GEM Simulation Studies

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Abstract

This report resumes the work as a Summer Student at Desy in 2011 in the group FLC (Research with Lepton Colliders) more precisely in the subgroup TPC (Time Porjection Chamber). I performed simulations of the propagation and interactions of electrons and ions in Gas Electron Multipliers (GEMs) with the Garfield++ code. The aim was to understand the functions provided by Garfield and to find values for the gain and the ion-Backdrift in order to optimise the GEMs configuration.

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1 Introduction

1.1 International Linear Collider

The aim of the ILC is to measure particles that are not part of the standard model, hence the need to reach higher energy scales with every new generation of colliders. Hadron and lepton colliders contribute equally to the understanding of particle physics. hadron colliders like the LHC are used as discovery machines. They can reach a higher centre of mass energy in comparison to lepton colliders. The loss of energy due to synchrotron radiation is smaller for particles with higher masses.
However precision measurements are difficult with a hadron collider. The initial states are not well enough known as hadrons are composite particles whose constituents have different energies. Therefore the center of mass energy is not fixed in each collision and the final states are often very confusing and hard to analyse.
However Electron-Positron-Colliders can measure the properties of discovered particles with a high precision. The initial states are exactly defined by their quantum numbers and energies etc. All hadronic final states have clear signatures. Furthermore it is possible to polarise the electrons or positrons. That allows to increase or suppress the cross section of weak interactions[1].
The last exempler of Electron-Positron-Colliders was LEP (Large Electron Positron Collider) which is a 27 km circumference circular collider built at CERN with a maximal centre of mass energy of 209 GeV. It was shut down in 2000.
To increase the energy in e^--e^+-collisions above the level of LEP a circular shaped collider cannot be used any more. This is because of the loss of energy of the particles during each circulation due to synchrotron radiation. The energy difference per circulation can be described by:

$$\Delta E_{syn} \sim \frac{E^4}{R \cdot m^4} \tag{1}$$

While the loss increases with the fourth power of the beam energy, it decreases only linearly with the colliders radius. Therefore, to reach an energy of 500 GeV with the next Electron-Positron-Collider it would need to have a circumference of 500 km and still loose an energy of 12 GeV during each circulation. This would cost of 15 billion Euros (for LEP it was 2 billion Euros) and hence is not feasible. However using a linear collider of 15 km in length, the same energy scale could be reached. Hence the next Electron-Positron-collider has to be a linear collider.

One project for such a linear e^+-e^--collider is the Internation Linear Collider (ILC). It will have a centre of mass energy of 200-500 GeV. One aims to obtain an integrated luminosity of $\int L dt = 500\,\mathrm{fb}^{-1}$ over the first four years. Figure 1 shows the future design of the ILC.

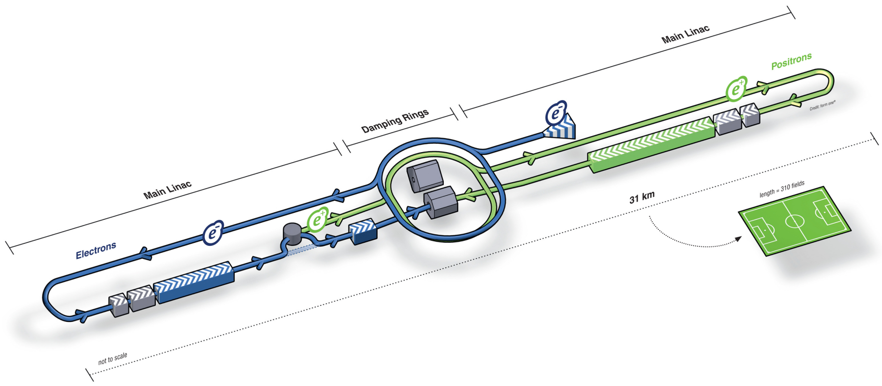


Figure 1: The design of the International Linear Collider

1.2 International Large Detector

To be able to investigate the Higgs-mechanism at the ILC in detail, detectors that are able to perform high precision measurements are needed. Two detectors will be constructed in order to compare the results. One of these detectors is the International Large Detector (ILD), Figure 2 shows a sketch.
The beam axis is surrounded by the vertex detector which itself is enclosed by a Time Projection Chamber (TPC). A TPC will be used as main tracking system. Around the TPC the electromagnetic calorimeter, the hadronic calorimeter and the magnet coil are built. The magnetic field will induce a bending of the charged particle tracks which will be seen in the TPC. From the bending the particles momentum can be calculated.
And finally the muon detector being the outer shell of the detector because of the low cross section of muons.

