Electric field and proportional light simulation in the gas phase of the XENON experiment

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1 Introduction

XENON is a project currently in the design and testing stage to build a double phase detector for dark matter search. The detector has an expected event rate of 1 event/100 kg/year for WIMPS, Weakly Interacting Massive Particles, the leading candidate for dark matter. These thermally created particles are expected to have a mass of approximately 100 GeV and are included in Super Symmetry theory.

Theorists have postulated the existence for dark matter as an explanation for the observed inconsistencies both within cosmological theory and observed phenomenon. The most powerful evidence for the existence of dark matter results from a drastic difference between the expected and calculated orbital velocities of spiral galaxies. The observed data does not follow the expected pattern defined by Kepler's law of gravity with the observed mass of the galaxy. This inconsistency can be reconciled with the inclusion of large amounts of unobservable mass. Theoretical cosmology has defined a value for the expected mass of the universe to be a value of Omega equal to one for a closed universe. The current observed matter brings the value of Omega to be considerably smaller than one with the remaining value being theorized to be thirty percent dark matter and seventy percent dark energy. One candidate to make up the missing matter are WIMPS. The acronym Weakly Interacting Massive particles refers to the fact that they do not interact electromagnetically or with the strong force. These particle exist throughout the universe. The XENON detector will be a one tonne dual phase liquid/gas detector. We hope to observe the WIMPs with the detector by observing the scattering of the WIMP off of a target and determine the nature of the particle by measuring and observing the resulting energy and phenomena. The challenge is increased by the extremely low expected energy of the interaction. Xenon's unique qualities make it an excellent choice to be used in the dark matter detector. The large mass of the nucleus, the high atomic number and the high density make it a good option. The ease of maintenance at -100C helps to simplify the structure of the chamber. Xenon stands out as ideal for this specific experiment because of its high ionization, high electron drift velocity, low diffusion, high scintillation yields, and distinct charge/light ratio. These qualities, paired with easy availability, make xenon to be a superior choice.

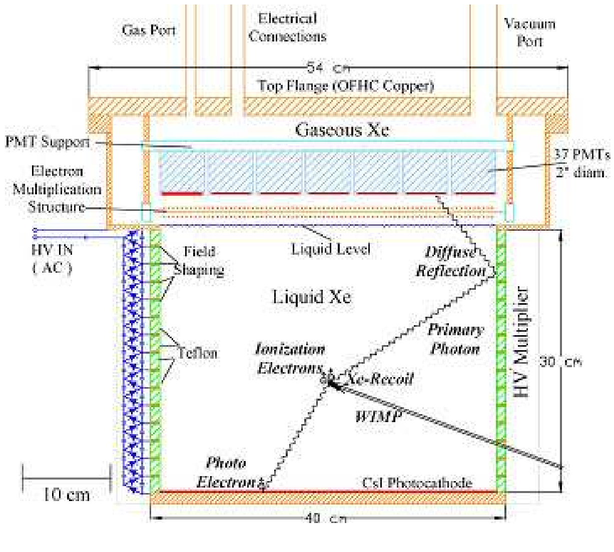

Figure 1: Drawing of TPC demonstrating the process of a WIMP interaction

2 Detector structure

The detector shown in figure ?? consists of a cylinder 30 cm positioned vertically with a 38 centimeter diameter holding approximately 100 kg of purified liquid xenon. The base for the structure is a copper plate coated with CsI from which the photons release electrons. The chamber is surrounded by Teflon to reflect UV light. Copper rings maintain and shape the electric field with the strength of 5 kV/cm. The larger structure on top holds the PMTs (PhotoMultiplier Tubes) and the wire for the proportional scintillation in the gas. This structure is made of copper and seals the charge collection chamber on the top. Two rings of sixteen PMTs read both the direct and proportional light defined in the next section. To increase light collection walls of the detector are made of Teflon material characterizing by the high diffusive light reflection.

3 A signal from WIMP interaction

A WIMP interacting in the xenon of the chamber will create a low-energy nuclear recoil in the xenon that then causes both UV scintillation photons (direct light) and ionization electrons. A WIMP nuclear event with an energy equal to one of a gamma ray or electron the ratio of proportional to direct light of the WIMP interaction will be much less than the ratio for a gamma ray. Created electrons are drifted in the TPC and extracted at the change from liquid to gaseous xenon where they produce the proportional light.

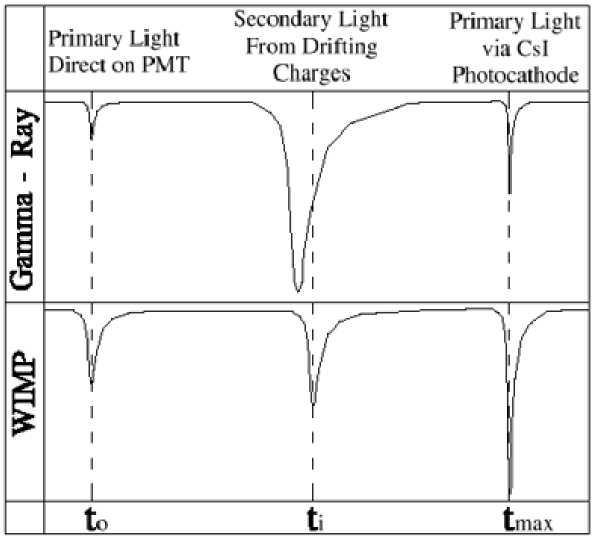

Figure 2: Comparison of the signal created by a gamma ray interaction to one of a WIMP interaction

Most of the events in the detector are characterized by three signals shown in figure ?? The first is created by the immediate scintillation light, followed by the proportional light produced by drifting electrons in the gas phase and finally the proportional scintillation signal from the CsI photoelectrons extracted from the liquid. The first and the last event are separated by 150 microseconds, equal to the maximum drift time. The design of the chamber should ensure rejection of background better than 99.5 percent and allow for very low energy. The main sources for background are gamma and beta decay from 85Kr, Radon, and 136Xe double beta decay from impurities in the xenon, muon induced neutrons, neutrons from contamination, and gamma rays emitted by the PMTs.

