Summer Student Report

Electroluminescence as an alternative Readout Scheme for a Time Projection Chamber

Done in the TPC group at DESY by

Torsten Hartmann

Supervisor: Klaus Dehmelt

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1 Introduction

Electroluminescence has certain advantages which makes it interesting for the developement of a new readout scheme in a Time Projection Chamber (TPC). The most important point is, that this process has the potential to avoid secondary ionization at the detector of a TPC.

During the summmer student program 2010 the process of electroluminescence was investigated through a Geant4 simulation. A TPC geometry, like it will most likely be implemented in the International Linear Colider (ILC), is used for the simulation. First results can be seen as a proof of principle that an investigation of the electroluminescence inside a TPC can be done by Geant4 based simulations.

2 Main concept of a Time Projection Chamber

In principle a Time Projection Chamber (TPC) is a large cylinder filled with a noble gas and a certain fraction of buffergas. If a particle passes the gasvolume, it ionizes the gas and leaves ions and electrons along its path through the TPC. Typically around one hundred electrons (for an argon gas filled chamber and particle energies around 6 GeV) are produced per centimeter due to primary ionization. The electrons now are getting accelerated due to an electric field applied between the endcaps of the cylindrical TPC volume (see picture 2.1).

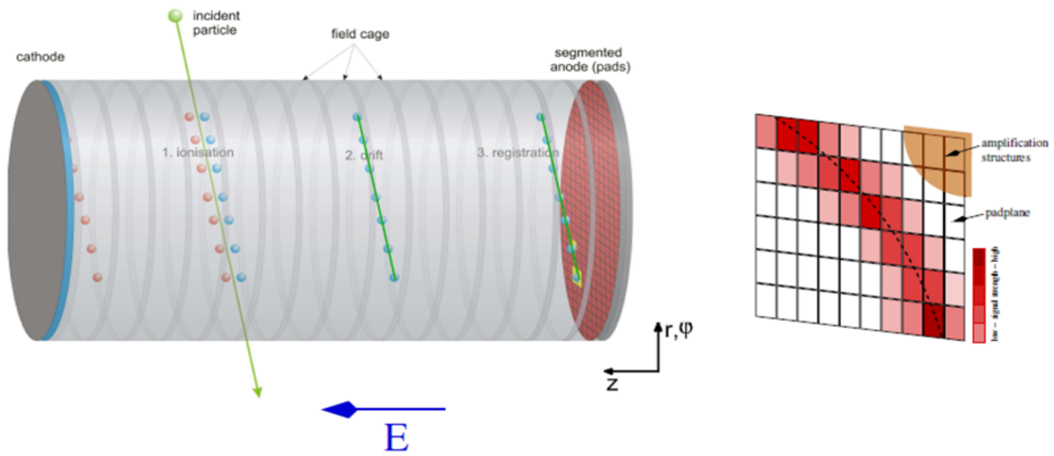


Figure 2.1: Schematical picture of a Time Projection Chamber. The smaller right image shows a cut-out of the detector surface.

The electrons drift towards the anode. At the anonde there is also the detection electronic. The electrons produce a signal on the detector depending on where they hit it. Due to this, the position of the track in the chamber is already determined in two dimensions. To get the last coordinate, one uses the fact, that one knows the time of flight of the electrons which is just the moment between the interaction and the moment of detection of the electron. In edition one can calculate the driftvelocity of the electrons in the TPC gas. With all these information one gets the missing coordinate and has now a three dimensional image of the track in the TPC.

To detect the incomming electrons they have to be avalanched. There are different ways to do this, and the detection afterwards. One way is to use GEMs (Gas Electron Multipliers) another to use MicroMegas (MICRO MEsh GAseous Structures).However, independent of the way how the avalanche happens, normaly one electron produces some tenthousend secondary electrons near the detector. The electrons will be detected on the readout plane. The ions in contrairy will have to drift back to the cathode.

3 Problem of secondary ionization

The ions inside the TPC can cause problems and in the end could lead to a reduction in the spacial resolution of the detection.