1.2.1 Time Projection Chamber

The idea of TPCs came about in the 1970s, the great advantage of this device is that one is able to record charged particle trajectories in 3D.
In the ILD, a TPC will be used as the main tracking device. It will have a length of $L = 4.3\,\mathrm{m}$ and a diameter of $\o = 3.6\,\mathrm{m}$. Figure 3 shows the sketch of the TPC.
The detection volume is a gas filled cylinder. When a charged particles enters into the volume it ionises the gas. The produced electrons drift under the influence of an electric field (drift field) towards the anode. This field is of the order of $100\,\mathrm{V/cm}$. The signal of the initial electrons wouldn't be high enough to reach over the threshold of the anode, therefore an amplification is necessary which will be explained in 2.1. The amplified signal is detected by the anode. Due to the segmentation of the anode it is possible to determine the coordinates of the track in x and y. To have access to the z coordinate

[1]The Weak Force only couples to left handed particles respectively right handed Anti-particles.

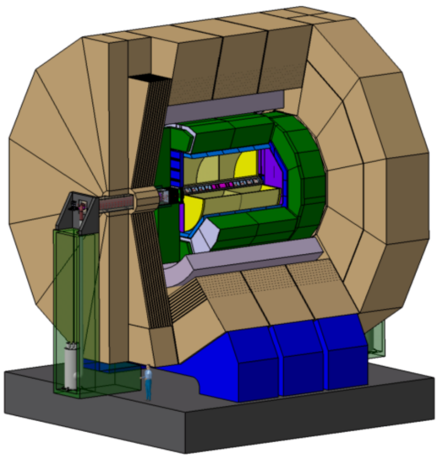


Figure 2: Scheme of the International Large Detector. It's constituents are: Vertex detector around the beam axis, TPC (yellow), ECAL (blue), HCAL (green), magnet coil and cryostat (violet) and muon detector (brown).

the drift velocity of the electrons v_D must be known. Then the z coordinate can be calculated with:

$$z = v_D \cdot (t_1 - t_0) \tag{2}$$

where t_1 is the arrival time at the anode and t_0 is the time of the particle passage. t_0 can be given by the beam collision time or an external trigger.
In measuring the trajectories in 3D with the TPC we can find the radius of the track curvature of the charged particles due to a magnetic field. From this radius we can calculate the particle's momentum.

In the TPC we are also able to measure the loss of energy $\frac{dE}{dx}$ of the particle. Plotting it over the momentum, particles can be identified (see Figure 4)

2 Signal Amplification with GEMs

The number of electrons produced when the passing charged particle ionizes the gas is not high enough to reach over the threshold of the anode. Therefore the signal has to be amplified and a higher number of electrons, which is proportional to the number of initial electrons has to be produced.
The considered amplification devices that is aimed to be used in the TPC in the ILD are Gas Electron Multipliers (GEMs). Their setup and their working principle will be explained in 2.1.
The main parameters that describe the quality of the amplification process and therefore have to be optimised are the following:

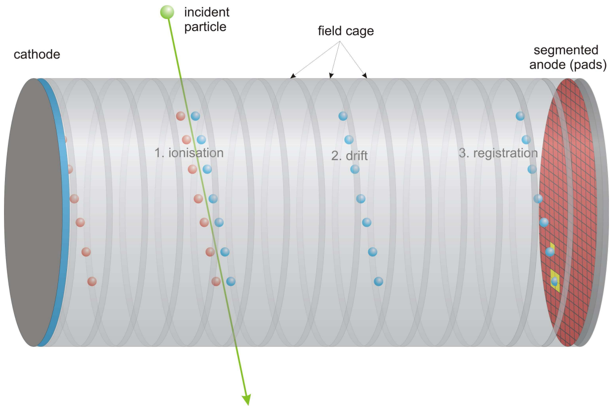


Figure 3: Scheme of a TPC

Gain The most important parameter is of course the gain which is defined by:

$$\text{Gain} = \frac{\text{Number of produced electrons}}{\text{Number of initial electrons}} \tag{3}$$