4 The subject of study

In my research I studied the ionization electrons drifting through the gaseous state of xenon in the small prototype detector. Using computer simulations I calculated the electric field in the charge collection chamber based on the geometries for the prototype detector with a structure of wires or mesh. I simulated the drift of electrons through the chamber and calculated both the production of photons and the location of this production. The goal of my research is to add insight into the differences between the two structures to aid in the decision for the superior one.

5 Software tools

By using the Garfield [?] program I was able to create a simulation test chamber with wires. The Garfield program allows for the input of the geometry of the chamber with a periodic repetition of wires and charged, or grounded planes to simulate condition within the detector. The Garfield program does track drift electrons with the inclusion of both transversal and longitudinal diffusion defined by a Monte Carlo simulation. This program allows for a precise calculation superior to one calculated by hand. The main flaw in the program, the omission of dielectric and grid geometry, can be solved with the purchase and use of an additional program, Maxwell [?], that can define the simulated chamber and run through Garfield. In order to perform similar calculations for the number of photons emitted and the paths of drift electrons for a three dimensional chamber with a mesh replacing the row of wires I used Maxwell to create the chamber and electric field and then applied the program in Garfield to calculate the photons produced. Maxwell uses the Finite Element Method (FEM) to calculate the electric field. The calculations become more precise with the simplification of the geometry of the chamber as this results in fewer elements with better calculations. In order to achieve the most precision I created a chamber of one fourth of a space in the mesh and then defined the total area as a repeating mirror images in X and Y of the defined space. This structure allows for very precise measurements.

6 Results

I used the computer program Garfield to simulate the electrons drift through an electrostatic field in pure gaseous xenon in order to calculate the number of photons emitted by each electron. I began by creating the electric field within the Charge Readout Chamber for the prototype detector with the geometry of a charged plane, a row of wires 2.8mm above the plane, grounded, and the PMT cathode 6.3mm above the wires, grounded. Two simplifications needed to be made in order to construct this, the first being replacing a mesh with the base plane to create a steady voltage and the second is to assume that the liquid level rests precisely on the bottom plane so no dielectric exists in the chamber. These simplifications must be made in order to employ the Garfield program in the construction of the electric field as the simulation does not allow for the inclusion of dielectrics.

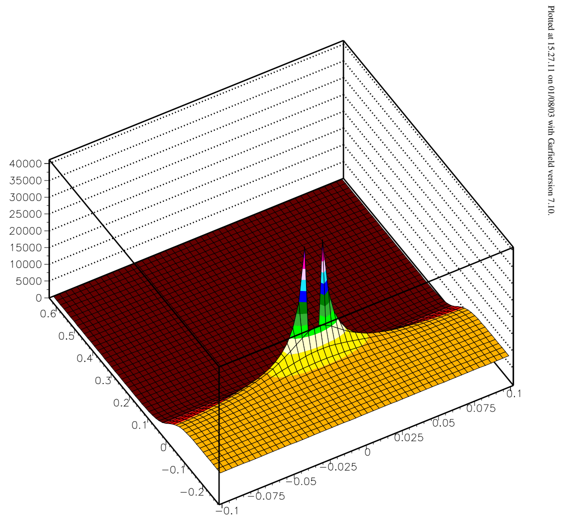

Figure 3: Surface Plot of the Electric Field in TPC in the region of one wire

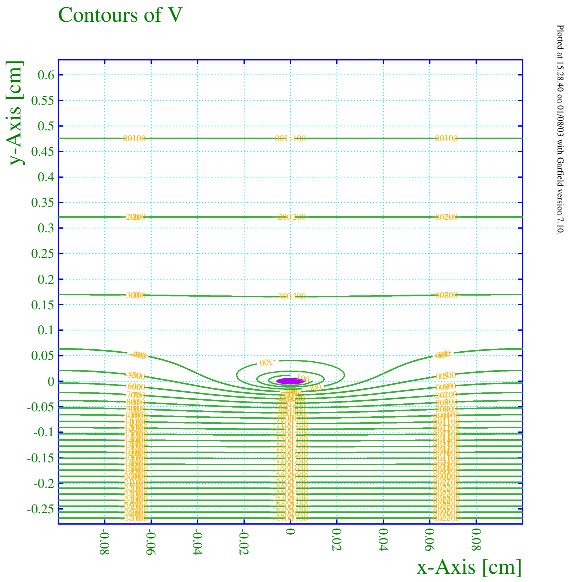

Figure 4: Contour Plot of Potential in TPC with wires in the region of one wire

With the field within the cell constructed I then tracked the drift lines of electrons for a section of the periodically repeating chamber so that electrons drifting from any point along the plane follows a path.

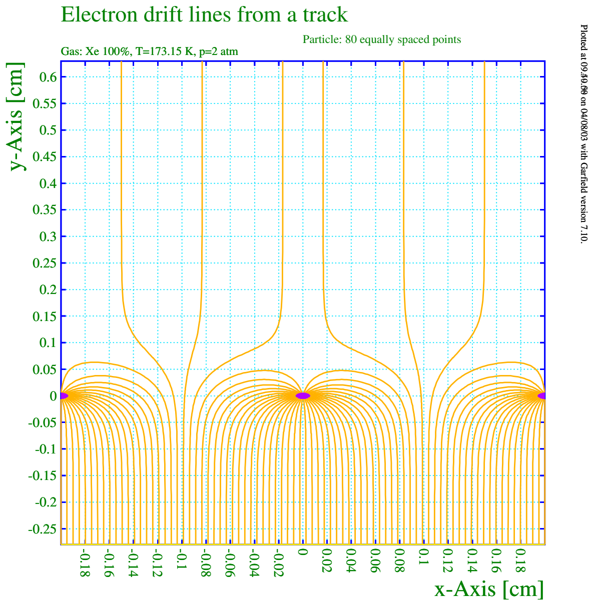

Figure 5: Electron Drift Lines in periodic TPC chamber with wires for the region including three wires

One can very easily see that the electrons emitted from the plane below parallel voltage lines do not hit any of the wires, but instead proceed through the xenon to the PMT cathode. These lost electrons produce approximately a 5 % inefficiency rate of electrons.