Due to the primary ionization of the gas inside the TPC, besides the electrons, which shall be detected, there will also be ions produced. The ions are much heavier then the electrons and because of that will drift much slower towards the cathode. This leads to the fact that there will always be a certain amount of electrons inside the TPC. With respect to the fact, that each primary particle will produce arround 40000 primary electrons along its track (for a track length of 4 m and around 100 ionizations per centimeter), this is a rather small amount of ions compared to the neutral atoms in the TPC. So, besides the fact that one cannot avoid these primary ions, they will on the other hand also not desturbe the measurements in a recognizable way.

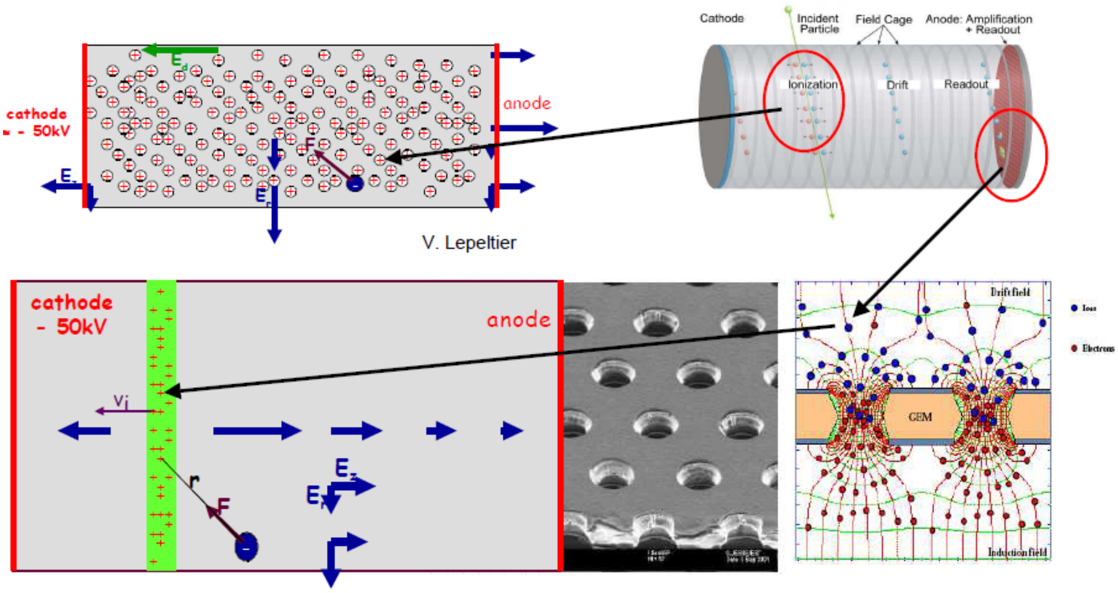


Figure 3.1: Primary and secondary ion generation inside a TPC. The secondary ions are generated due to the avalanche process of the incoming electrons. The avalanche takes place at the detector unit (down right pictures).

For the ions, which are produced during the avalanche near the anode, this is different. Each electron will produce itself around 3000 secondary electrons and so, also ions. So there will now be 3000*100 ions per centimeter track length produced close to the anode.

These ions in additon will have to drift a far distance before they will reach the cathode (see Figure 3.1). Due to this, one can say, that for each detected interaction in a collider there will be a disc of high ion density produced at the anode. In Figure 3.2 the possible bunch structur of the ILC is shown. Each 200 ms there is a bunchtrain of particles coliding and so also an iondisc will be produced. Because the bunches in one bunchtrain are only separeted by around 370 ns the ions of one bunchtrain will accumulate at the anode. Between two bunchtrains there is a time gap of 199 ms. For ions in argon this means that they will drift in this time around 80 cm far. One can estimate that for a TPC of 240 cm length there will be around 3 ion discs inside the TPC at the same time. This may urgely disturb the electormagnetic field inside the TPC, which is wanted to be as homogeneous as possible. This again will now possibly lead to a lower reachable track resolution.

