines, at the lower edge of the ground termination (z-coordinate ~ 1440 mm), a large value of electric field greater than 100 kV/cm takes place owing to the edge effect at this point on the outer conductor; however, compared to the original design, for the cases with a LAr gap added, the spatial extent of the high field is reduced

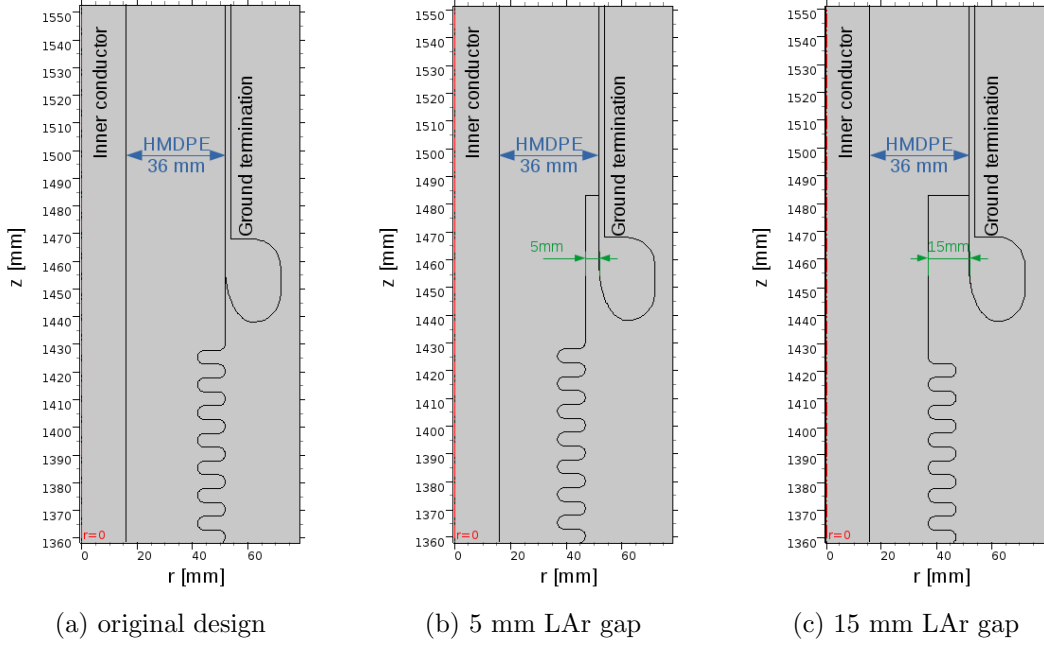


Figure 3.35: Geometries of the three HVFT models. (a) The original design with a 36-mm-thick HMDPE insulator. (b) The first modified design with a 5-mm-thick LAr gap inserted. (c) The second modified design with a 15-mm-thick LAr gap applied.

and more localized. Since high fields in extended spatial regions are more prone to create discharges as more energy is stored in larger volumes of space, this approach although does not help to mitigate the values of the electric field in this region, it in fact effectively limits the spatial extents of the critical fields.

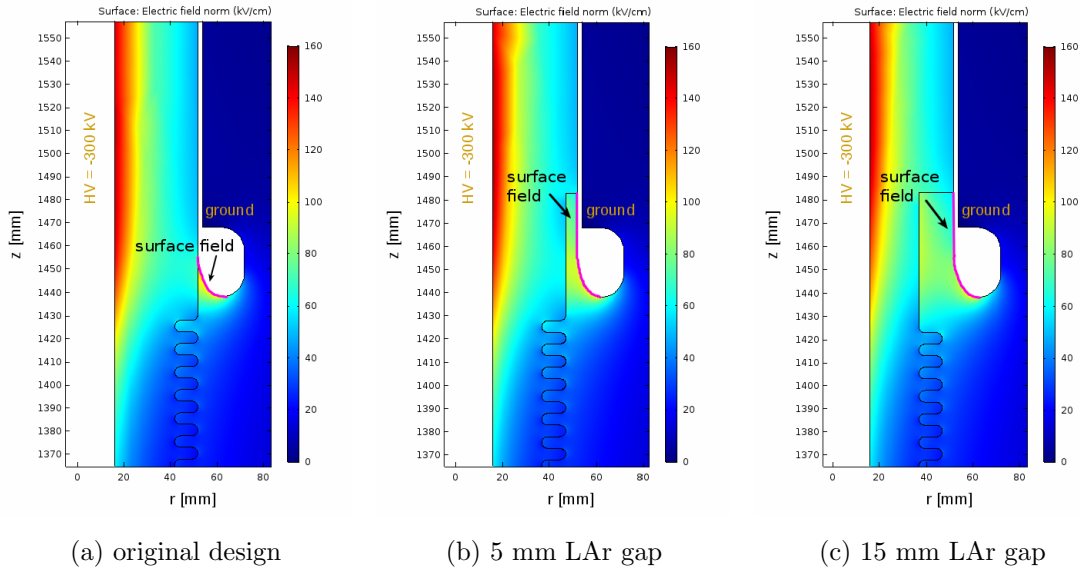


Figure 3.36: Electric field distributions in the vicinity of the HVFT ground termination for the three models: (a) the original model with a 36-mm-thick HMDPE insulator, and the modified models with a (b) 5 and (c) 15-mm-thick LAr gap, respectively.

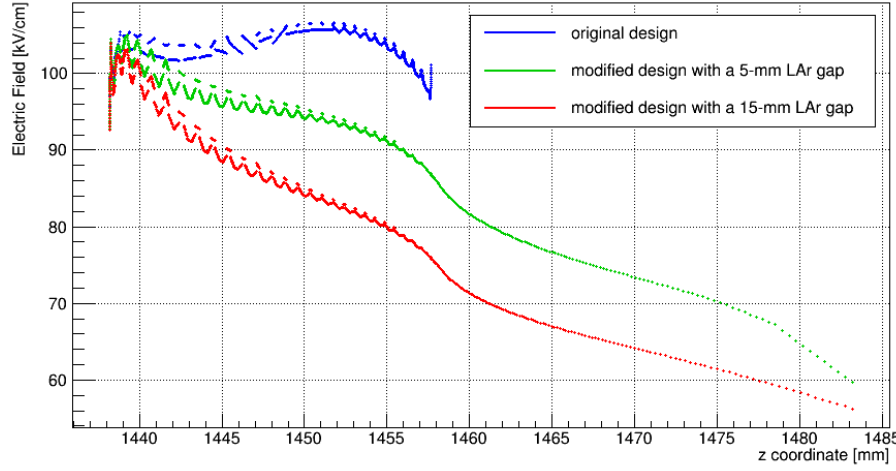


Figure 3.37: Electric fields on the surface of the ground termination facing the HMDPE insulator for the three designs.

3.2.2 Connection between HVFT and Cathode

Additionally, in order to transmit the high voltage from the HVFT to the cathode over a distance longer than 5 m, a connecting component is required. In order to support the large electric potential on the inner conductor (~ -300 kV), the connecting component is designed with a 24-mm-thick HMDPE insulator to assure an insulation rigidity larger than 2 MV. Initially, the normalized electric field in the vicinity of the connecting component was studied. In order to minimize the electric field in LAr in the region between the field cage and the connecting component, a series of degraders were added on the HMDPE surface. Figure 3.38 displays the electric field distribution in this region around the LAr level. Considering the LAr region between the field cage and the connecting component, the electric field is close to 0 because of the same potentials applied to the corresponding degraders and the field shapers at the same heights. Nevertheless, one compromise for the introduction of the degraders is as one can see from the zoom graph around the first and the second degraders. A large local electric field > 300 kV/cm in the LAr gap between a degrader and the HMDPE insulator takes place, which is owing to a great potential difference between the inner conductor (-300 kV) and the first degrader (-36 kV).

To better illustrate the effect of the degraders along the connecting component to the cathode in the field inside the LAr, we compared the cases with and without degraders on the HMDPE surface. Figure 3.39 displays the electric field distribution in the area between the field cage and the connecting component with the scales on both cases adjusted in order to provide a more distinguishable display on the value of the electric field in the LAr. In the area close to the LAr level, where the potential difference between the field shapers (~ -30 – -60 kV in the region shown in the figure) and the inner conductor (-300 kV) is large, the electric field is > 20 kV/cm in the case without degraders (Figure 3.39a) and approximates 0 when the degraders are introduced (Figure 3.39b). To show in a more quantitative way, electric fields along three vertical cut lines (denoted as L1, L2 and L3 in Figure 3.39) at different distances from the field cage are considered for both configurations, and the results can be found in Figure 3.40. From the three line graphs displayed, one can see that the electric fields along the cut lines for the cases with degraders (green marks) are much more uniform with values less than 5 kV/cm, compared to the cases without degraders,

where the electric field increases linearly with the height in the detector. In all cases, we verify that using the degraders we guarantee a negligible and uniform field inside the LAr.

