

Simulation of GEM detector using Geant4 and Garfield++

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Abstract

The CERN gas team (EP-DT-FS) has defined several strategies to reduce the greenhouse gas emissions coming from particle detectors. Different set-ups have been implemented to study both gas systems and gaseous detector performance. In this scope, Monte Carlo simulation of the detector with different gas compositions is useful. In this project, Geant4 is used to calculate the properties of the primary ionization electrons that are produced by photons of the ^{55}Fe source. Garfield++ computes a passage of the electron avalanche through the gas. An analysis of simulation results allows to study GEM performance under different conditions and details of physical processes that are present in the experimental set-up.

1 Introduction

The future Physics Program of the Large Hadron Collider sets important challenges for all detector systems. Concerning the muon systems, one of the changes will be to reduce operational cost and gas emission while maintaining high performance level. In this contest, the EP-DT-FS gas team has set different R&D programs. One of these consists of studying the performance of Gas Electron Multiplier detectors (GEM) in a gas recirculation system and under high irradiation at the CERN gamma irradiation facility (GIF++) using both Ar/CO_2 and $\text{Ar}/\text{CO}_2/\text{CF}_4$ gas mixtures. In order to validate the triple-GEM operation with gas recirculation, Monte Carlo simulation of the GEM detector can be used to estimate its performance, based on the properties of the gas (drift velocity, ionization energy, etc) and physical processes causing an interaction between particles and matter. Moreover, different characteristics of the system, such as photon sensitivity of the gas gap, can be calculated using a Monte Carlo simulation, but are much harder to measure in a real experiment.

This project is aimed to calculate different properties of the GEM detector and their dependency on a change in gas mixture composition. Simulation is divided by 2 stages: primary ionization of a gas by initial photons and further creation and development of an avalanche. The first stage uses a physical toolkit Geant4 mainly because of its flexibility and a wide range of supported physical processes. Stages are separated from each other, so initial particles can be easily changed. For example, a ^{55}Fe source, used in this project, can be replaced by a beam of high energy muons, and Geant 4 is able to handle a simulation of ionization with different processes. The second stage is responsible for a passage of electron avalanche through a matter of the detector. In this case, a Garfield++ toolkit is suitable due to the detailed simulation of low energy electromagnetic interaction and influence of gas properties. Data transfer between two stages (and therefore two different applications) is organized using root files. They can be easily analyzed to compare real experimental measurements and simulation results. The architecture of this project combines flexibility and universality of Geant4 and detailed physical model of Garfield++ while maintaining an easily separable structure to facilitate cross-checks at any point.

2 Geant4

2.1 Method

A primary role of Geant4 in this project is to simulate a passage of γ particles through the first gas gap of the triple-GEM detector between the window and first GEM foil. As gamma source, we choose ^{55}Fe , as it is used in laboratory set-ups. The main physical processes, contributing to the generation of primary ionization electrons, are photoelectric effect and generation of Auger electrons. The effect of the Compton scattering is negligible due to the low energy of the photons (5.9 keV for ^{55}Fe source). Theory predicts 2 peaks in the energy spectrum of the electrons: 2.7 keV corresponds to the photoelectric effect and 3.2 keV - to the Auger electrons. A value of the second peak should be 92% of the first peak value according to the probability of Auger electron emission.

The simulated geometry represents a part of GEM detector and consists of window and gas gap. In this simulation, window comprises kapton foil (50 μm), copper covering (5 μm) and aluminium foil (10 μm). The mixture of the gas in the gap can be changed. By default, it consists of 70 % Ar and 30 % CO_2 . Different gases, such as CF_4 , can be added. This application does not study how electrons hit the first GEM foil, it only saves the initial characteristics of the electron right after its creation. Therefore, in this stage, the GEM foil is not simulated.

A tracking function of the application is implemented via TrackingAction of Geant4. Custom action launches when a new particle is created inside of the gas gap. The initial properties of the particle are stored in the ROOT Tree. The action saves x, y, z coordinates of the particle, 3 projections of its momentum, energy, time, id of the parent particle and PDG code. A PDG code is used to distinguish electrons from other particles.