Ion-Backdrift With every secondary electron, an ion is produced as well. When the ions drift back into the drift-volume they change the electric field and can also attach electrons so that the track can't be properly reconstructed any more. Therefore the ion-backdrift has to be minimised. The ion-backdrift is defined by:

$$\text{Ion-Backdrift} = \frac{\text{Number of ions entering into the drift volume}}{\text{Number of produced ions}} \tag{4}$$

Electron Transparency Another parameter which is important for the track reconstruction is the electron transparency. It indicates the number of initial electrons that pass the amplification device over the total number of initial electrons. The less initial electrons are collected, the less information we have about the track. Hence a reconstruction becomes difficult.

Discharge When a discharge takes place a huge amount of electrons are produced causing a high flow of current. The number of electrons isn't proportional to the number of initial electrons any more and therefore the signal is lost. It is also possible that this high current destroys the amplification device or even the electronics of the anode if it hits it.

2.1 GEM setup

Gas Electron Multipliers consist of a Kapton foil of about 50 μm thickness which is enclosed by two copper layers with a thickness of 5 μm each (see figure 5(a)). The foil

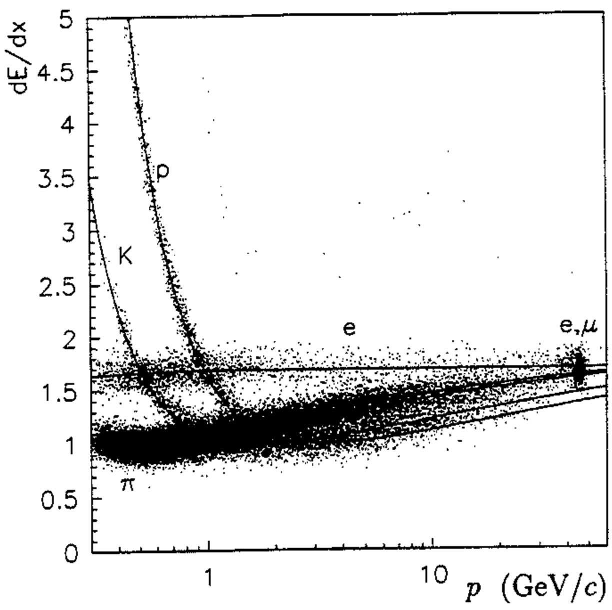


Figure 4: Specific energy loss over particle momenta

is perforated with double conical holes in a hexagonal pattern. The pitch between the holes is 140 μm, the outer diameter is d_{out} = 70 μm and the inner diameter is about d_{in} = 55 μm. The double conical shape of the holes is due to the manufacturing process. At the copper layers a voltage of several 10 V is applied, the resulting electric field is focused into the holes (see figure 5(b)) so that it achieves very high values of several 10 kV/cm. In these intense fields the initial electrons are accelerated to energies high enough to induce ionisations and produce secondary electrons in avalanches. These secondary electrons are extracted from the GEM holes due to the electric field between the GEM plane and the anode, called induction field.
With a single GEM typical amplifications up to the order of 10^3 can be achieved.
To ensure a stable operation low GEM voltages are usually used. This requires a setup of several GEMs (GEM stack) to achieve the same or even higher amplifications (typically of the order of 10^4).

2.2 Advantages of GEM stacks

Many free parameters In GEM stacks the voltages of every GEM can be adjusted and adapted to our needs. Therefore we also can have different electric field between the GEMs (transfer fields). Other amplification devices, for example MicroMEGAS have only one amplification field that can be adjusted.
Hence with GEM stacks we have more optimised values for the gain, ion-backdrift and electron transparency.