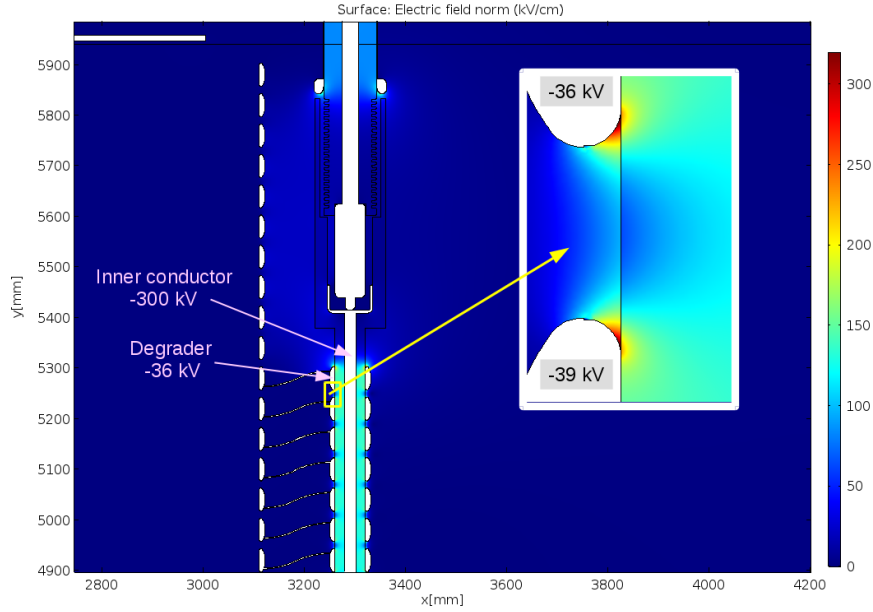


Figure 3.38: Electric field distribution around the field cage and the top part of the connecting component inserted between the HVFT and the cathode.

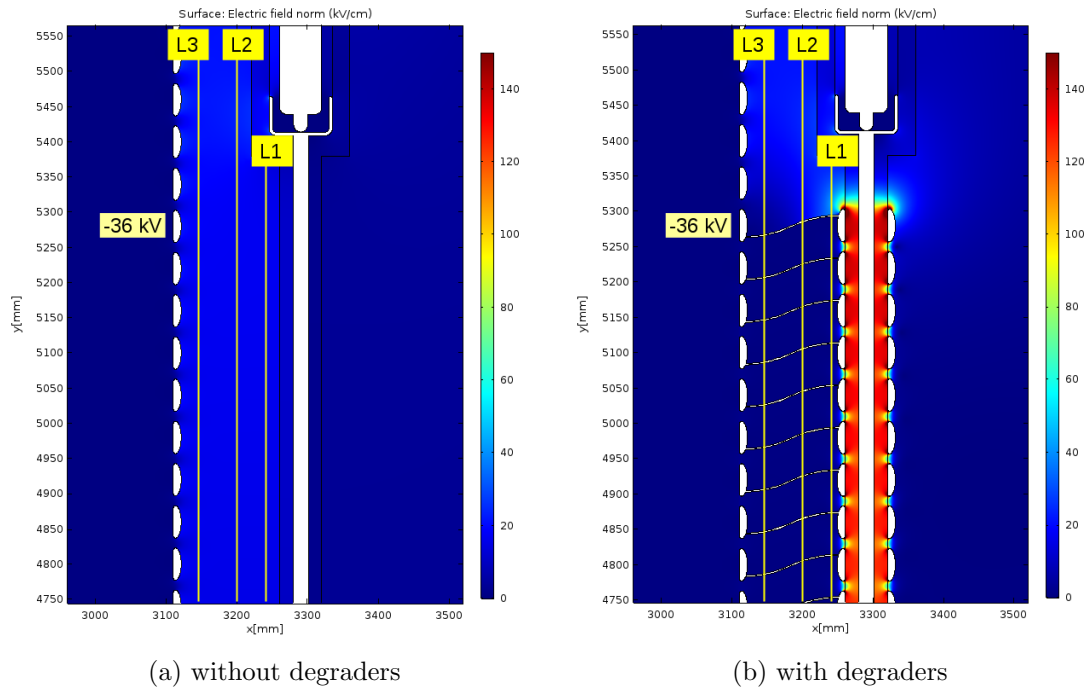


Figure 3.39: Comparison of the electric field distribution in the LAr region between the field cage and the connecting component of the cases (a) without and (b) with degraders. The electric field scale is adjusted for a better distinguishment for the values.

After assuring the necessity of adding the degraders on the connecting component, we

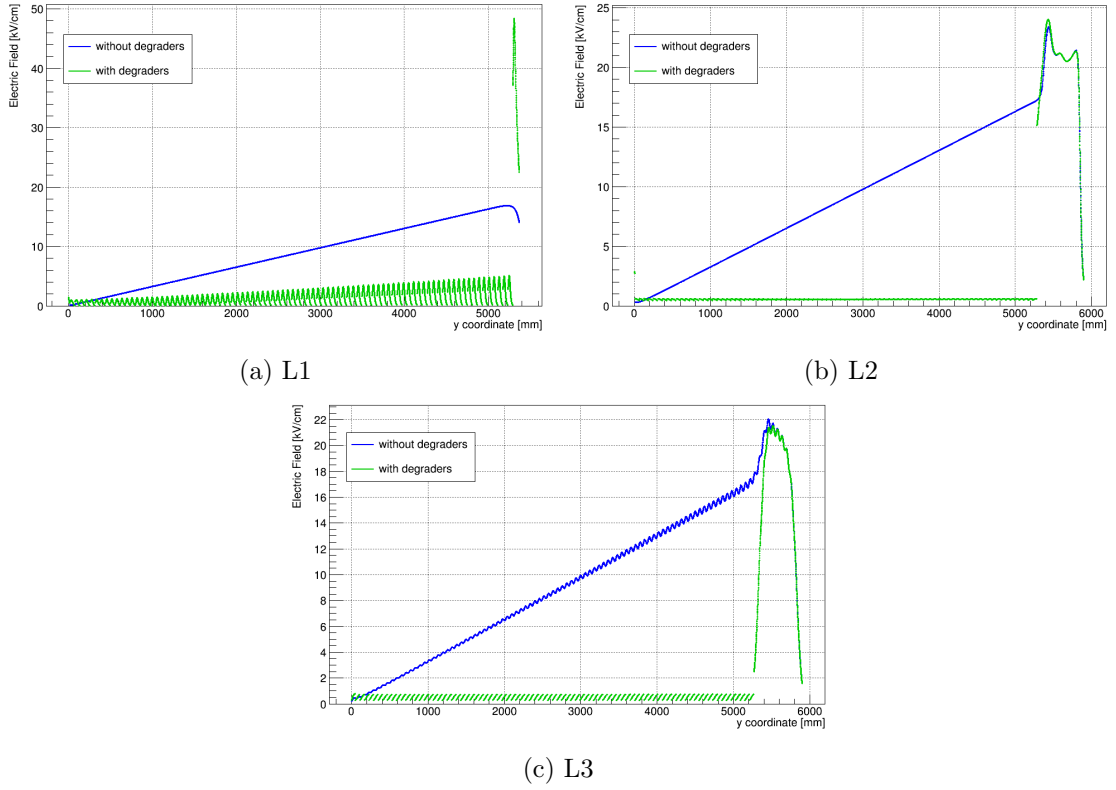


Figure 3.40: Electric fields along three vertical cut lines between the field cage and the connecting component with a distance of (a) 5 mm (b) 50 mm (c) 100 mm away from the degraders. Cut lines are plotted as L1-L3 respectively in Figure 3.39.

looked for a way to minimize the highest electric field reached on the surface of the first few degraders. Firstly, the field is high in this region as it is the junction between three materials similar to what is occurring to the ground termination of the HVFT shown earlier. The design of this connecting component was optimized in order to minimize this field. Similarly, taking advantage of its axial-symmetric geometry, a simplified axial-symmetric model comprising only the inner conductor, the HMDPE insulator and the degraders was used. The first proposal was to design a new shape for the degraders which can be viewed from Figure 3.41 in comparison with the original design.

Figure 3.42 displays the comparison between the two cases. From the colored surface of Figure 3.42a and 3.42b, which show the normalized electric field around the connecting component, lower field values are obtained in the case of the new design. In addition, Figure 3.42c studies the electric field along the surface of the connecting component, the degraders and the HMDPE insulator, as a function of the vertical coordinate. Blue lines correspond to the original design and red lines to the new one. With the new shape applied, the field is reduced by 80 kV/cm. At a height corresponding to one third of the total length of the connecting component, since at this position the potential difference between the inner conductor and the degraders is lower, a reduction of 50 kV/cm in the electric field strength in this region can be obtained.

The other approach carried out, in order to reduce the electric field reached on the surface because of the high potential differences between the inner conductor and the degraders, is to enlarge the HMDPE thickness. As the field reduces according to $1/R$,

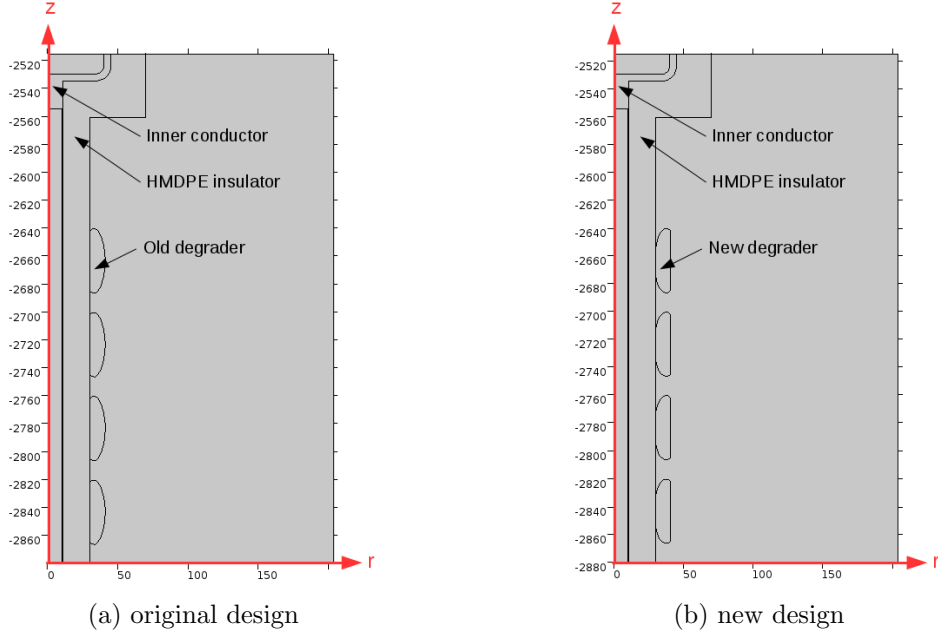


Figure 3.41: (a) Original and (b) new design for the shape of the degraders.