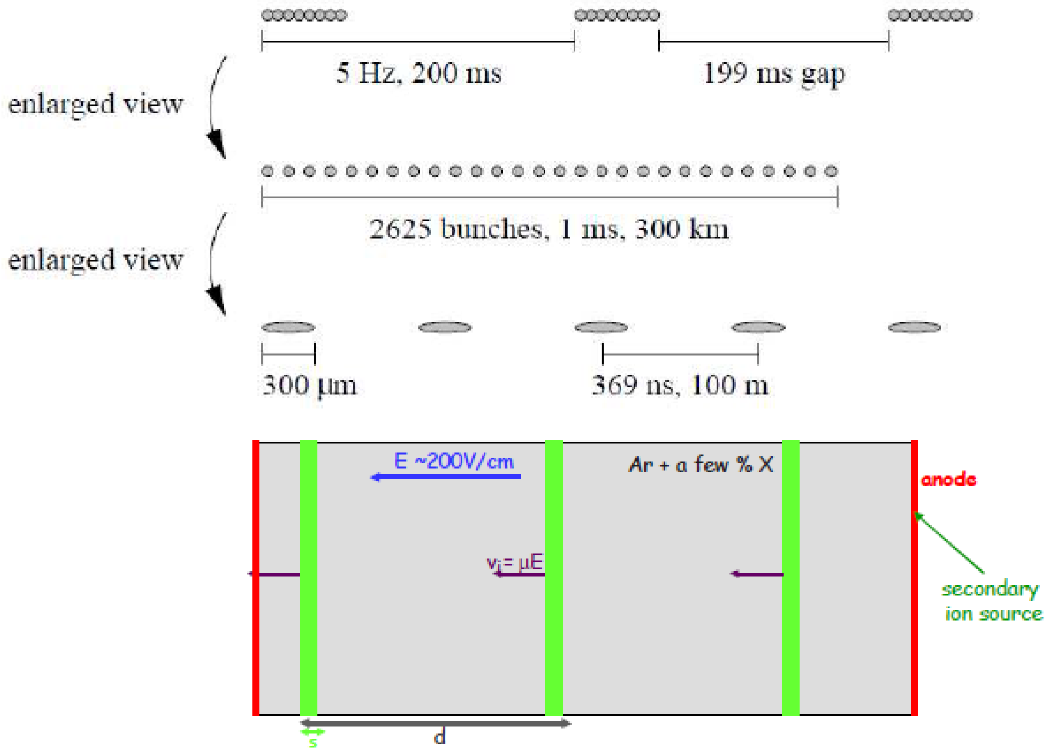


Figure 3.2: Schematical image of the bunch structure how it is planed for the ILC. The lower picture shows the ion discs which propagates through the TPC.

4 Main idea of electroluminescence

To avoid a disturbance of the electromagnetic field inside the TPC one has to get rid of the ion discs. The first idea could be to decrease the length of the TPC so that it is shorter than the gap between two ion discs. This would mean that the ion disc produced by the first bunchtrain is already absorbed at the cathod before the second bunchtrain will lead to new interactions. But it will also crucially limit the number of tracks one could detect with the TPC. One also could try to use another gas except of argon which has a higher mobility for electrons and ions. But this would also increase the difusion of the electrons and so would decrease the resolution. Same would be with increasing the electric fieldstrenght. In the end one could think about a gating device which would close the detector after the avalanche and absorb the ions. But the switching would have to be very fast and also this methode would mean additional material inside the TPC, which one always tries to avoid.

An other way has yet not been investigated in total. It would mean to use electroluminescence which would lead to a significant decrease of the ions near the detector [MB10]. The electroluminescence process in a noble gas is mostly due to the following reaction:

radiative de-excitation of excited molecules

$$Ar_2^* \rightarrow 2Ar + h\upsilon$$

where Ar^*_2 is mainly formed through a three body collision

$$Ar^* + 2Ar \rightarrow Ar_2^* + Ar$$

Figure 4.1: Process of electroluminescence for the example of argon gas.

So it is a de-exitation process of noble gas molecules which are produced due to a three body collision inside the noble gas. The exited gas atoms are produced by inelastic scattering of high energy electrons (see also [CM] and [MB10]).