With the drift lines tracked I then proceeded to calculate the number of photons emitted by the electron as a function of the electric field and the origination of the electron. I used A.I. Bolozdynya's equation [1] for the emission of photons at high electric fields for my computations. Number of photons N_{ph} is defined as following:

$$N_{ph} = 70[\frac{E}{p} - 1.0]xp \tag{1}$$

where: E is the electric field in kV/cm, p is pressure in torr and x is the drift path in cm. To accurately perform this calculation in the varying electric field I calculated the number of photons emitted for all points along the path.

Interestingly, even though the equation for number of photons is linearly dependent on the length of the path, the electrons which follow the longest path and still strike the wire emit the lowest number of photons since they pass through a low field. The sudden decrease in number of photons emitted for the final seven electrons is because these electrons pass by the wire and so do not pass through the area of the strongest field.

I then was interested in discovering where in the path of the electrons the majority of the photons were emitted, whether this process occurred in the drift field or mostly in the highest field close to the wire. I plotted the fraction of total photons that were emitted as a function of the fraction of the total path for three cases of electrons, two from the extreme points of origin and one from between these two extremes.

For the electron emitted directly under the wire and from a distance x=0.05cm from the wire the emission of electrons was rather linear with only a sharp increase in photon production in the final 10the photons were emitted in the first 90majority. The final electron did not hit the wire and so did not produce interesting results.

I then performed similar calculations for a chamber of the same geometry except with the wires replaced with a mesh. In order to create this electric field I used Maxwell to define the three dimensional space and create the field using FEM, finite element method. I then tracked the paths of one hundred electrons emitted from the area corresponding to one square of the mesh.

Using the same equations for photon emission at high electric fields I calculated the created photons for all positions with a field of 10 kV/cm. The sudden dip on production of photons for the five center

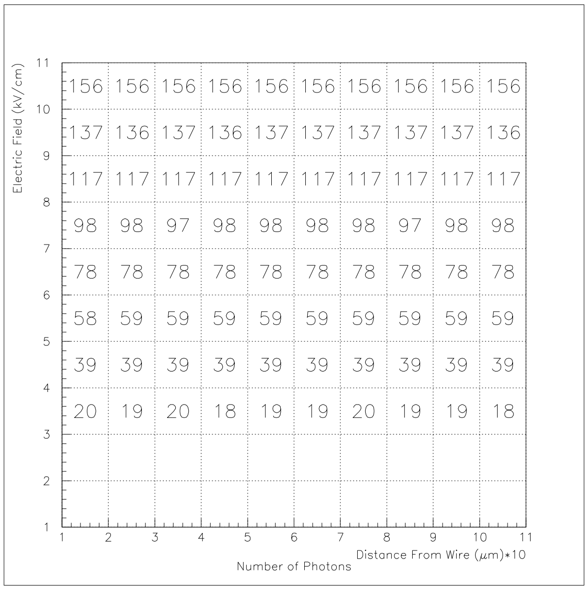

Figure 6: The number of photons created for positions separated by 10 microns from 0 to 100 microns with electric field from 3kV/cm to 10kV/cm