with a thicker insulator the field will be reduced. The results are displayed in Figure 3.43. The upper limit of this thickness is constrained by the diameter of the flange on the top part of the cryostat. The connecting component will be inserted into the cryostat through this flange; therefore, it should fit inside this diameter. In our studies, the HMDPE was thickened from the original value of 19 mm to the upper limit of 39 mm, which is the same thickness as the insulator used in the HVFT, in steps of 5 mm. In the original design with a 19-mm-thick HMDPE insulator, the electric field in the termination of the first degrader is 160 kV/cm as shown in Figure 3.42b, while this value decreases to 70 kV/cm (less than 50 %), with a 39 mm thickness. In addition, the electric field strength goes below 50 kV/cm after moving one third down of the total length of the connecting component.

Finally, we combined the advantages obtained from the two strategies. Figure 3.44 compares the original design and the new one with the new degrader shape and an enlarged thickness of 39 mm for the insulator. As it is displayed in Figure 3.44a and 3.44b, the field distribution around the connecting component, reduces from 238 kV/cm to 71 kV/cm in the termination of the first degrader. Figure 3.44c represents the electric fields along the surface at different heights of the connecting component. By applying this modification, all local fields can be effectively reduced to one third of the values with respect to the original design.

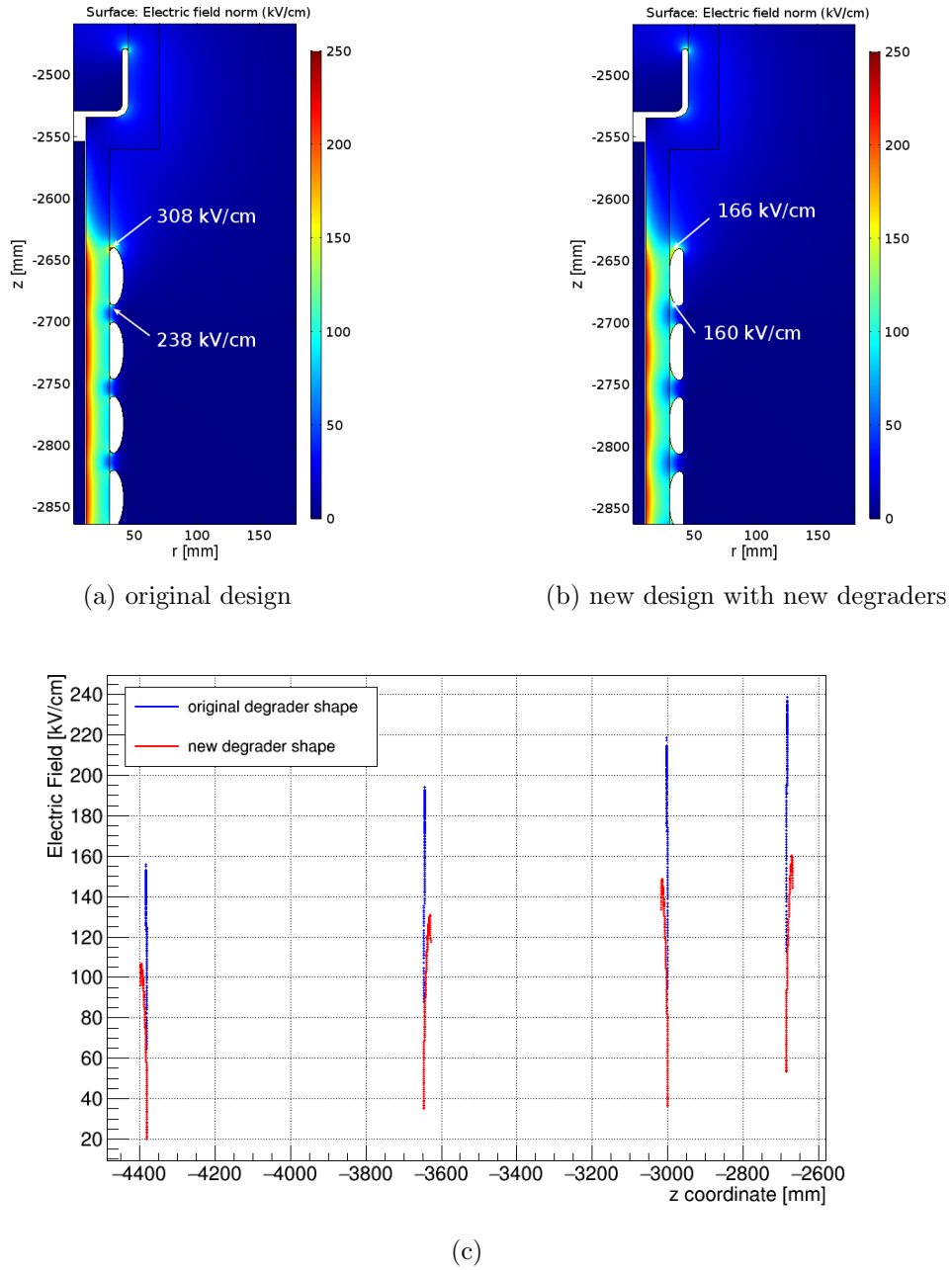


Figure 3.42: Comparison of the electric field distribution between the original design and the new design with the new shape for the degraders.

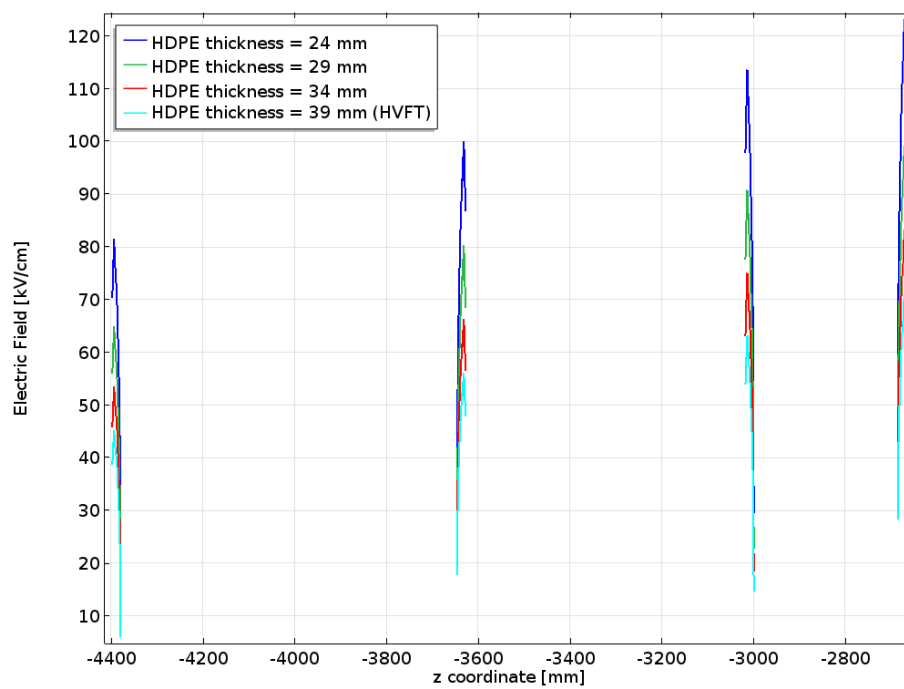


Figure 3.43: Electric field in the termination of the degrader at various heights with different thicknesses of the HMDPE insulator. The original design for the thickness of the HMDPE is 19 mm, while we study the thickened cases with a thickness ranging between 24 and 39 mm in steps of 5 mm.