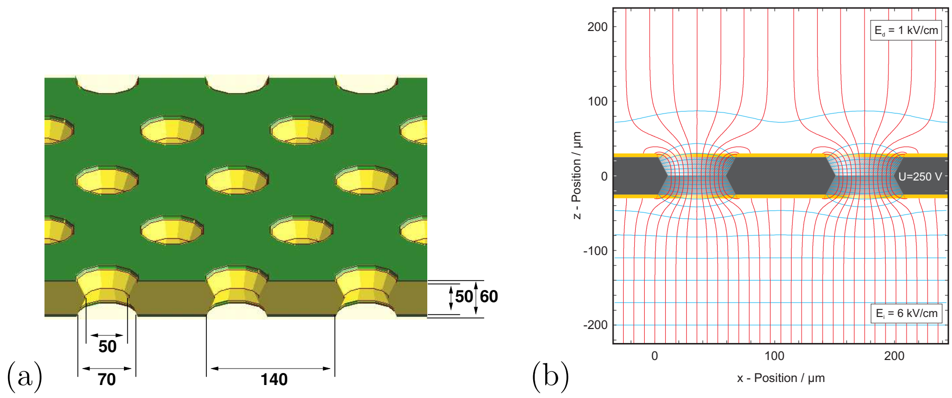


Figure 5: (a) Sketch of a standard GEM's geometry. The lengths are given in µm (b) Simulated field settings of a GEM with an applied voltage of 250 V.

Intrinsic ion feedback suppression GEMs have the property that they capture some of the ions produced in the electron avalanches. An aim which is in process for the ILD's TPC is using a triple GEM stack where the upper GEM is only used for the ion-backdrift. Hence, it will be operated at very low voltages to capture the ions on the copper surface. Meanwhile the other two GEMs will be used to amplify the signal.

Low discharge probability Discharges can cause high flows of current which can destroy the GEMs or even the electronics of the anode. However the risk that the current hits the anode is quite small compared to other amplification devices where the amplification takes place directly in the field above the anode and not in holes that have a certain distance to the anode.

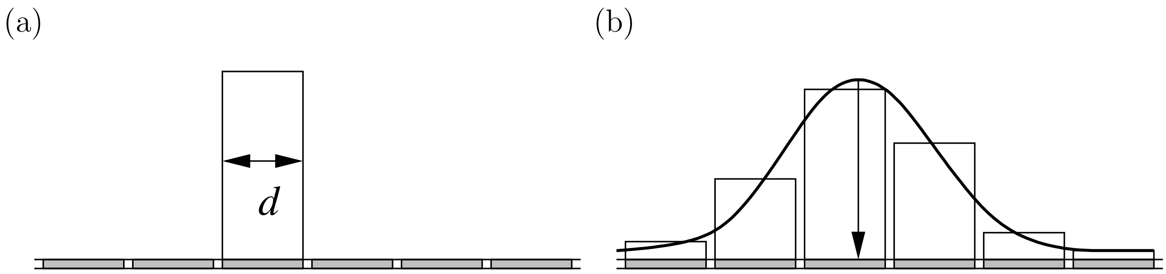


Figure 6: Illustration of charge-sharing to get a good spatial resolution with pad readout.

Wide signal on the anode To have a diverging signal over the anode is important to obtain a good spatial information with a pad-readout which will be used in the TPC. Figure 6 shows an illustration of the charge sharing principle. If the signal would hit only one pad, the spatial information is not better than the pad width d (Figure 6 (a)). However if the signal is spread over several pads a weighting function of positions taking

into account the charge collected on every pad, can be used to get the position where the most charge was collected. This is the position where the signal hit the anode.
To get good spatial information, 3 to 4 pads should be hit. As one pad has a width of about 1.27 mm this corresponds to a signal width of about 4 to 5 mm.

3 Garfield simulations of GEMs

The Garfield code is able to simulate detectors which uses gas and semi-conductors as sensitive medium. More precisely it simulates the propagation and interactions of electrons, ions and photons in gases or semi-conductors. I worked with the C++ version of the Garfield code called Garfield++.