The emitted light is in the VUV-Region (see 4.2). The number of photons is over a wide range proportional to the electric field strength (see figure 4.2). This is why electroluminescence is also known as proportional scintillation. In figure 4.2 the same messurement was done by several groups. The unexpected different slopes might be due to different amounts of impureties inside the messured xenon gas. As shown in figure 4.2 some impureties have absorption bands close to the emmited VUV photons. So, many of these photons will be absorpt by the impureties, leading to a lower photon gain for a certain electric field strength. At some point when the applied electric field is to high, one leaves the region of proportionality, as also can be seen in figure 4.2. In this region the electrons in addition ionize the gas and the secondary electrons participate in the process of electroluminescence. The idea of using the electroluminescence is now, that the primary, by the incoming particle generated electrons will be accelerated inside the detectorstructure. The detector will consist of a small gas volume where the acceleration takes place and where the electrons will produce VUV-photons. These photons then will be detected by a readout structure at the very end of the detector (for more details see [MB10]). This would mean that one would do an optical avalanche and that one will produce much less ions than with the other ways of detection. Of course one will have to be careful not to reach to high field strength in the acceleration region because then one would again generate ions near the anode. As mentioned above, the use of Electroluminescence as detection method is not completly investigated yet.

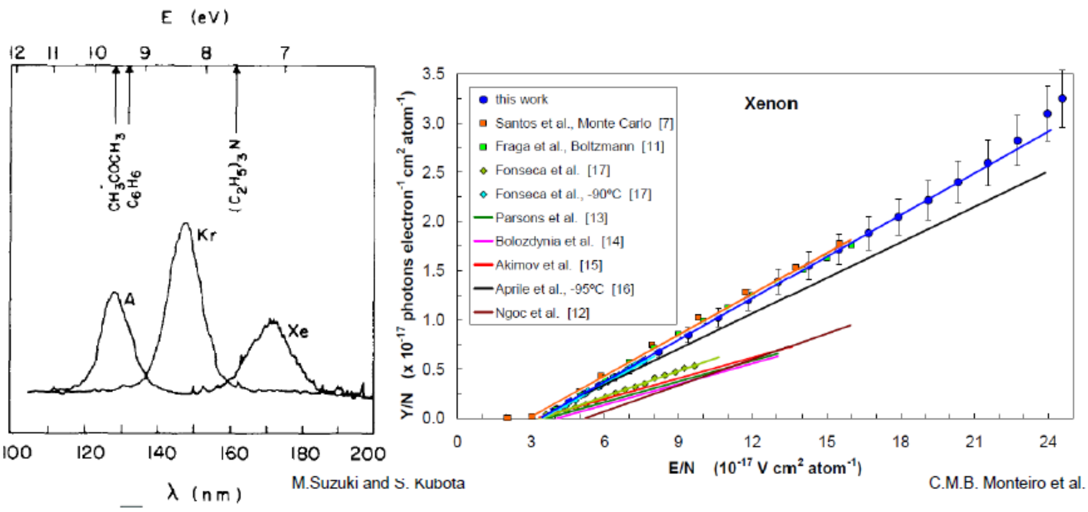


Figure 4.2: The left picture shows the energy and wavelength range of the electroluminescence photons emitted by the stated noble gases. The right graph shows messurements concerning the photon yield inside xenon in an electroluminescence process. [Cha], [CM]

5 Summer student project

The goal for the summer student work was to set up a simulation of the electroluminescence process inside a TPC detector.

5.1 Simulations with Geant4

The work is based on Geant4 (Geometry and Tracking, Version 4), which is a powerful C++ based simulation tool, developed at CERN and frequently used in HEP physics, e.g. for the simulation of the ATLAS detector. Geant4 allows you to define your own detector geometry, to generate primary particles and to apply various physical processes to these primary and the eventually produced daughter particles. Many processes, such as for example the description of multiple scattering, are already implemented in the common libraries of Geant4. For the electorluminescence process thought, there is no implemented library. It exits an external code, which was written by H. Araújo for the ZepIII-prototype in which the process of electroluminescence is described for the Zepline geometry [HA06]. The main task was to get these process implemented in a simulation of a TPC like it will be used in the ILC and to modify it in the way that it works correctly for this type of geometry.