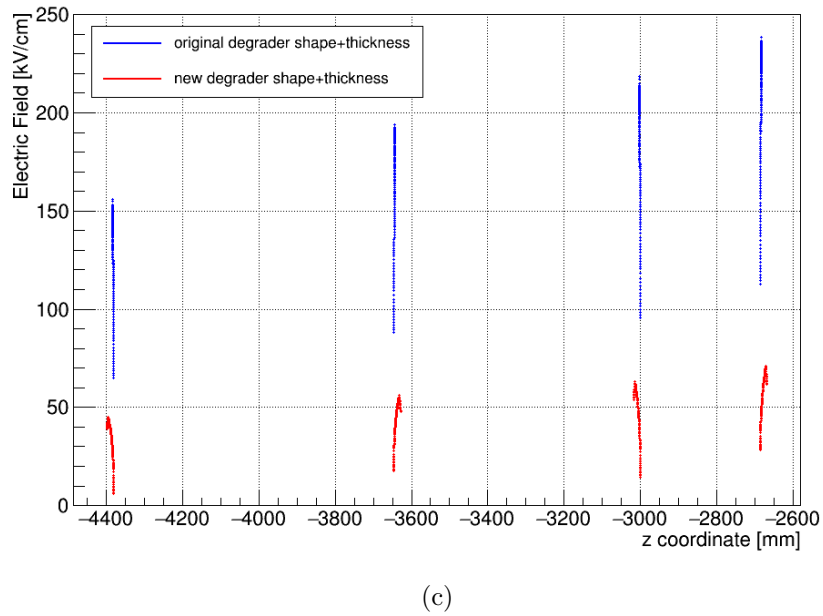
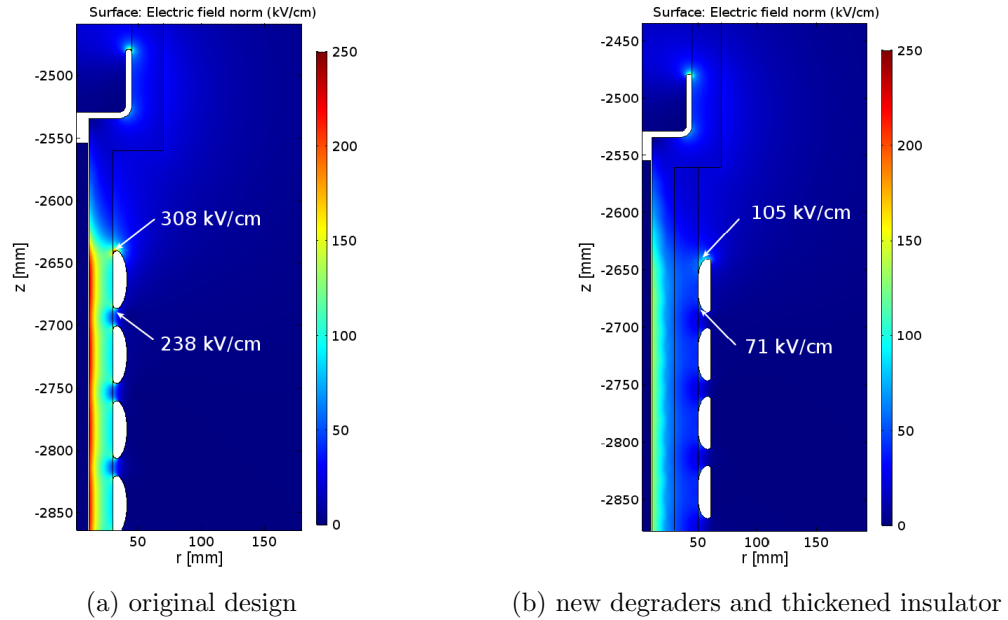


Figure 3.44: Comparison of the electric field distribution between the original design and the new design with the new shape for the degraders and an enlarged thickness (39 mm) of the HMDPE insulator.

Chapter 4

Capacitance Study on the Anode

The anode serving as the charge readout plays a crucial role in the detector; therefore, a performance study on a piece of anode module was conducted which provides us with a better understanding on its characteristics. A close-up picture of the 2D low-capacitance anode comprising two sets of perpendicular strips whose copper track pattern allows a two view readout on the same PCB, can be found in Figure 4.1a. Figure 4.1b is a schematic drawing used to explain the interconnections between both views. The physical readout channel is built from a series of 0.4-mm-diameter copper pads and the connecting strips. The strips filled with red are those in one view, and the ones with white in the other view. Both views are integrated on the same PCB layer. The black tracks and vias with a diameter of 0.2 mm denoted in black, function as the connections for strips from the same view, and are assembled on the other layer 1.5 mm below. The readout pitches indicated by arrows are 3 mm long. The anode made up of two sets of orthogonal copper strips, possessing an interwoven pattern and containing FR4 insulating material in between, acts like a capacitor; therefore, individual internal capacitance between any of the two strips is expected. As shown in Figure 4.1b, the capacitance between two parallel strips is marked in blue, and the capacitance between two perpendicular strips is in green.

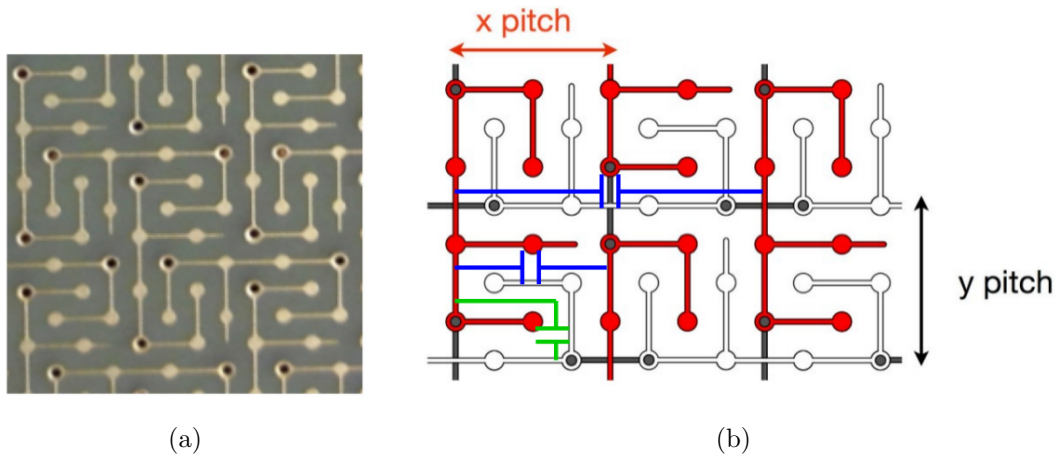


Figure 4.1: (a) Close-up picture of the 2D anode. (b) Schematic drawing of the anode pattern with internal capacitance between any of the two strips marked as blue and green for parallel and perpendicular strips respectively. [16]

The existence of this internal capacitance can affect charge readout results owing to signal cross-talk between the strips; that is, when incoming charges reach one of the strips, because of the capacitance to other strips, certain numbers of charges can be induced on those neighboring strips, and the signals detected on these strips would be mistaken as generated by incoming particles.

As a result, for a better understanding on the effect of this phenomenon, capacitance studies on the anode were carried out from two approaches — measurement and simulation. From the measurement's point of view, one piece of stand-alone $50 \times 50 \text{ cm}^2$ anode, consisting of 160 strips in each view was used. The capacitance between strips were measured with an LCR meter in the clean room. As for the simulation, in terms of simplicity and efficiency, two simplified models possessing the same structure as the anode but with a smaller size were used, with each composed of 6 and 12 strips in one view, respectively. In the following sections, the results from the simulations will be displayed, followed by those from the measurements.

4.1 Simulations with Simplified Models

To understand the interference between any of the two strips, the *capacitance matrix* is introduced, providing a quantitative comprehension in the correlations between strips to a high extent of precision. In terms of simplicity and efficiency, two simplified models, comprising 6 and 12 strips in one view respectively, were simulated to study their linear relation. Later, the results for a piece of $50 \times 50 \text{ cm}^2$ anode consisting of 160 strips can be directly extrapolated from those obtained from the two simplified models.

4.1.1 Capacitance Matrix

Regarding a capacitance matrix, there are in fact two kinds of capacitance matrices existing in the industry, each with a different definition bringing about some confusing issues. The *Maxwell Capacitance Matrix* is typically generated as the direct output from an electrostatic simulation which is used by most field solvers of simulation programs, while the *SPICE Capacitance Matrix* is used more often and better suited for a circuit simulation [31]. In fact, to study an equivalent circuit of a model, the SPICE parameters should be taken into account while generally the Maxwell parameters are those given in a simulation program. A straightforward calculation can be conducted to transform between the two matrices. In the following section, a brief introduction of both the SPICE and the Maxwell capacitance matrices, as well as the derivation from one to the other will be elaborated.

SPICE Capacitance Matrix

Taking a simple model with a set of five conductors as an example, a schematic diagram of these five conductors labeled from 1 – 5 and a common return path labeled as 0 is shown in Figure 4.2 [33]. Between each pair of conductors say the i -th and j -th, there exists a coupling capacitor C_{ij} ; on the other hand, for every single conductor (i -th), a capacitor to the return path (C_{ii}) also takes place. The formalism of the SPICE capacitance matrix is the combination of all the capacitance values, where the matrix of this five-conductor

model has a form of

$$\begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} \end{pmatrix}. \quad (4.1)$$

The diagonal values are the capacitance between one conductor and the return path, and the coupling capacitance between two conductors is stored in the off-diagonal elements. A capacitance matrix is symmetric as C_{ij} and C_{ji} both denote the coupling capacitance between the i-th and the j-th nodes.

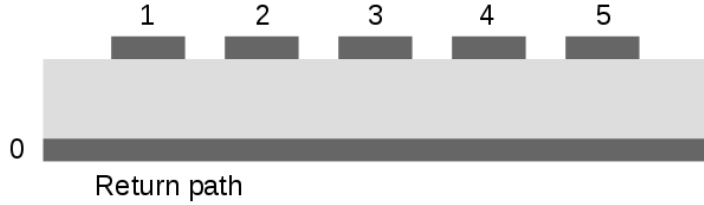


Figure 4.2: A model composed of five conductors in the study of the SPICE capacitance matrix.

The corresponding equivalent circuit of this five-conductor model is displayed in Figure 4.3 [33]. To obtain the capacitance of any of the capacitors which should be plugged into the circuit, one can directly retrieve to the matrix elements shown in Equation 4.1.