The main issue of my work during the Summer Students Programme was to find out how the Garfield code works, what options are available and how Garfield can be applied to GEMs. Therefore reading the code was necessary in order to understand the provided functions.
The documentation on http://garfieldpp.web.cern.ch/garfieldpp/ where example scripts for GEMs are available, was very helpful as well.
The following subsections describe the approach to do GEM simulations with Garfield, show some output plots and presents some first results.

In order to take into account electric fields in the detectors structure the potential

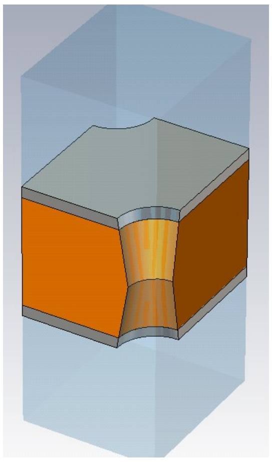


Figure 7: Basic cell of a single GEM.

has to be simulated in advance by Finite Element Methods (FEM) like ANSYS or CST. The Garfield code provides an interface for the output files of ANSYS simulations.
In order to simulate electron avalanches in GEMs we built at first an elementary cell of a single GEM (see Figure 7). For these we simulated the potential with ANSYS.
The output files we introduced into Garfield, which applies a mirror periodicity in order

to reconstruct the whole GEM plane.
As an output from Garfield we can get for example the drift lines of the electrons and ions, a visualisation of the electric field which is calculated from the potential, or the number of electrons and ions produced in avalanches. This last value is important to get values for the gain and the ion-backdrift.
The same approach as described here is valid for double and triple GEM stacks with the only difference being that the corresponding basic cell consists of several single GEM basic cells arranged in a stack. The aim of the Garfield-simulation is to obtain values for the gain and the Ion-backdrift and to determine their dependence on different GEM parameters like the GEM voltages or the distances between the GEMs in the stacks.

3.1 Output Plots of Garfield

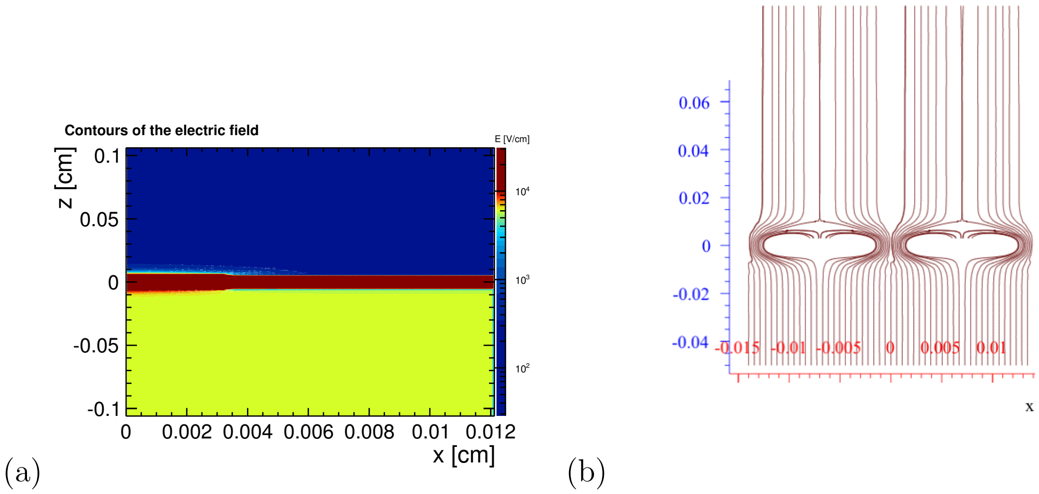


Figure 8: (a) Countour plot of the electric field calculated by Garfield for a single GEM. (b) Drift lines of ions in a single GEM to visualise the field lines.