5.2 Performed steps

First it was necessary to define the wanted detector geometry. The geometry is a describtion of the Large Prototype which is already build and which is a realization of the TPC as it shall be installed inside the ILC detector. Against its name the prototype is still much smaller then the TPC will be, thought. The TPC-Large-Protoype (in the following just TPCLP) has a length of 60 cm and an outer radius of around 40 cm. During the definition of the geometry one has to define all the materials which are inside the geometry. For the case of the simulated TPCLP, the wall structure is simulated in much detail to make it compatible to the one of the real Large Prototype. The gas inside the TPC is defined as pure xenon. This is because the work of H. Araújo is based on xenon gas and so all the needed parameters for the simulation were directly accessable. The gas volume inside the TPC is split into two parts. One part with a length of 59 cm and another with a length of 1 cm. The electric fields which are simulated differ inside the two gas regions. Inside the bigger volume, the drift volume, an electric field strenght of $1\,\frac{\mathrm{kV}}{\mathrm{cm}}$ is defined. In the smaller region, the scintillation region, it is $5\,\frac{\mathrm{kV}}{\mathrm{cm}}$. This deveation is done because for the case of a real electroluminescence detector scheme there will be only a small gas region in which the electrons will be accelerated enough to cause electroluminescence. Figure 5.1 shows the defined geometry as it is displayed by Geant4.

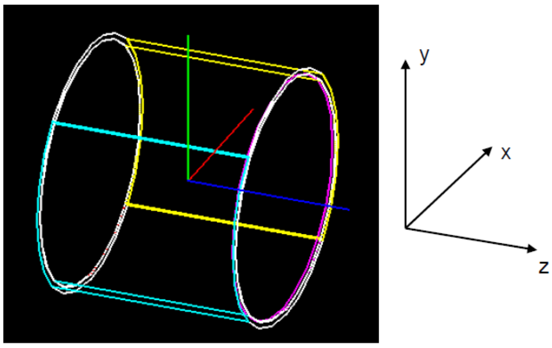


Figure 5.1: Defined detector geometry as it is displayed by Geant4.

The next step is to give the program a primary event. This was done with a particle gun, which shoots 6 GeV electrons parallel to the x-axis through the TPC (see figure 5.2).

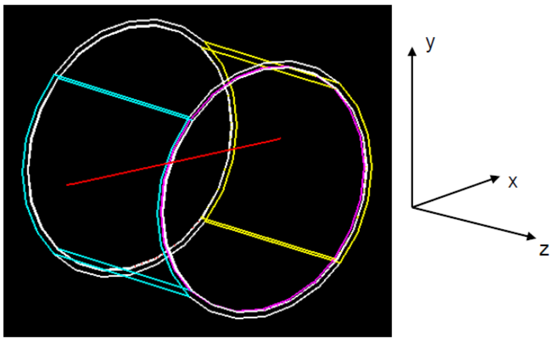


Figure 5.2: Detector and primary particle (a 6 GeV electron, red line).

But with only primary particles there are no interactions simulated. This will only be done when the wanted physical processes are implemented in the so called physics list of the simulation. There one can define for each expected particle all the wanted physical processes. For example one will expect an electron to do multiple scattering, ionization and to produce Bremsstrahlung. So all these processes have to be implemented in the physics list of the simulation. Luckily Geant4 has for all these processes inbuild libraries. Picture 5.3 shows a simulation in which five 6 GeV electrons passed the TPC parallel to the x-axis. One can see some tracks from secondary particles which have been generated by the electrons.

But there exists no library for the Electroluminescence. So these process had to be implemented from the external.

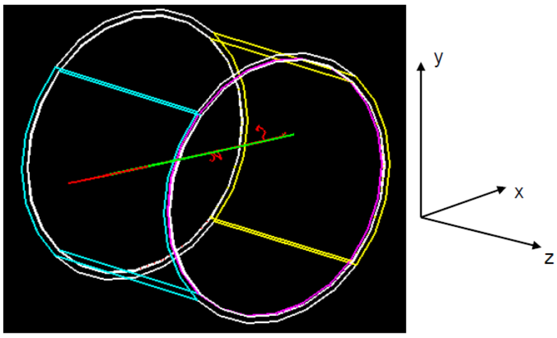
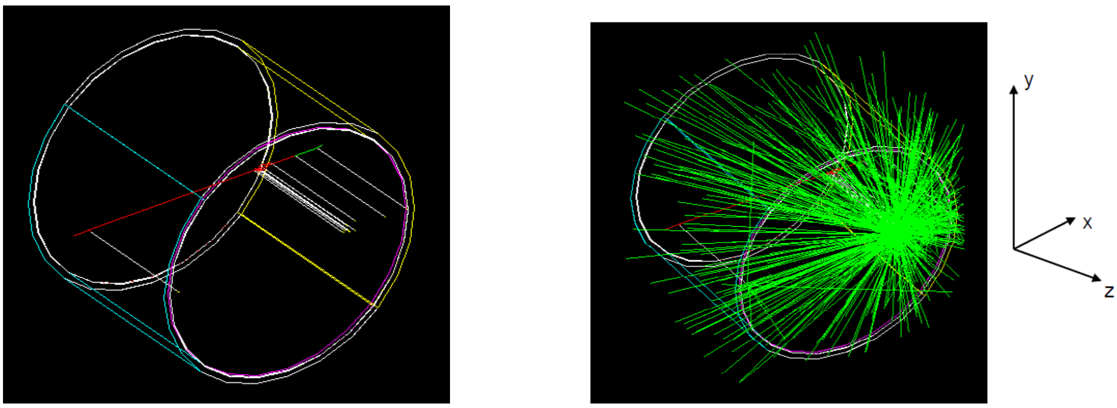