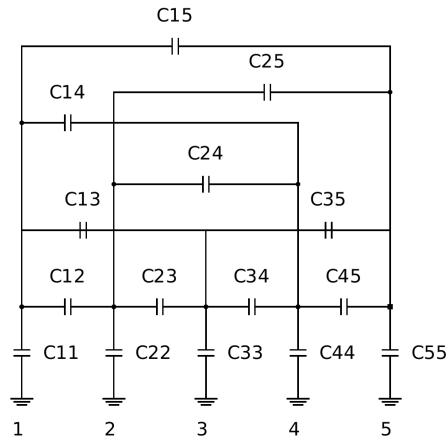


Figure 4.3: Equivalent circuit of this five-conductor model.

Maxwell Capacitance Matrix

Apart from the above mentioned SPICE capacitance matrix, whose elements are the parameters used in an equivalent circuit, there is on the other hand, another capacitance

matrix that is the direct solution of a field solver, the Maxwell capacitance matrix. Basically, a field solver calculates the Maxwell capacitance matrix through one or more Maxwell equations under certain boundary conditions.

A Maxwell capacitance matrix provides a comprehension in the relation between voltages and charges on a set of conductors [34]. Again, for a model composed of five conductors, whose schematic diagram can be found in Figure 4.4 [33], the relation derived directly from the self-capacitance of a single conductor,

$$Q = c \cdot V \quad , \quad (4.2)$$

is valid.

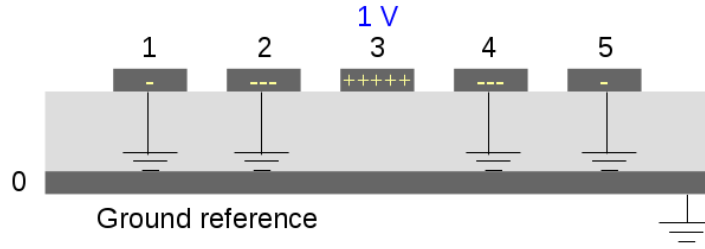


Figure 4.4: A model composed of five conductors in the study of the Maxwell capacitance matrix.

Conductor 0 is defined as the ground reference and is kept at 0 V at all times. According to Equation 4.2, the number of charges on conductor #1 Q_1 , given the voltages on all conductors V_1, V_2, V_3, V_4 and V_5 , is

$$Q_1 = C_{11} \cdot V_1 + C_{12} \cdot (V_1 - V_2) + C_{13} \cdot (V_1 - V_3) + C_{14} \cdot (V_1 - V_4) + C_{15} \cdot (V_1 - V_5) \quad , \quad (4.3)$$

which can be arranged as

$$Q_1 = (C_{11} + C_{12} + C_{13} + C_{14} + C_{15}) \cdot V_1 - C_{12} \cdot V_2 - C_{13} \cdot V_3 - C_{14} \cdot V_4 - C_{15} \cdot V_5 \quad . \quad (4.4)$$

As a Maxwell capacitance matrix, for a generic set of n number of conductors, is defined by the equation

$$\begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{bmatrix} = \begin{pmatrix} c_{11} & c_{12} & \cdot & \cdot & \cdot & c_{1n} \\ c_{21} & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_{n1} & \cdot & \cdot & \cdot & \cdot & c_{nn} \end{pmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ \cdot \\ V_n \end{bmatrix} \quad (4.5)$$

where $[Q_1 \ Q_2 \ \cdot \ \cdot \ \cdot \ Q_n]^T$ and $[V_1 \ V_2 \ \cdot \ \cdot \ \cdot \ V_n]^T$ are the charge and voltage vectors respectively and the remains is the capacitance matrix, with elements denoted in a lower-case c to distinguish from the real capacitance between two conductors C , the first row of the Maxwell capacitance matrix can be directly extrapolate from Equation 4.4, where

$$\begin{vmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} \end{vmatrix} = \begin{vmatrix} C_{11} + C_{12} + C_{13} + C_{14} + C_{15} & -C_{12} & -C_{13} & -C_{14} & -C_{15} \end{vmatrix} \quad . \quad (4.6)$$

Similarly, all the elements on the other four rows can be obtained with the same approach [34].

The procedure of the Maxwell capacitance matrix calculation solved by a field solver is as the following [33]:

1. A 1-V electric potential is set to the j-th node and all the others are set to ground.
2. Given the boundary condition, the Laplace's equation in its simplest differential form,

$$\nabla^2 = 0 \quad , \quad (4.7)$$

is solved to calculate the potentials in space.

3. The electric field on the surface of each node is then calculated from the electric potentials through

$$\mathbf{E} = -\nabla V \quad . \quad (4.8)$$

4. The total charges induced on each node is calculated according to the Gauss's law

$$Q_i = \oint_i \mathbf{E} \cdot d\mathbf{A} \quad . \quad (4.9)$$

5. The elements on column j are computed from the definition

$$c_{ij} = \frac{Q_i}{V_j} \quad . \quad (4.10)$$

6. The same process from 1. – 5. is repeated until the whole matrix is obtained.

Every matrix element between two conductors is a measurement of the number of access charges induced on the conductor with one of the conductors at 1 V and all the others to ground. This is a specialized condition where in general, to obtain the big picture of the exact capacitance between any of the two conductors in a equivalent circuit, some simple operations should be carried out.

In the Maxwell capacitance matrix, all off-diagonal elements are always negative as they are computed from the number of charges which possess an opposite sign. The absolute values of these elements represent the coupling capacitance between the two nodes, which holds a relation

$$C_{ij}(SPICE) = -c_{ij}(Maxwell) \quad (4.11)$$

with the SPICE capacitance matrix, for the transition from a Maxwell capacitance matrix element, to the parameter directly used in the circuit. On the other hand, the diagonal elements represent the *loaded capacitance* or the *total capacitance* which is the capacitance to the return path and to all the other conductors that are also grounded. Hence, to obtain the capacitance of one single conductor to the return path in a circuit model, the relation of the diagonal matrix elements between a Maxwell and a SPICE capacitance matrix

$$C_{ii}(SPICE) = \sum_j c_{ij}(Maxwell) \quad (4.12)$$

should be applied [33].

4.1.2 Simulation Model

As indicated earlier, two simplified models were used to study the linearity between the capacitance and the size of the anode in order to directly extend the results for other cases. In this section, a model consisting of 12 strips will be shown as a representative. Figure 4.5a is the 3D geometry of this model used in the simulations with an area of around $3.75 \times 3.75 \text{ cm}^2$. The two outer most strips as representatives in one view marked in red are denoted as $y1$ and $y12$, and the two from the other view marked in blue are denoted as $x1$ and $x12$. Figure 4.5b provides a detailed indication on the structure and the dimensions of this 3D model. The strips are made of copper and the insulator in between is FR4 with a relative permittivity $\epsilon_r = 4.5$ applied to the simulations.

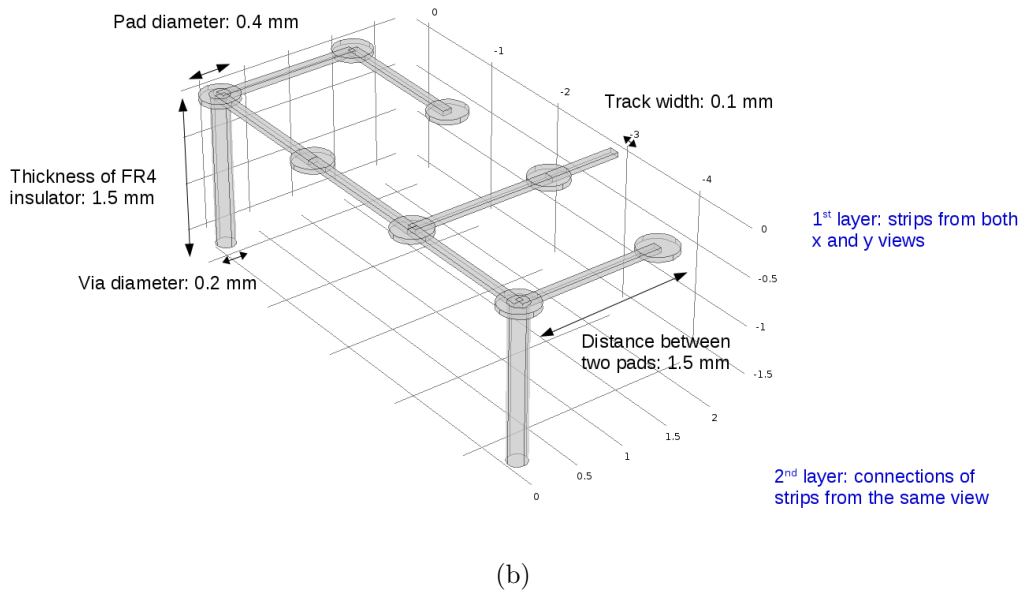
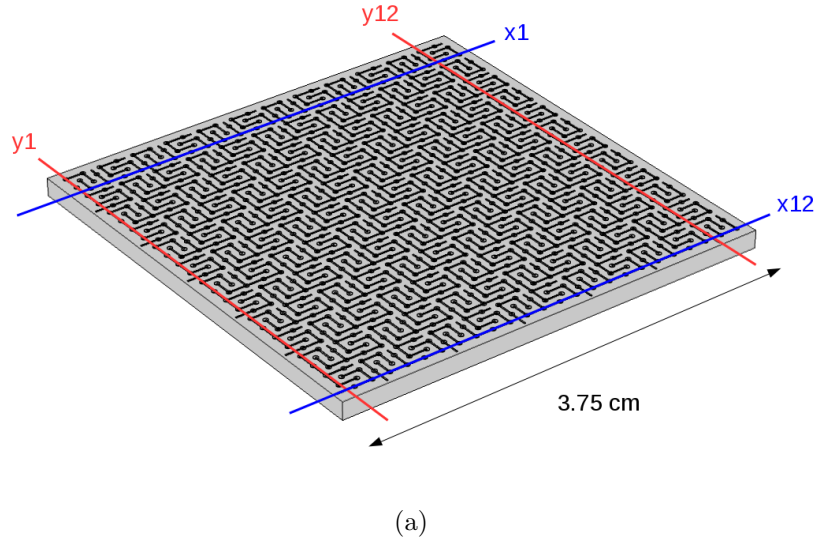


Figure 4.5: (a) 3D geometry of the simplified model used for anode simulations. (b) Detailed dimensions of the structure.