In Figure 8(a) the contour plot of the electric field of a single GEM is shown. The upper blue zone indicates with the field strength of the order of 10^2 V/cm is the drift region and the lower yellow zone with a field strength of the order of 10^3 V/cm
Figure 9 shows the plot of drift lines given by Garfield. The yellow lines indicate the electrons and the brown ones indicate ions.
There are 5 initial electrons starting 0.015 cm above the GEM's surface and entering into the holes, where they produce secondary electrons and ions in avalanches. Some of the drift lines end on the GEM's surface (at approximately $z = 0$) right next to the GEM holes . This demonstrates the intrinsic ion feedback suppression explained in 2.2.
The holes of the GEM are perceptible from the high density of interaction points. A brown marker indicates an ionisation induced by an electron taking place. A green maker stands for an excited gas molecule that goes back into it's ground state by send out a

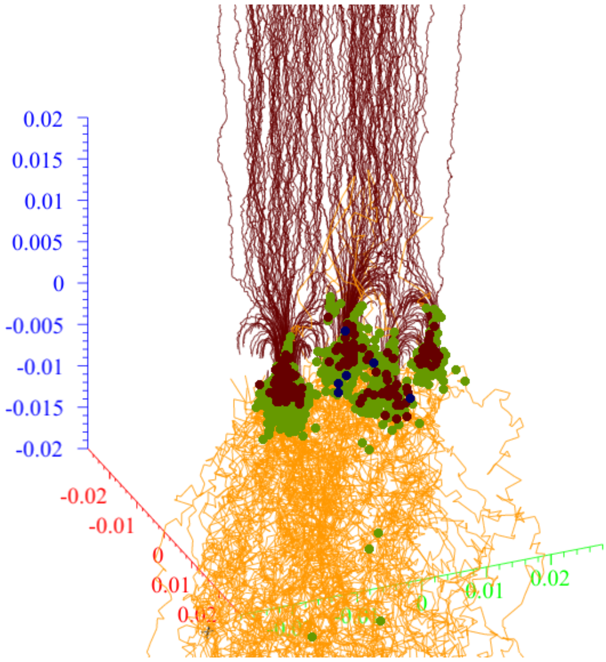


Figure 9: Drift Lines of electrons (yellow) and ions (brown) and their interaction points with the gas (brown: Ionisation, green: Excitation, blue: Attachment) for a single GEM

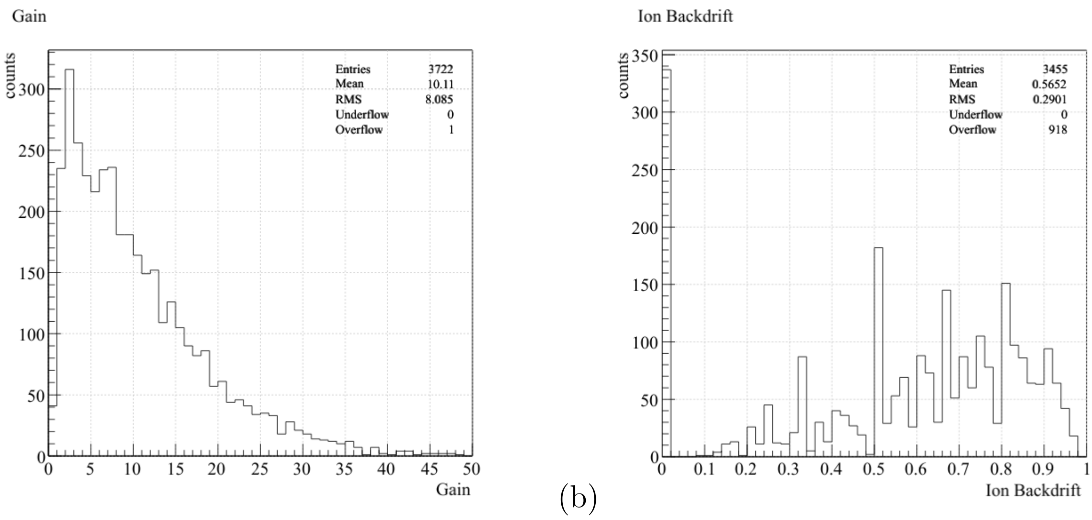
photon. sending out a photon. And attachments of electrons to ions or gas molecules are marked by a blue point. These electrons don't contribute to the gain any more.