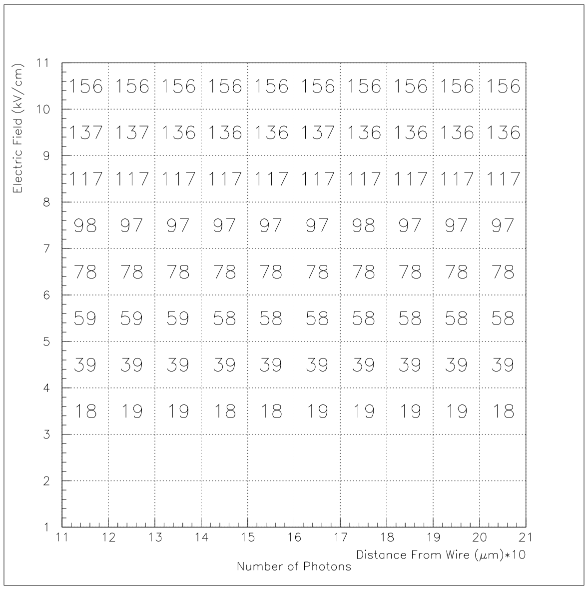

Figure 7: For positions from 100 to 200 microns

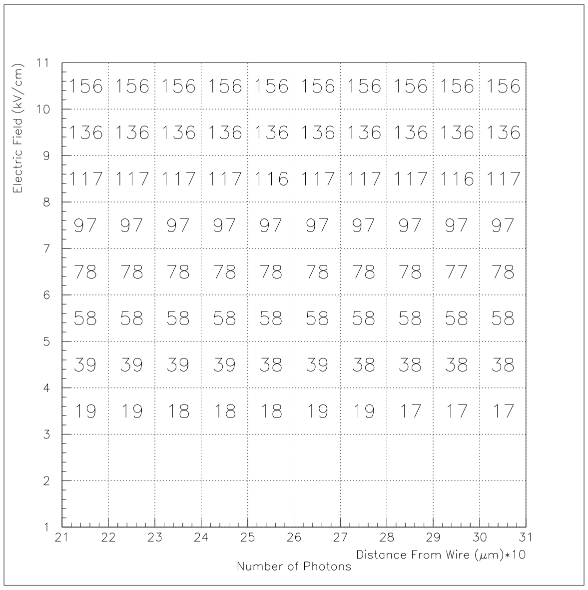

Figure 8: For positions from 200 to 300 microns

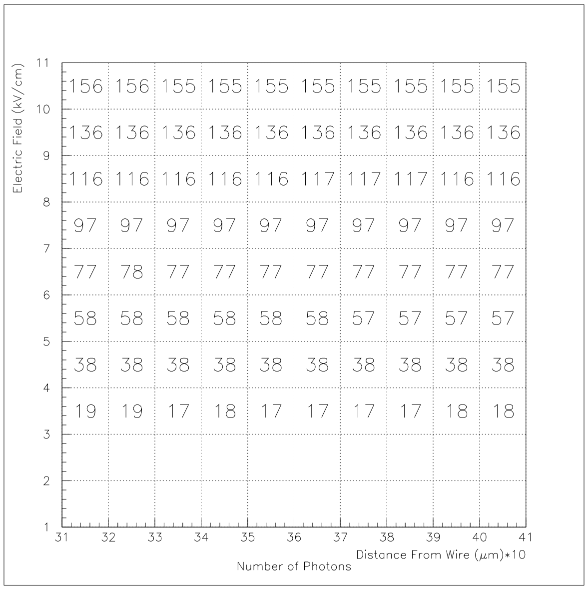

Figure 9: For positions from 300 to 400 microns

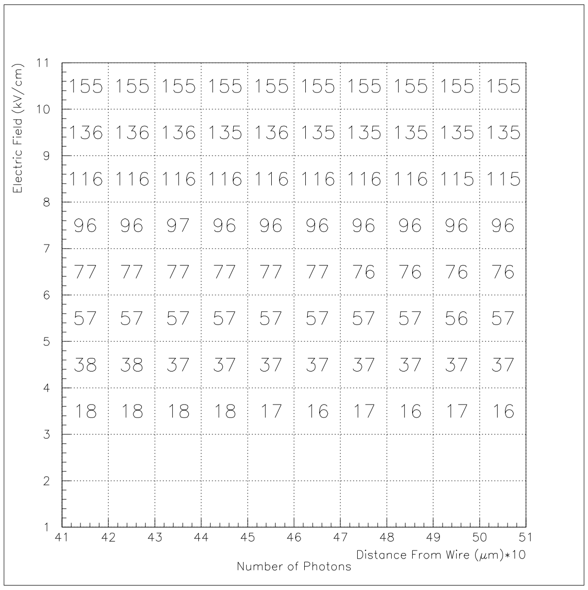

Figure 10: For positions from 400 to 500 microns

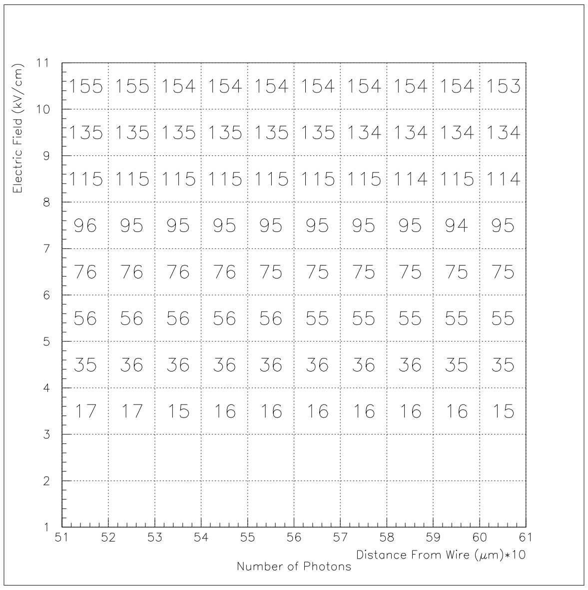

Figure 11: For positions from 500 to 600 microns

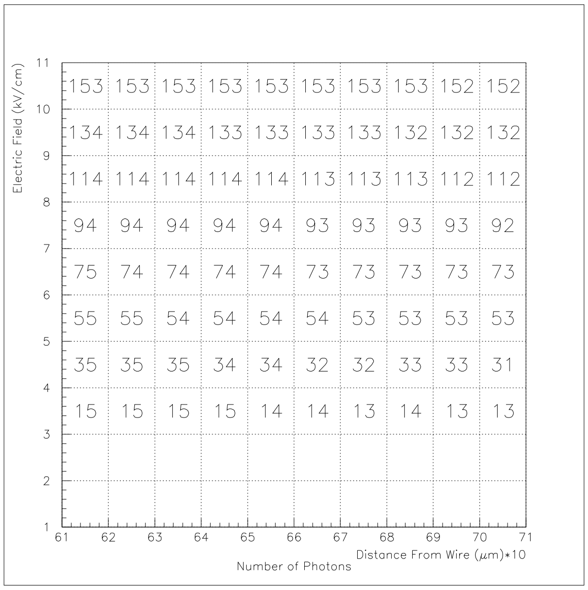

Figure 12: For positions from 600 to 700 microns

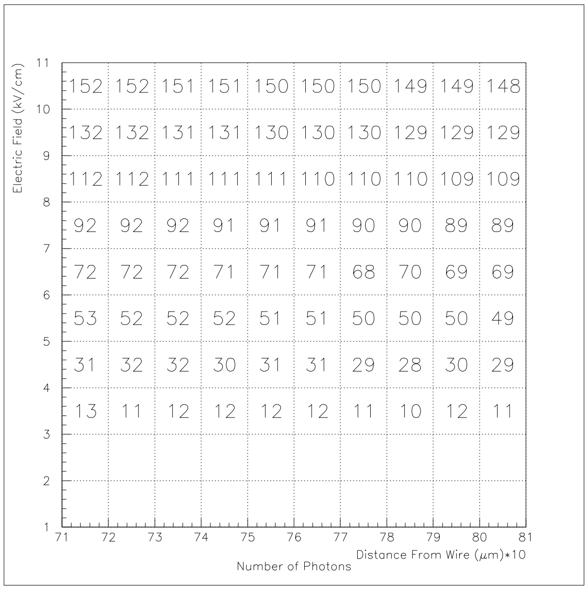

Figure 13: For positions from 700 to 800 microns

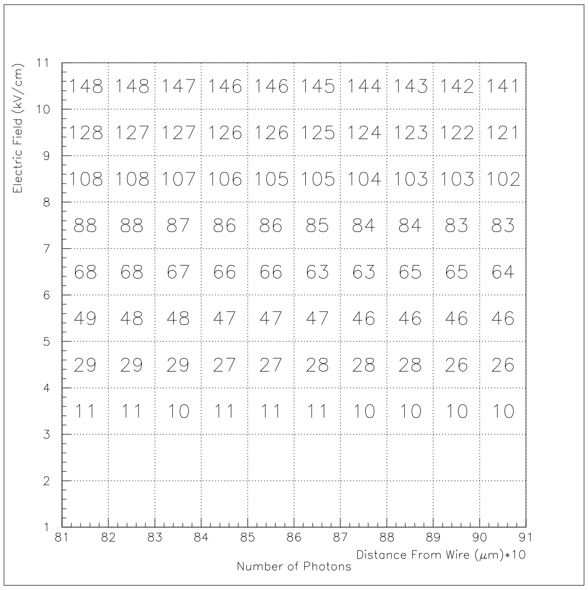