The capacitance matrix calculation procedure carried out by COMSOL *Multiphysics*® is the same as described in the previous section for the Maxwell capacitance matrix. During each run of the procedure, one strip is set to 1 V while all the others set to 0 V. Also, the reference ground is applied to the bottom boundary of the anode. The program provides a function of direct transition from the Maxwell to SPICE capacitance matrix; hence, all capacitance values can be acquired directly from the SPICE capacitance matrix. The capacitance matrix calculated from this model includes all the 12 strips in x-view and the 12 strips in y-view, which is a 24×24 matrix possessing a configuration as

$$\begin{pmatrix} C_{y1-y1} & \cdot & \cdot & C_{y1-y12} & C_{y1-x1} & \cdot & \cdot & C_{y1-x12} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ C_{y12-y1} & \cdot & \cdot & C_{y12-y12} & C_{y12-x1} & \cdot & \cdot & C_{y12-x12} \\ C_{x1-y1} & \cdot & \cdot & C_{x1-y12} & C_{x1-x1} & \cdot & \cdot & C_{x1-x12} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ C_{x12-y1} & \cdot & \cdot & C_{x12-y12} & C_{x12-x1} & \cdot & \cdot & C_{x12-x12} \end{pmatrix}_{24 \times 24} \quad (4.13)$$

With this matrix, capacitance between parallel and perpendicular strips can be obtained. The off-diagonal elements denote the coupling capacitance between 2 strips. For example, C_{yi-yj} (C_{xi-xj}) is the capacitance between the i-th and j-th strips from the y(x)-view, i.e. the capacitance between two parallel strips; C_{ym-xn} (C_{xm-yn}) is the capacitance between the m-th strip from the y(x)-view and n-th strip from the x(y)-view, i.e. the capacitance between two perpendicular strips. The diagonal elements represent the capacitance between one strip and the reference ground. For instance, C_{yi-yi} (C_{xi-xi}) is the capacitance between the i-th strip from the y(x) view and the ground.

The whole capacitance matrix is given in Appendix A. After obtaining the capacitance matrices for both the cases with 6 and 12 strips in each view, the linear relation between the size of the anode and the coupling capacitance had been found and the results for the case with 160 strips, which is the size of a anode module used in the measurement, could be directly extrapolated. For the capacitance between two parallel strips, the value increases linearly with the size of the anode module owing to the fact that the capacitance between two conductors is proportional to their cross-sectional area; the larger the size of the anode, the greater the area of the strips overlap. In total, the loaded capacitance also possesses a linear relation with the size of the anode module, as it sums up the capacitance between all parallel and perpendicular strips, that between parallel strips increases with the increment of cross-sectional areas while that between perpendicular strips increases by the numbers of strips added into the anode module. Table 4.1 summarizes some of the results, including the capacitance between one strip and ground, the capacitance between two closest parallel strips, and the capacitance between two perpendicular strips.

Table 4.1: Coupling capacitance of a piece of $50 \times 50 \text{ cm}^2$ anode module directly extrapolated from the simulated results.

Capacitance to ground	36.14 [pF]
Two closest parallel strips	1.3 [pF]
Two perpendicular strips	0.15 [pF]

4.2 Measurements with the LCR Meter

Measurements on a piece of stand-alone $50 \times 50 \text{ cm}^2$ anode were carried out with the anode placed on an isolated dielectric surface (an empty carton box of a height of $\sim 1 \text{ m}$ located on the floor) far away from any conducting materials as shown in Figure 4.6. A *Sourcetronic ST2831 LCR Meter* was used [35] for capacitance measurements. Figure 4.7 is a photo of this LCR meter calibrating with a 10 nF reference capacitor.

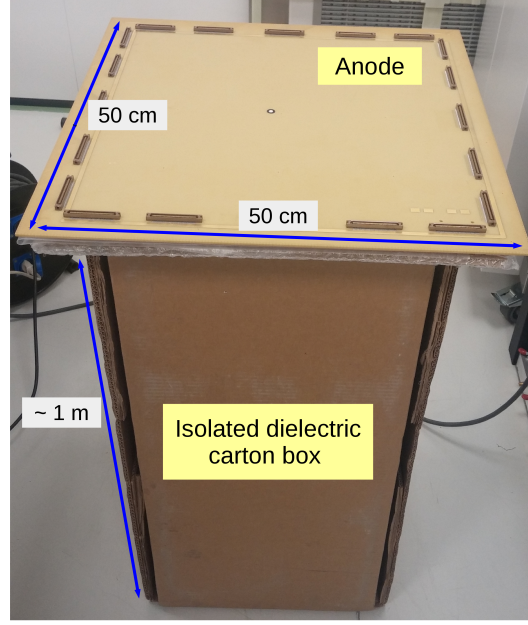


Figure 4.6: Experimental setup for anode capacitance measurements on an isolated dielectric carton box.

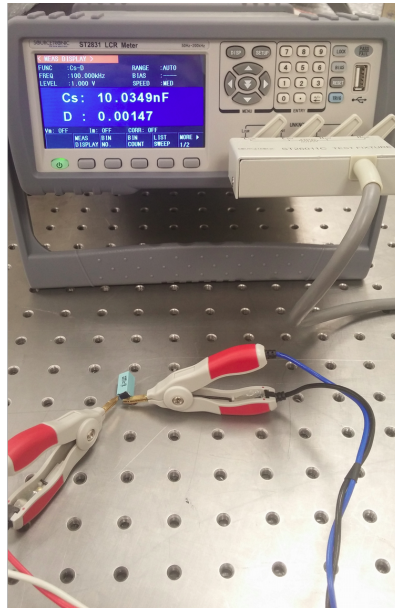


Figure 4.7: Sourcetronic ST2831 LCR Meter calibrating with a 10 nF reference capacitor.

To study the performance of the anode, we are interested in two phenomena, which should be explained under different configurations. On one hand, in terms of anode itself, to study the signal cross-talk between strips, capacitance between any of the two strips should be measured. On the other hand, to study the capacitance between the anode to the rest of the world, which is denoted as a *ground at infinity*, another measurement setup was applied with more details given in the following sections.

4.2.1 Cross-Talk Study

The cross-talk study only takes the anode itself into consideration. Figure 4.8 displays the experimental setup for this measurement, where Figure 4.8a is a schematic drawing with only a few strips drawn as representatives. In this configuration, among all 320 strips from both views (160 strips in each), apart from the 2 measured ones (marked in blue for 2 parallel strips; stands as well for perpendicular strips), all the other 318 ones (marked in red) are connected together with the anode back strip (brown square close to the edges of the anode). To exclude the interference from those 318 strips, the anode back strip is grounded, which is connected to the ground terminal of the LCR meter for a reference ground (as shown in Figure 4.8b, a close-up photo pointing out the connection).

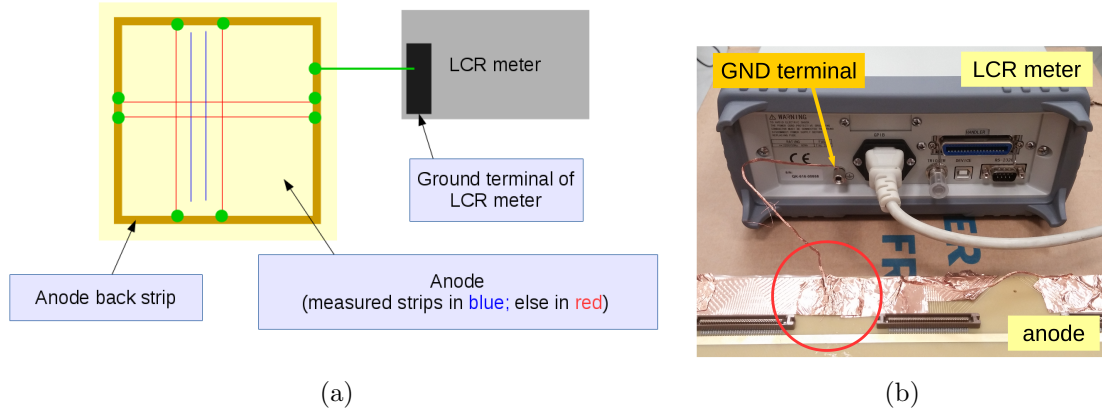


Figure 4.8: Experimental setup for cross-talk measurements. (a) Schematic drawing with only a few strips plotted. (b) Close-up photo pointing out the connection between the LCR meter ground terminal and the anode back strip (marked out in the red circle).

Figure 4.9 displays the capacitance measured between parallel strips, which are strips from the same view, with varying distances. The distance is shown in the number of strips, i.e. the closest parallel strips will be denoted as 1 in the abscissa and the next one as 2. One can see that the parallel capacitance decreases rapidly with the distance, where the closest parallel one is measured to be around 7.6 pF, and the second parallel one is 1.2 pF. In addition, measurements under various frequencies set to the LCR meter were conducted and the results show no differences.