3.2 Simulation Results

The following results were obtained in simulations of CERN standard GEMs in single, double and triple stack setups

3.2.1 Single GEM

The parameters of the single GEM are the following: the voltage applied between the two copper layers was $U_{\text{GEM}} = 300\,V$, the thickness of the drift region above the GEM was $d_{\text{drift}} = 1\,\text{cm}$ and the thickness of the region between the GEM and the anode, the so called induction zone, was $d_{\text{induct}} = 1\,\text{cm}$.
Figure 10 shows the distribution of the gain and Ion-Backdrift for 3722 simulated events in 80 % Ar, 20 % CO_2. It can be seen that both the gain and the ion-backdrift are random values spread over a wide range. Therefore a simulation of many events always has to be performed in order to get good statistics.
The obtained average values for the gain and the ion-nackdrift in three different gas mixtures are given in Table 1. As the statistics for the gases TDR and T2K are not sufficient to be able to get reliable values, the shown values aim to show the approximate



(a) (b)

Figure 10: (a) Distribution of the gain for 3722 simulated events in 80 % Ar, 20 % CO_2. (b) Distribution of the ion-backdrift for 3722 simulated events in 80 % Ar, 20 % CO_2

order.
It can be seen that we can achieve significantly higher gains only by changing the gas. Furthermore it is remarkable that the ion-backdrift doesn't grow related to the increment of the gain, when using another gas. This is an interesting issue that deserves further investigation.

Gas	Gain	Ion-Backdrift
Considered gas: 80 % Ar, 20 % CO_2	10.11	56.5 %
TDR: 93 % Ar, 5 % Methan, 2 % CO_2	61.4	71.5 %
T2K: 95 % Ar, 3 % CF_4, 2 % C_4H_{10}	943.5	79.5 %

Table 1: Simulation results for the gain and Ion-Backdrift for three different gas mixtures. As the statistics for the gases TDR and T2K aren't very good, the shown values aim to show the approximate order.

In the further simulations for the double and triple GEM stack we used the gas mixture 80 % Ar, 20 % CO_2 simply because the gain isn't as high as for the other gases and therefore the calculation time in the simulation isn't so long.

3.2.2 Double GEM stack

We performed the simulation of a double GEM stack with the parameters shown in Table 2 which are the parameters of an existing experimental setup.

E_{drift}	240 V/cm
d_{drift}	2 cm
$E_{trans/ind}$	1000 V/cm
$d_{trans/ind}$	0.2 cm

Table 2: Parameters of the used double GEM stack. E_{trans}/d_{trans} are the field/distance between the two GEMs and E_{ind}/d_{ind} the field/distance between the lower GEM and the anode.

The goal of the simulations of a double GEM stack are to compare the results with the values found by experiments.
The TPC group built a so called 'Small TPC' which consists of a small chamber with a diameter of ø = 25 cm and an unsegmented copper anode. A double GEM stack is used for the signal amplification. Figure 11 shows the drift volume on the left and the anode with the double GEM stack above on the right.
The Small TPC is operated with a ^{55}Fe source.

Figure 11: Experimental setup of the 'Small TPC' operated with a double GEM stack (on the right).

Figure 12 shows the drift lines of the electrons produced by one initial electron in an avalanche in 80 % Ar, 20 % CO_2. The initial electron ionises the gas when going through one hole in the GEM that touches the drift volume (GEM I). The secondary electrons are spreading due to diffusion so that in the GEM above the anode (GEM II) the electrons are amplified in 7 holes. Hence the resulting signal is broadened over a width of about 0.6 mm in the x and y direction. This is wanted to obtain good spatial information when using pad readout on the anode (see section 2.2).