Figure 14: For positions from 800 to 900 microns

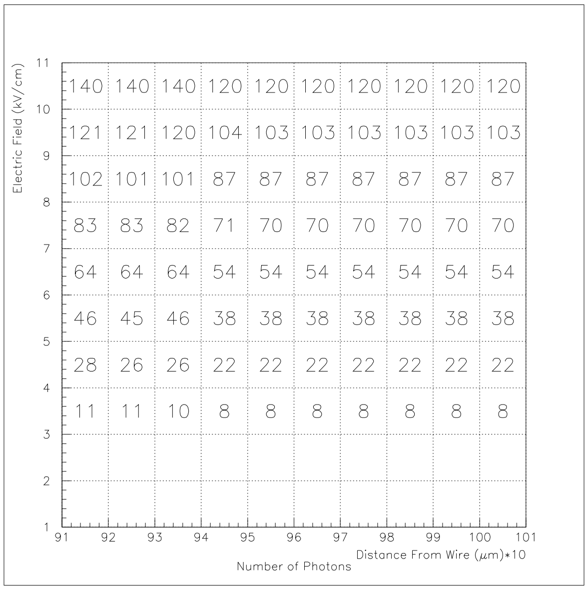

Figure 15: For positions from 900 microns to 1 cm

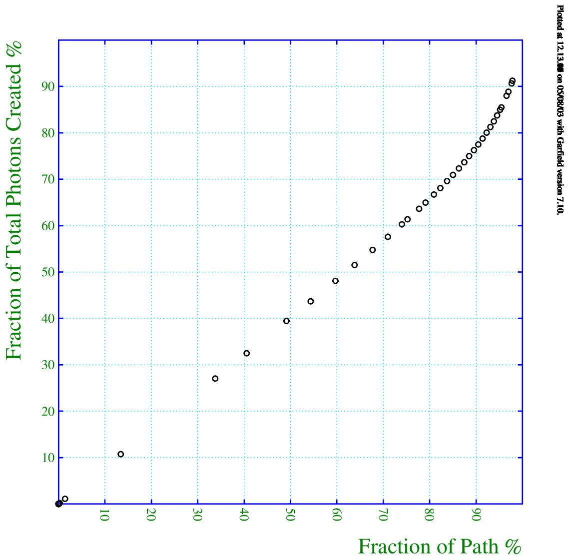

Figure 16: The fraction of total photons created as a function of the fraction of the path for an electron originating directly under wire at x=0

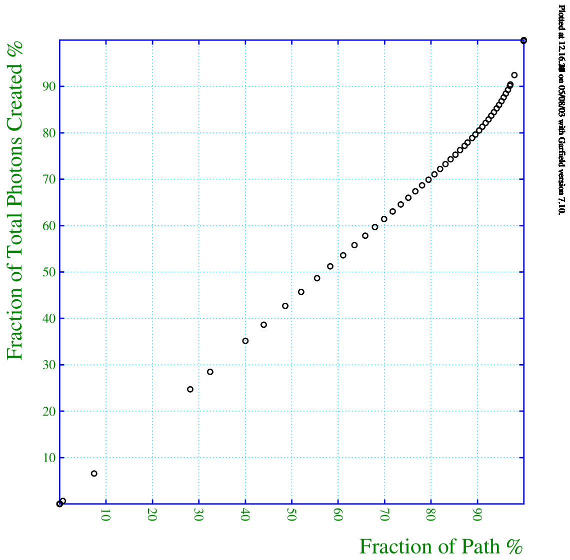

Figure 17: The fraction of total photons created as a function of the fraction of the path for electron originating at x=0.05cm

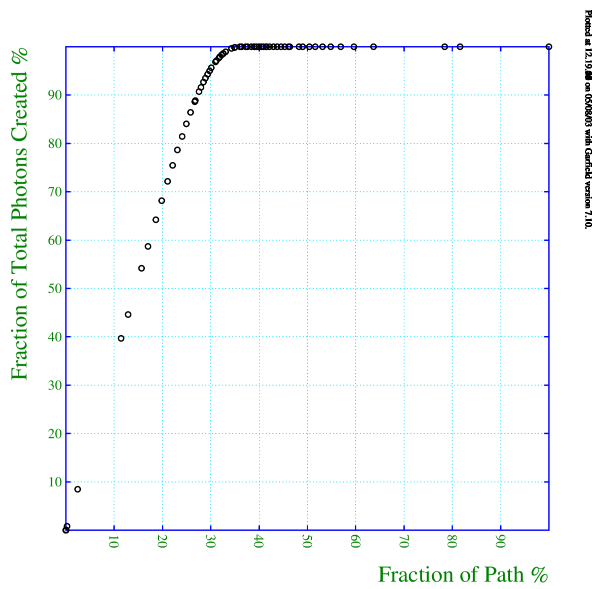

Figure 18: The fraction of total photons created as a function of the fraction of the path for electron originating at x=0.99cm