Similar approach was used to measure the capacitance between two perpendicular strips, i.e. strips from different views, with the results shown in Figure 4.10 with respect to various frequencies. Measurements were performed on strips from various positions. “Middle” denotes those in the center of the anode while “edge” denotes those close to the boundaries. As can be seen, capacitance between perpendicular strips is independent of

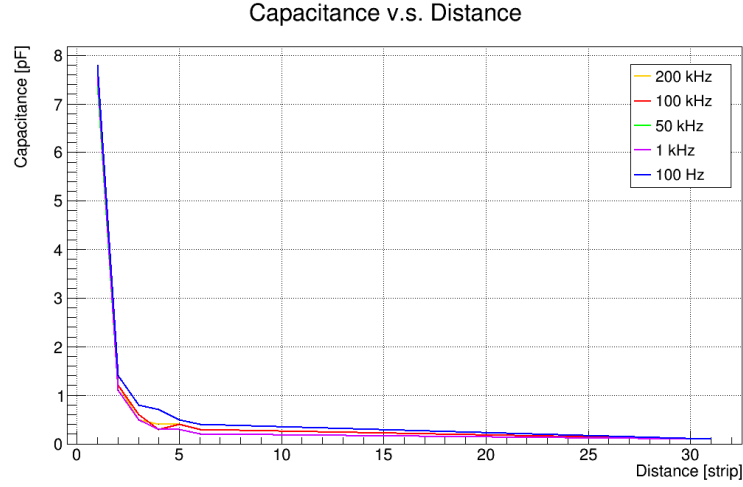


Figure 4.9: Capacitance between parallel strips with varying distances.

the positions which gives a value of ~ 0.5 pF between strips both from the middle parts, both from the edges, or each from different locations. The capacitance between the first and the second closest parallel strips are also included in this plot for comparison as one can see that the capacitance between perpendicular strips has a value with a factor of ten less than that of two closest parallel strips. The existence of the coupling capacitance will result in attenuation on the signals which will be observed by the preamplifier used in the experiment.

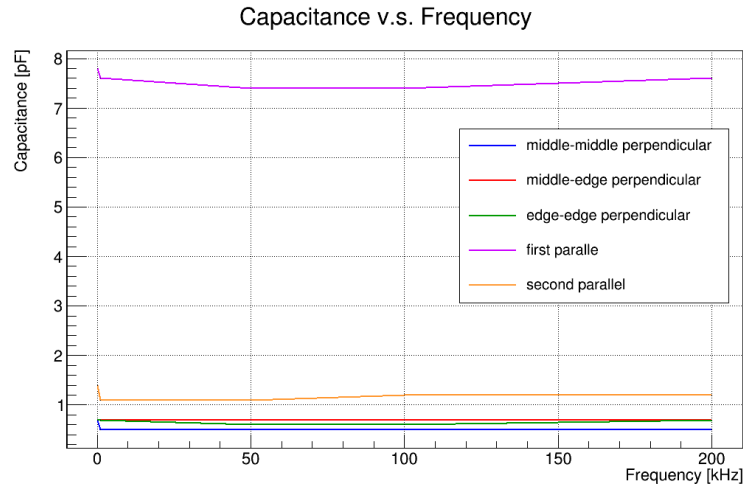


Figure 4.10: Capacitance between perpendicular strips at different positions.

4.2.2 Capacitance to Ground

In this second configuration where we would like to study the capacitance between the anode and the ground at infinity, only one out of the 320 strips is left unconnected to the others. All those 319 connected strips are also linked to the anode back strip. In this condition, the anode back strip together with the 319 strips are regarded as one single element which represents the ground at infinity. Therefore, it should be left floating;

namely, the anode back strip should not be in contact with the ground terminal of the LCR meter. A schematic diagram of this setup can be found in Figure 4.11a. The capacitance measured between the unconnected strip and this ground port is around 78 pF.

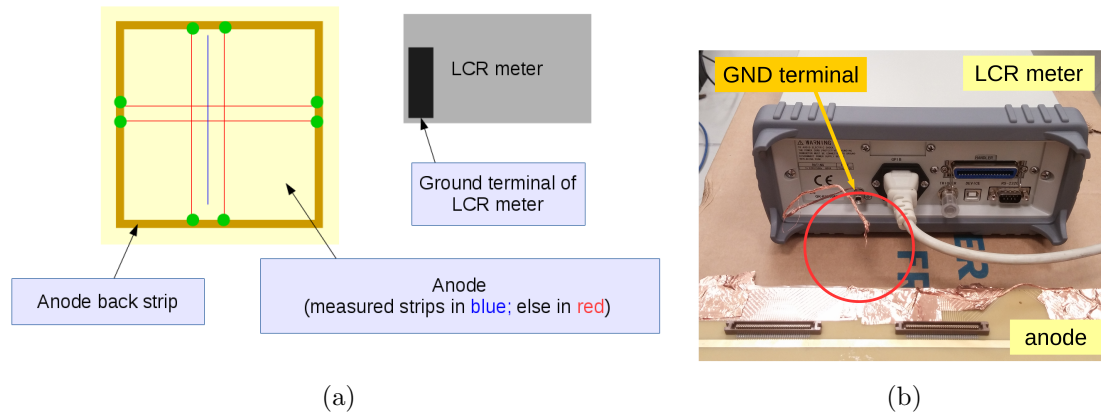


Figure 4.11: Experimental setup for measuring the capacitance between the anode and the ground at the infinity. (a) Schematic drawing with only a few strips plotted. (b) Close-up photo indicating the floating anode back strip which is not connected to the LCR meter ground terminal (marked out in the red circle).

Table 4.2 summarizes some of the most important results, including the capacitance between one strip and ground, the capacitance between two closest parallel strips, and the capacitance between two perpendicular strips.

Table 4.2: Coupling capacitance of a piece of anode module from the measurements.

Capacitance to ground	78 [pF]
Two closest parallel strips	7.6 [pF]
Two perpendicular strips	0.5 [pF]

Comparing the simulated (Table 4.1) and the measured (Table 4.2) results, the capacitance values obtained are of the same orders of magnitude. A phenomenon where the capacitance between two closest parallel strips is of a factor of ten larger than that between two perpendicular strips, and the stray capacitance which is the capacitance between one strip and ground gives a value with more than one order of magnitude larger than that between two parallel strips, is found in both the measured and the simulated cases. Nevertheless, the precise values acquired do not match; therefore, further investigations are needed to understand whether it is an issue with the simulations or the measurements.

Chapter 5

Conclusion

In this thesis, a preliminary study on the ProtoDUNE-DP detector had been carried out. Through simulations under electrostatic circumstances, we verified the uniformity of the electric field within the field cage and we studied the electric field distribution around various components along the TPC to guarantee the absence of any critical electric field values constrained by our guideline of 40 kV/cm.

The homogeneity of the electric field within the active volume of the TPC should be controlled and maintained so as to avoid any deviations under reconstruction processes. On the periphery of the detector, electric field distortions from the nominal value of 0.5 kV/cm take place owing to the edge effects. From the simulation results, the fiducial volume of the detector in where the electric field is uniform were determined. At the vertical boundary, which is 70 mm above the cathode, a perturbation of the drift field below 0.02 kV/cm can be found. On the contrary, in search of the horizontal boundary, electric field directions were studied in the gap between the end of the CRP and the first field shaper. In the region where the electric field deviates from the nominal value, only the drift velocities of the electrons are affected with the trajectories left undistorted, preserving the unambiguity of the reconstruction processes.

In order to prevent occurrences of electrical breakdown, all local electric fields within the LAr volume ought to be minimized. On the surface of the cathode to which a high voltage of -300 kV is set, electric field along the whole structure is below 30 kV/cm. On the other hand, owing to the structure of the small-radius wires on the ground grid, the electric field around the wires reaches a value larger than 50 kV/cm in the original design with wires of a 1 mm radius. To reduce the field strength, wires of different radii were studied and we found out that with a radius of 2 mm, the electric field on the surface of the wires can be reduced to less than 30 kV/cm.

To verify the operation of the CRP, electric field between each stage were examined. A 2 – 3 kV/cm electric field above the extraction grid allows the electrons to be efficiently extracted from the liquid to the gas phase. Between the two electrodes of the LEM, an electric field of around 35 kV/cm is required to provide the field strength for triggering electron multiplications, where in the simulations, because of the applied potentials, a field of 30 kV/cm were obtained. Later, charges will be drifted to the anode under a field of 5 kV/cm after leaving the LEM.

A delicately designed HVFT and a component connecting it to the cathode is indis-

pensable regarding the delivery of the drift high voltage. At the presence of a great electric potential of 300 kV, avoidance of any discharge processes requires all local electric fields in the LAr near by to be under a certain threshold. In the initial design of the HVFT, critical values of electric field were found on the surface of the outer conductor ground termination. A first approach by adding a LAr gap between the HMDPE insulator and the ground termination had been carried out to study its effect in diminishing the high electric field which showed an effect in reducing the spatial extent of the high field regions. Besides, investigations on the connecting component serving as the link between the HVFT and the cathode had been conducted. In the original design, because of great electric potential differences between the inner conductor and the degraders, local electric field of crucial values larger than 200 kV/cm were found on the terminations of the degraders near the top of the detector. By introducing an improved structure of the degraders and a thickened HMDPE insulator, the local field strengths can be reduced to one third of the original values. From the simulation's point of view, this design provides a good solution over the initial challenging layout; nevertheless, verification from manufacturing perspective is yet required.