Figure 5.3: Detector crossed by primary particle (a 6 GeV electron). Also visible are secondary charged particles produced due to ionization of the xenon gas.

During the summer student time the electroluminescence process was successfully implemented in the detector simulation. It now generates electrons along the tracks of the primary particles. These electrons are transported through the gasvolume which represents the drift region of the TPC and they cause electroluminescence photons when they reach the second logical gas volume which represents the scintillation region near the detector plane. The interesting data, namely the position and momentum of the optical photons can be stored in a data file for postsimulation analysis.

Figure 5.4 shows the simulated electroluminescence. In (a) the electrons are shown, which are generated along the track and then drifted towards the anode. In (b) one can see also the optical photons. They are only genereted inside the second logical gas volume.



(a) **(b)**

Figure 5.4: The left picture shows the electrons which are drifted by the electroluminescence process towards the anode (white lines). The right picture displays the in the scintilation region produced electroluminescence photons (green lines) generated by only one primary 6 GeV electron.

5.3 Results

As a result a first investigation of the optical photons produced by electroluminescene was done. In figure 5.5 a histogram of the photons which penetrated the anode plane is shown. These electrons are stated as detectable, because in the end the detector will be placed shortly above the anode. The simulation was done with 1000 6 GeV electrons which were crossing the TPC volume parallel to the x-axis. They generated 299043 photons inside the scintillation region. The photons have an energy of around 7 eV which is just the energy one would expect for proportional scintilation in xenon (see also figure 4.2). 126123 of the produced photons penetrated the anode plane and are thus stated as detectable. This means that each primary particle produced in this simulation around 300 photons of which around 42% are detectable. As one can see from the histogram most of the photons are generated around $y = 0$, which means that they display well the track of the primary particle. Some photons nevertheless penetrate the anode far away from $y = 0$. This can for example mean, that they have been caused by a secondary charged particle which has been generated due to ionization of the gas.