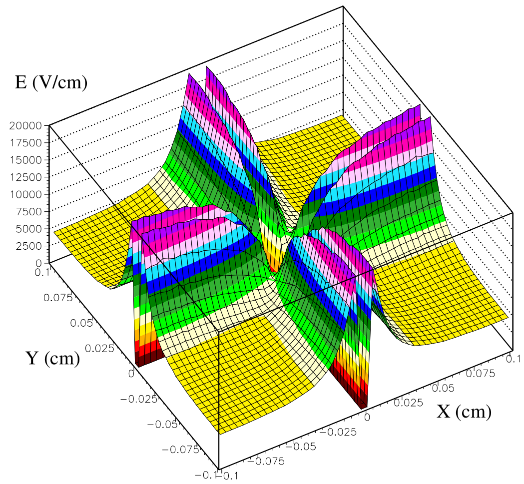

Figure 19: Electric Field in chamber with Mesh for the region around one cross in the mesh

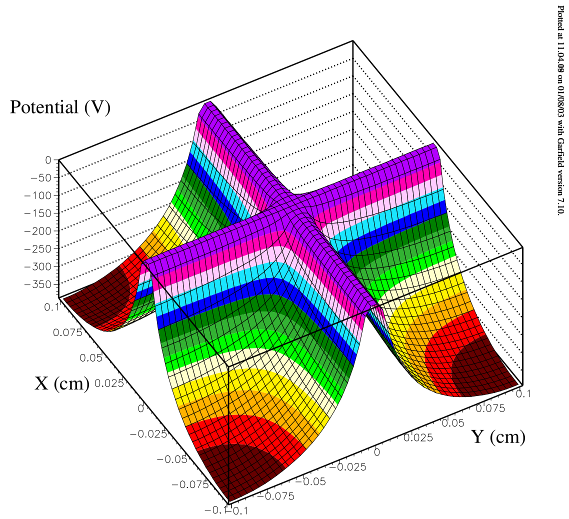

Figure 20: Potential in chamber with mesh for the region around one cross in the mesh

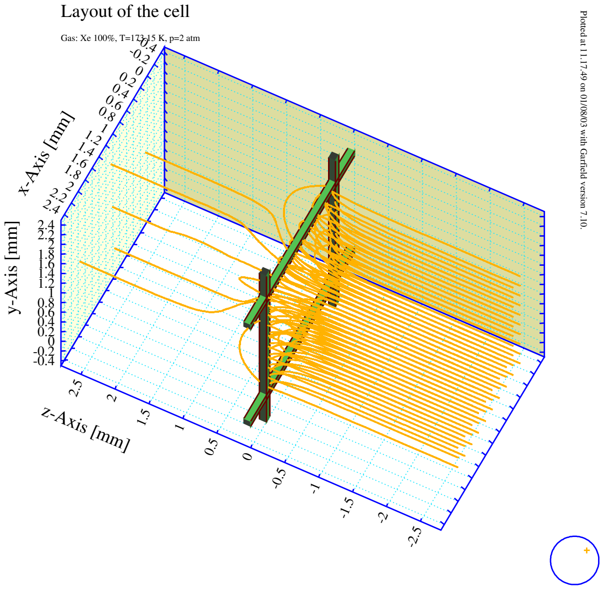

Figure 21: Drift Paths of Electrons in periodic chamber with mesh for one square of the grid

electrons results from these electrons escaping the mesh, otherwise the production is rather uniform.

I analyzed the paths of three electrons- one beginning in the corner, one midway through the first quadrant of the mesh, and one from the center of the mesh, in order to discover where along the path followed by the electrons the photons were emitted.

In the first case where the electron follows a straight path toward the mesh the production of photons is very linear with eighty-five percent of photons created in the first ninety percent of the drift path. One can see that the electric field is rather linear and then has a sharp increase as one approaches the wire.

In the path of the second electron which strikes the mesh the photon creation is as well around eighty-five percent of the photons created on ninety percent of the path. The electric field dips slightly before increasing for this electron as it curved toward the mesh.

This electron misses the mesh completely. One can see the production of photons persists as long as the electron is under the mesh in the high field, but halts as the electron passes into the low field past the mesh. I was also able to use Garfield to discover that no electron multiplication occurs at electric fields ranging from 1 to 10 kV/cm. A successful match to experimentally achieved results.

I would like to continue with the simulation and design testing for the detector with calculations for the efficiency and photon creation with the inclusion of diffusion for Monte Carlo simulations. I would also like to simulate the mean value for both wires and mesh to create a comparison to help determine which structure is superior for the actual detector.

I was able to calculate the inefficiency for wires and mesh to both be about five percent of electrons lost. I determined that the electric field of the mesh is more uniform resulting in a more linear creation of photons. Despite this small improvement the majority of photons were created in the drift field in both the chambers with wires or mesh. In this aspect both wires and mesh are encouraging options and therefore other differences can decide which structure is ideal for the chamber.

References

[1] A.I.Bolozdynaya,
Two-phase emission detectors and their applications
Nucl. Instr. and Meth. A 422 (1999) 314

[2] R. Veenhof,
GARFIELD: simulation program for gaseous detectors.

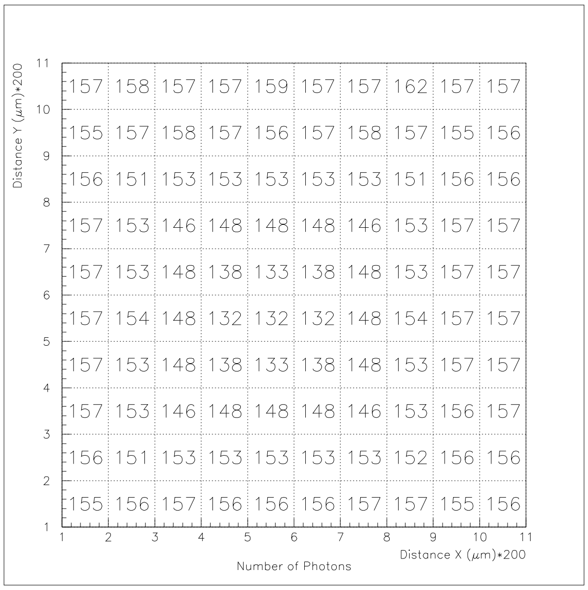

Figure 22: The number of photons emitted along the drift lines of a hundred equally spaced starting positions in the chamber with mesh in text format