The capacitance studies on the anode provides us with a better understanding on the capacitive coupling relation of the readout strips on the anode and its effect on signal attenuation and potential cross-talk. Both simulations and measurements indicate a fast decrease of capacitance between parallel strips with increasing distances. On the other hand, the capacitance between two perpendicular strips is a factor of 10 less than that between two closest parallel strips. In addition, the stray capacitance gives a value of more than one order of magnitude larger than that between two parallel strips; among all coupling capacitance, the stray capacitance dominates. As the capacitance is a function only of the geometry of the design and the dielectric material inserted between the electrodes of a capacitor, to reduce the stray capacitance, a redesign of the anode is required. This can be carried out by reducing the area of the strips or changing the dielectric material (FR4 with $\epsilon_r = 4.5$) into some other materials with smaller permittivities. As the size of the strips affects the charge readout efficiency, the possibility of making the strips thinner is limited.

These electrostatic simulations and performance studies on the ProtoDUNE-DP detector provide us with an initial cognizance on the revolutionary technology used for a dual-phase LAr-TPC, and subsequently open the way to next-generation larger neutrino detectors.

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Appendix A

Capacitance Matrix

The capacitance matrix of the anode module with 12 strips in each view is shown in this appendix. This matrix has a configuration as shown in Equation A.1, consisting of $24 \times 24 = 576$ elements. As the number of elements is too large to be included in one table, the results are shown separately into two sections in the following tables with each consists of 12 columns and 24 rows of the results from the capacitance matrix. The matrix elements marked in red in Equation A.1 are displayed in Table A.1 and those in blue are shown in Table A.2. The capacitance matrix elements displayed here correspond to the SPICE capacitance matrix which possess positive values. For those having negative values result from numerical errors owing to the weakness of the coupling.

$$\begin{pmatrix} C_{y1-y1} & \cdot & \cdot & C_{y1-y12} & C_{y1-x1} & \cdot & \cdot & C_{y1-x12} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ C_{y12-y1} & \cdot & \cdot & C_{y12-y12} & C_{y12-x1} & \cdot & \cdot & C_{y12-x12} \\ C_{x1-y1} & \cdot & \cdot & C_{x1-y12} & C_{x1-x1} & \cdot & \cdot & C_{x1-x12} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ C_{x12-y1} & \cdot & \cdot & C_{x12-y12} & C_{x12-x1} & \cdot & \cdot & C_{x12-x12} \end{pmatrix}_{24 \times 24} \quad . \quad (\text{A.1})$$

Table A.1.: First 12 columns of the capacitance matrix for a piece of anode with 12 strips in each view.

	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12
y1	2.88E+00	1.02E-01	2.28E-04	6.48E-07	5.00E-09	2.07E-11	3.03E-13	1.59E-15	2.04E-17	-4.00E-19	-2.39E-20	-1.14E-21
y2	1.02E-01	2.71E+00	1.02E-01	2.04E-04	9.25E-07	3.32E-09	3.97E-11	1.78E-13	2.74E-15	7.22E-18	-6.94E-20	-1.84E-20
y3	2.29E-04	1.02E-01	2.65E+00	1.02E-01	2.26E-04	6.45E-07	4.99E-09	2.04E-11	2.94E-13	1.35E-15	1.93E-17	-2.75E-19
y4	6.50E-07	2.05E-04	1.02E-01	2.71E+00	1.02E-01	2.04E-04	9.27E-07	3.31E-09	3.99E-11	1.76E-13	2.59E-15	7.12E-18
y5	5.00E-09	9.25E-07	2.27E-04	1.02E-01	2.66E+00	1.02E-01	2.26E-04	6.43E-07	4.97E-09	2.02E-11	2.85E-13	1.27E-15
y6	2.09E-11	3.33E-09	6.47E-07	2.05E-04	1.02E-01	2.71E+00	1.02E-01	2.05E-04	9.32E-07	3.30E-09	3.95E-11	1.77E-13
y7	3.09E-13	3.98E-11	4.99E-09	9.28E-07	2.26E-04	1.03E-01	2.67E+00	1.02E-01	2.27E-04	6.41E-07	4.95E-09	2.05E-11
y8	1.68E-15	1.81E-13	2.04E-11	3.31E-09	6.45E-07	2.05E-04	1.02E-01	2.72E+00	1.03E-01	2.04E-04	9.29E-07	3.33E-09
y9	1.94E-17	2.77E-15	2.93E-13	3.99E-11	4.97E-09	9.32E-07	2.27E-04	1.03E-01	2.67E+00	1.02E-01	2.27E-04	6.46E-07
y10	-5.96E-19	5.71E-18	1.35E-15	1.77E-13	2.03E-11	3.30E-09	6.43E-07	2.05E-04	1.02E-01	2.72E+00	1.02E-01	2.04E-04
y11	-3.48E-20	-1.61E-19	1.92E-17	2.60E-15	2.85E-13	3.95E-11	4.95E-09	9.29E-07	2.27E-04	1.02E-01	2.65E+00	1.02E-01
y12	-1.27E-21	-1.86E-20	-2.15E-19	7.76E-18	1.27E-15	1.76E-13	2.05E-11	3.34E-09	6.48E-07	2.05E-04	1.02E-01	2.78E+00
x1	1.10E-01	1.48E-01	1.49E-01	1.48E-01	1.49E-01	1.48E-01	1.50E-01	1.48E-01	1.49E-01	1.48E-01	1.49E-01	1.51E-01
x2	1.20E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.48E-01
x3	1.08E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.49E-01
x4	1.20E-01	1.46E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.49E-01
x5	1.08E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.48E-01
x6	1.20E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.48E-01
x7	1.09E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.49E-01
x8	1.20E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.49E-01
x9	1.08E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.49E-01
x10	1.20E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.49E-01
x11	1.08E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.49E-01
x12	8.43E-02	1.20E-01	1.08E-01	1.20E-01	1.09E-01	1.20E-01	1.08E-01	1.20E-01	1.09E-01	1.21E-01	1.09E-01	1.22E-01

Table A.2: Second 12 columns of the capacitance matrix for a piece of anode with 12 strips in each view.

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12
y1	1.10E-01	1.20E-01	1.08E-01	1.20E-01	1.08E-01	1.20E-01	1.09E-01	1.20E-01	1.08E-01	1.21E-01	1.08E-01	8.43E-02
y2	1.49E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.20E-01
y3	1.49E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.08E-01
y4	1.49E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.20E-01
y5	1.49E-01	1.46E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.09E-01
y6	1.49E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.47E-01	1.20E-01
y7	1.49E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.08E-01
y8	1.49E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.47E-01	1.20E-01
y9	1.49E-01	1.46E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.46E-01	1.09E-01
y10	1.49E-01	1.46E-01	1.46E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.46E-01	1.46E-01	1.47E-01	1.20E-01
y11	1.49E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.47E-01	1.47E-01	1.47E-01	1.46E-01	1.08E-01
y12	1.51E-01	1.48E-01	1.49E-01	1.48E-01	1.49E-01	1.48E-01	1.49E-01	1.48E-01	1.49E-01	1.48E-01	1.49E-01	1.22E-01
x1	2.76E+00	1.02E-01	2.27E-04	9.25E-07	4.98E-09	3.99E-11	2.93E-13	2.75E-15	2.48E-17	2.78E-20	-2.03E-20	-1.89E-21
x2	1.02E-01	2.74E+00	1.02E-01	2.05E-04	6.47E-07	3.32E-09	2.06E-11	1.78E-13	1.38E-15	8.87E-18	-1.81E-19	-2.57E-20
x3	2.26E-04	1.02E-01	2.66E+00	1.03E-01	2.27E-04	9.26E-07	4.98E-09	3.97E-11	2.92E-13	2.65E-15	2.12E-17	-1.64E-19
x4	9.24E-07	2.04E-04	1.02E-01	2.73E+00	1.02E-01	2.05E-04	6.46E-07	3.31E-09	2.05E-11	1.76E-13	1.32E-15	6.57E-18
x5	4.98E-09	6.45E-07	2.27E-04	1.02E-01	2.68E+00	1.02E-01	2.27E-04	9.24E-07	4.97E-09	3.95E-11	2.90E-13	2.87E-15
x6	3.98E-11	3.31E-09	9.25E-07	2.04E-04	1.02E-01	2.74E+00	1.02E-01	2.04E-04	6.45E-07	3.30E-09	2.05E-11	1.87E-13
x7	2.95E-13	2.05E-11	4.98E-09	6.44E-07	2.26E-04	1.02E-01	2.69E+00	1.02E-01	2.27E-04	9.26E-07	4.98E-09	4.07E-11
x8	2.78E-15	1.77E-13	3.97E-11	3.31E-09	9.23E-07	2.03E-04	1.02E-01	2.74E+00	1.02E-01	2.05E-04	6.48E-07	3.38E-09
x9	2.51E-17	1.37E-15	2.91E-13	2.05E-11	4.97E-09	6.43E-07	2.26E-04	1.01E-01	2.67E+00	1.03E-01	2.27E-04	9.40E-07
x10	1.01E-20	9.13E-18	2.64E-15	1.77E-13	3.95E-11	3.30E-09	9.25E-07	2.04E-04	1.02E-01	2.74E+00	1.02E-01	2.07E-04
x11	-2.19E-20	-1.56E-19	2.12E-17	1.32E-15	2.89E-13	2.06E-11	4.99E-09	6.46E-07	2.27E-04	1.02E-01	2.67E+00	1.03E-01
x12	-1.67E-21	-1.95E-20	-5.37E-20	7.14E-18	2.80E-15	1.89E-13	4.05E-11	3.37E-09	9.39E-07	2.06E-04	1.03E-01	2.96E+00