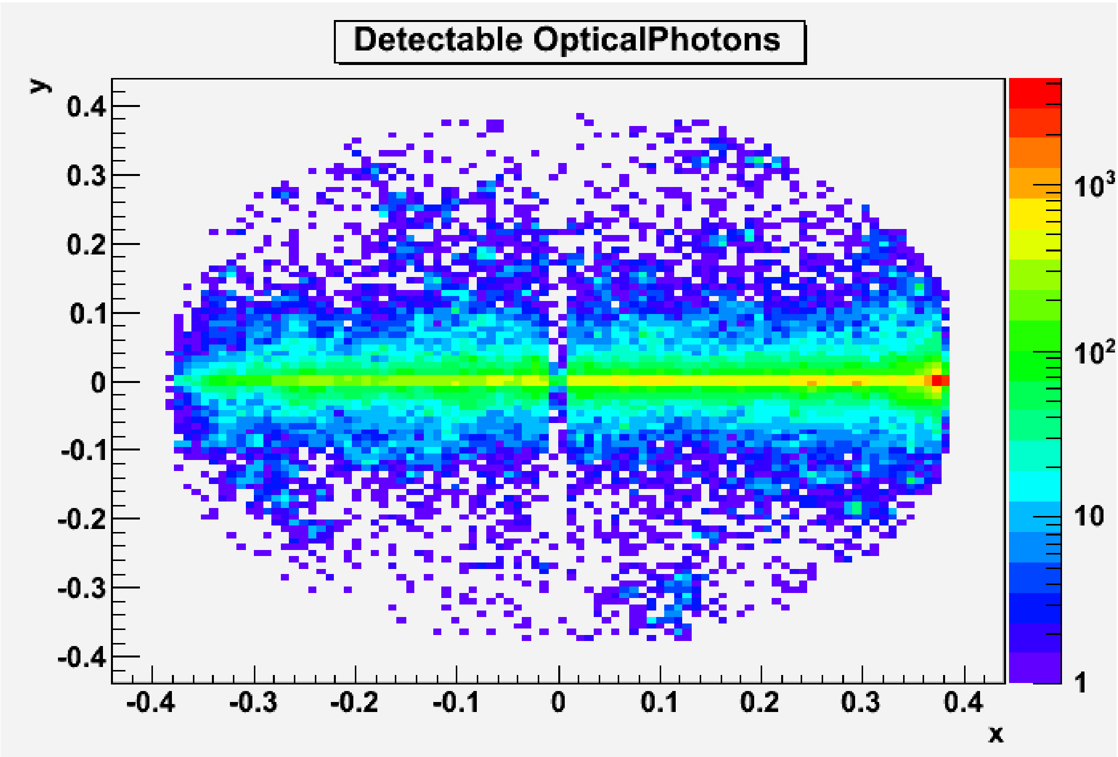


Figure 5.5: The histogram shows all electroluminescence photons which penetrated the anode plane. The histogram was generated from 1000 primary 6 GeV electrons which passed the detector volume parallel to the x-axis. 299043 photons have been produced, 126123 of them penetrated the anode plane and are therefore stated as detectable.

5.4 Outlook

What one has to be aware of is, that the investigation is not yet according to true physical processes. First of all the gas inside the TPC is taken to be xenon. In the real TPC of the ILC argon will be used insted. So one should change the gas in the simulation. Then, of course, one however needs to know the parameters for the yields inside argon. Second, the process of primary ionization is not well described in Geant4. It would lead to better results if one would simulate the generation of primary electrons, for example in the way of just randomly distribute around one hundred electrons per centimeter along the track of the primary particle and then use these electrons for the electroluminescence process. Then, the transportation from the point of generation through the drift and afterwards through the scintillation volume is at the moment not perfectly described, as there is just a straight transportation towards the anode. Nevertheless the code already gives the possiblity to load a fieldmap which describes the electric field inside the TPC. If one would implement such a fieldmap, the transportation of the electrons would be better simulated. Also up to now there is no reflection inside the TPC. As one could imagine, photons which are emitted away from the anode could still penetrate it when they are reflected from the TPC inner walls. This would lead to signals which are not longer directly related to the track. Coming to the detector geometry one could implement a readout structur as it would be used in a real TPC and which detects the electroluminescence photons to reconstruct the track. Then one could also implement the yields of such a readout structur, leading to a full simulation of the electroluminescence process and then to the possiblity to say with a good amount of certainty, whether or not the process of electroluminescence could be an alternative to the todays readout structures in TPCs.

6 Credits

I would like to use the opportunity to thank some people which in the one way or the other supported my work at DESY.

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I also want to thank the rest of the FLC- and TPC-group members for the nice working atmosphere.

Last but not least I want to thank my roommates at the DESY-hostel Frederik, Magnus and Mohamed for the nice time.

Bibliography

[Cha] Charpak, G.: Emission and Absorption of Photons in gaseous detectors

[CM] C.M.B. Monteiro, J.A.M. Lopes L.C.C. Coelho J.F.C.A. Veloso J.M.F. dos Santos K. Giboni E. Aprile, L.M.P. Fernandes: Secondary Scintillation Yield in Pure Xenon

[HA06] H.M. Araújo, et. al.: The ZEPLIN-III dark matter detector: Performance study using an end-to-end simulation tool. *Astroparticle Physics 26* (2006)

[MB10] Markus Ball, Jochen Kaminski Thorsten Lux, Philip Bechtle: A common proposal for an electroluminescence TPC and tracking calorimeter (2010)