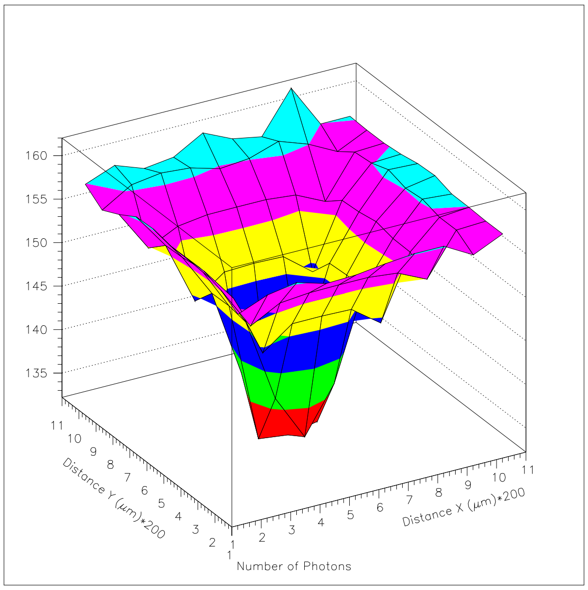

Figure 23: The number of photons emitted along the drift lines of a hundred equally spaced starting positions in the chamber with mesh in a surface plot. The extreme decrease in the center is due to the five electrons which do not strike the grid

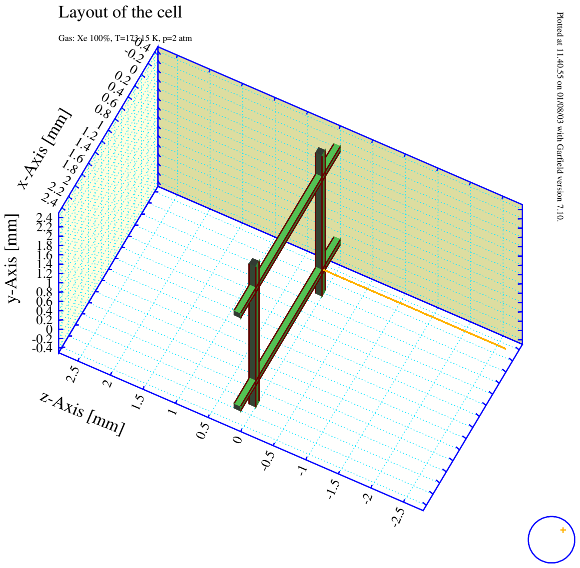

Figure 24: Drift path of one selected electron to analyse the extreme paths

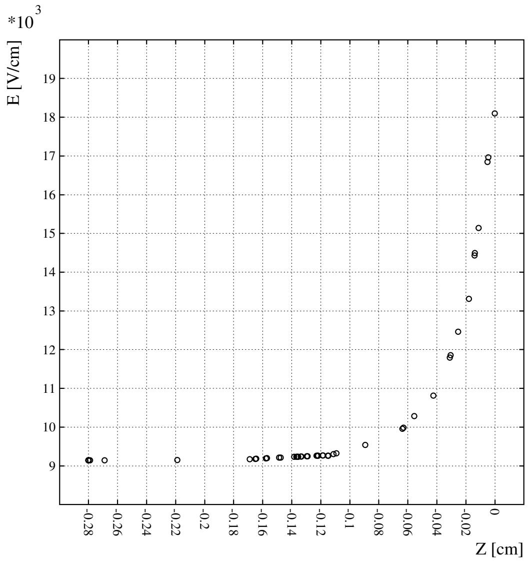

Figure 25: Electric Field as a function of Z along path of electron tracked in figure 24

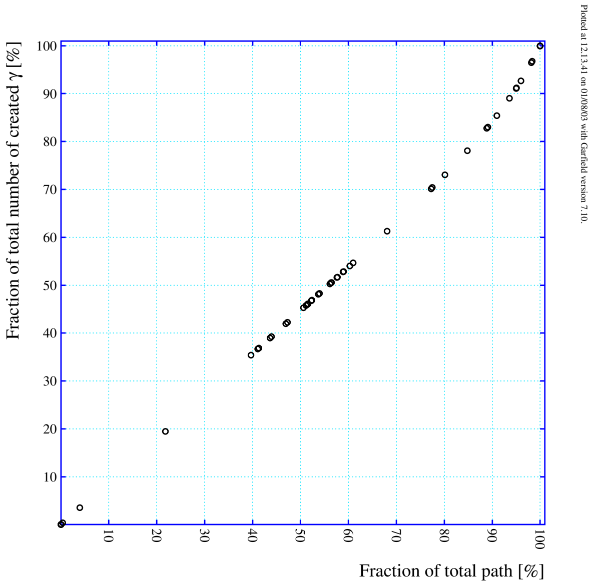

Figure 26: Fraction of total photons emitted as a function of fraction of path of the electron's path tracked in figure 24

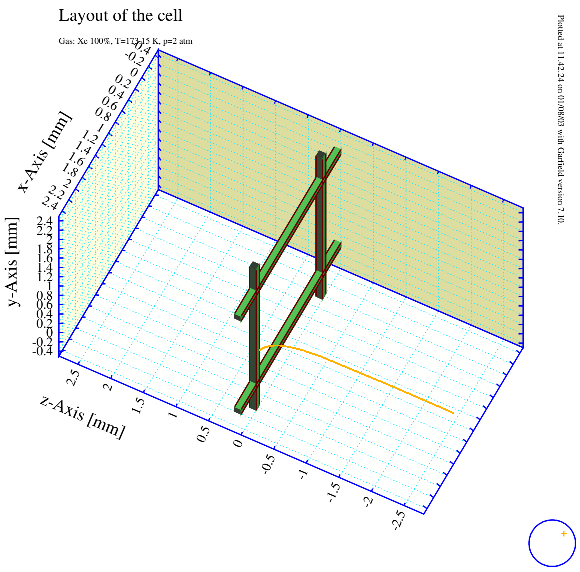

Figure 27: Drift path of one selected electron to analyse the path between the twe extremes