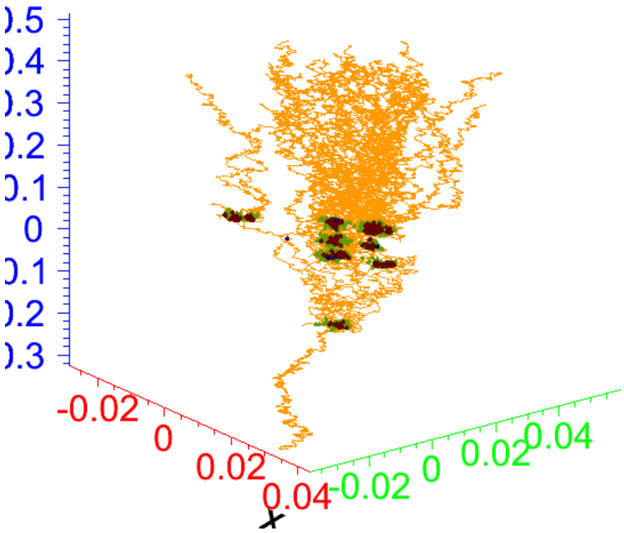


Figure 12: Drift Lines of electrons produced by one initial electron in a double GEM stack in 80 % Ar, 20 % CO_2.

We simulated 100 events in a gas of 80 % Ar, 20 % CO_2. The gain took values between 0 and 1000 and the Ion-Backdrift between 0 and 85 %. The average values are:

Gain:	249.7
Ion-Backdrift:	60.6 %

However 100 events are not enough to get reliable statistics, therefore further simulations are required.

3.2.3 Triple GEM stack

Simulations of triple GEM stacks are necessary to find optimal parameters for the induction, drift and transfer fields and distances.
In our case we used exactly the same parameters as for the double GEM stack shown in Table 2 in order to compare the two simulations.
Figure 13 shows the drift lines of the electrons produced in avalanches in a triple GEM in 80 % Ar, 20 % CO_2 starting with one initial electron. Like in the double GEM we can see how the signal gets very broad. It spreads over a width of about 1 mm in the x and y direction.

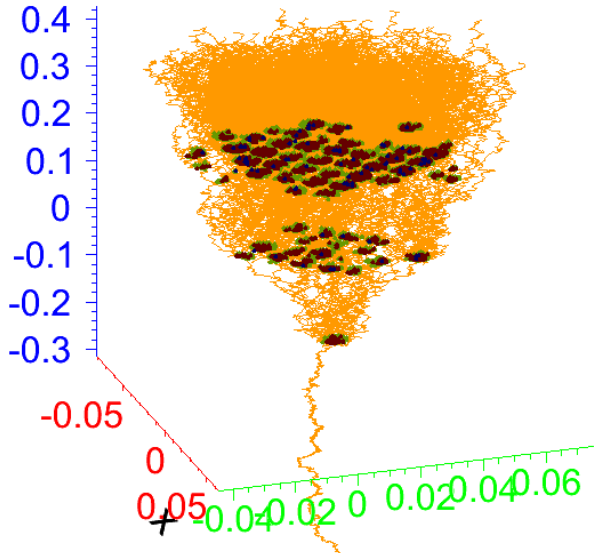


Figure 13: Drift Lines of electrons produced by one initial electron in a triple GEM stack in 80 % Ar, 20 % CO_2

We simulated 10 events and found gains in the range of 1000 to 5000 and values for the ion-backdrift between 76 % and 79 % with the following average values:

Gain:	3625
Ion-Backdrift	78.2 %

Compared to the double GEM stack the amplification of the triple GEM stack is a factor of 15 higher and the ion-backdrift increases with about 20 %. We see that this setup isn't good to suppress the ion-backdrift. The next step would be to simulate the triple GEM stack for a low voltage on the upper GEM that touches the drift volume as explained in section 2.2.

4 Summary and Outlook

We have shown that it is possible to simulate single, double and triple GEM stacks with the Garfield++ code for the potential of the structure simulated by ANSYS previously. Furthermore we have learned how we can obtain the values for the gain and the ion-backdrift.

Further simulation work will aim to get better statistics for the double GEM stack in order to compare the results with experimental values obtained with the Small TPC. For the triple GEM stack further simulations have to be effected in order to optimize the gain, the electron transparency and the Ion-Backdrift.

References

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