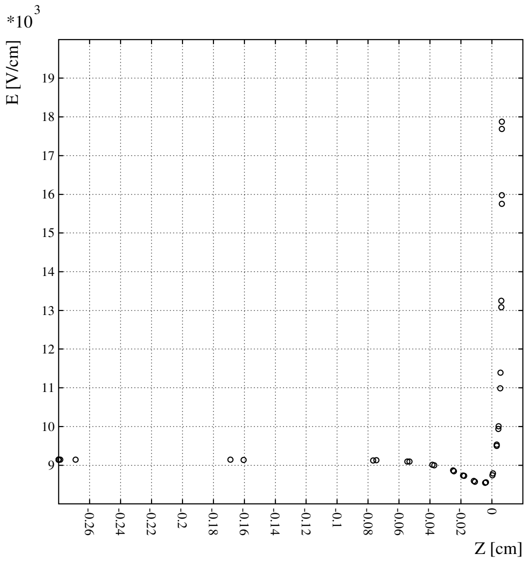

Figure 28: Electric Field as a function of Z as a function of Z along path of electron tracked in figure 27

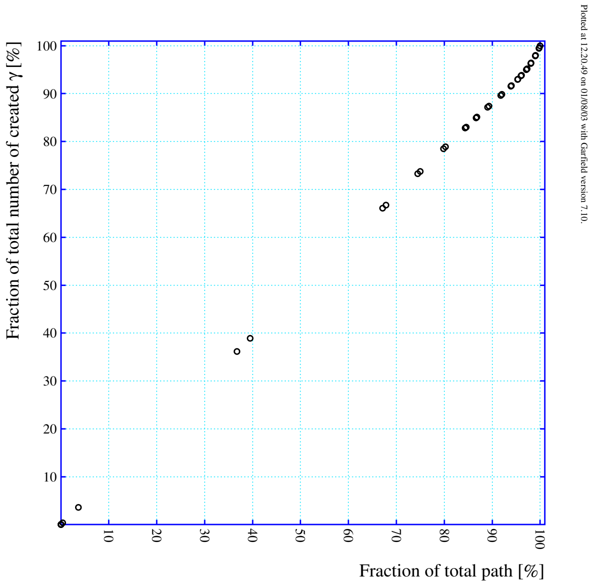

Figure 29: Fraction of total photons emitted as a function of fraction of the electron's path tracked in figure 27

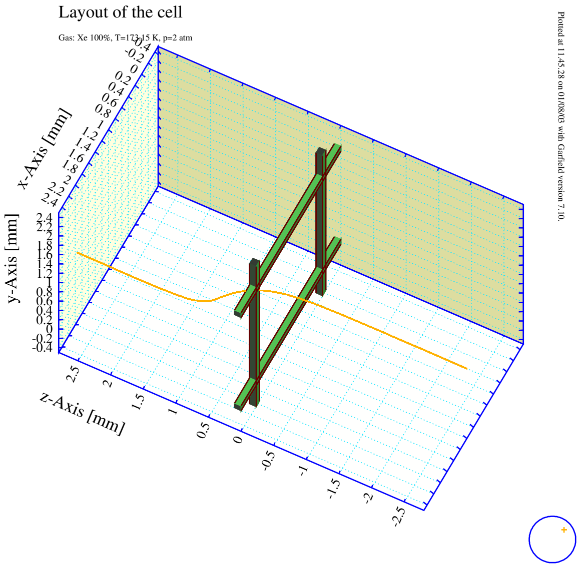

Figure 30: Drift path of one selected electron to analyze the extreme path

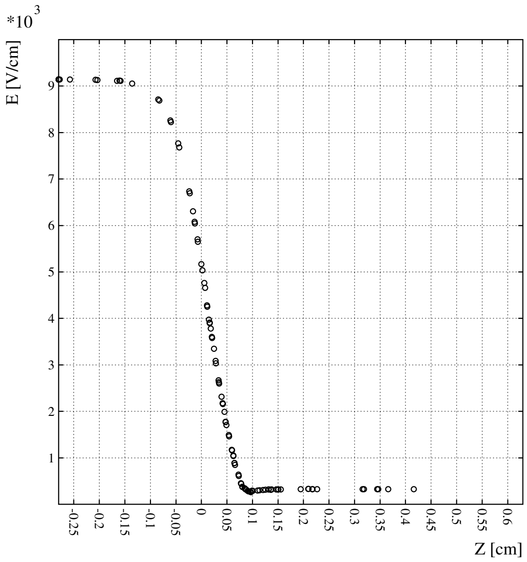

Figure 31: Electric Field as a function of Z as a function of Z along path of electron tracked in figure 30

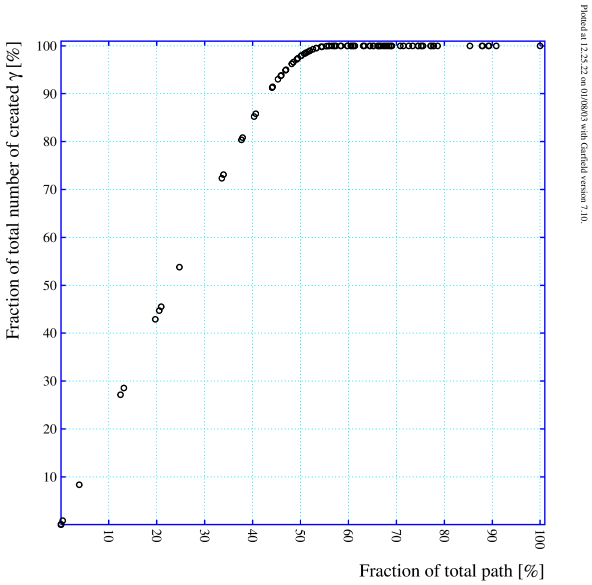

Figure 32: Fraction of total photons emitted as a function of fraction of the electron's path tracked in figure 30

[3] *Maxwell*,
Electric Field Simulator by Ansoft Co. Pittsburg, PA, USA