Geant4 is able to simulate a passage of particle in the electromagnetic field. In our case uniform electrical field can be defined, but it does not affect the results of the application. Electrical field does not change a trajectory of photons and the characteristics of electrons are saved before they can be affected by the electromagnetic field.

2.2 Discussion

Properties of the electrons were analyzed to cross-check the chosen Geant4 physical model. Photon sensitivity of the gas gap can be easily measured as a ratio between produced primary ionization electrons and the number photons reaching the gap (not absorbed by the window layers). The dependency of the sensitivity on gap thickness follows an exponential law. For 1 cm of pure Argon, a measured value of photon absorption equals 59 %, experimentally measured value is 35 %. For a gas mixture consisting of 70 % Ar and 30 % CO_2 it is 49 % and for a gas mixture with CF_4 (45 % Ar , 15 % CO_2 , 40 % CF_4) absorption is 39 %. This divergence can be explained by both physics model and methods of particle count.

An energy spectrum of particles (shown in figures 1a and 1b) partially corresponds to the physical processes that are present in studied interactions. The main peak in the electron energy spectrum (2.7 keV) corresponds to the emission of an electron from K-shell due to a photoelectric effect. 5.6 keV electrons are emitted from L1/L2-shell. A ratio between peak values follows the probabilities of emission from K- and L1/L2-shell (96% and 4% accordingly). Auger electrons with energy 3.2 keV are not seen. Existence of this emission in Geant4 physics model was checked in different application and examples, and these electrons were not found. This leads to a conclusion that this particular auger electron emission is not implemented in low energy physics model. A majority of photons found in the gas gap has energy 2.9 keV that corresponds to a K-shell characteristic x-ray emission. A probability of this process is 8 % for every K-shell photoelectric emission and it is in agreement with the measured ratio. L-shell characteristic x-ray emission with energy 0.3 keV is not found.

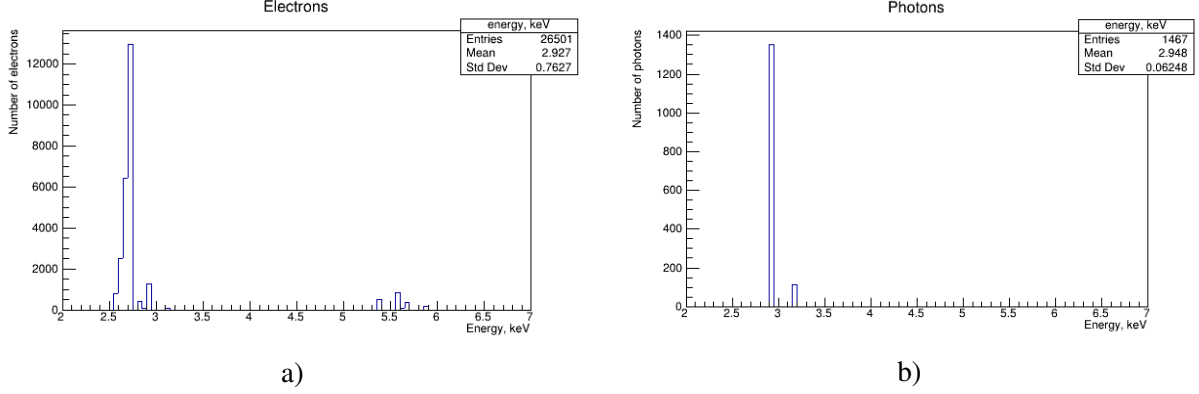


Figure 1: Energy spectrum of particles created inside of the gas gap: a) - electrons, b) - photons

3 Garfield++

3.1 Method

The Garfield++ toolkit is used for the detailed simulation of particle detectors that use a gas mixture or a semiconductor material as a sensitive medium. In our case, the main features of this software are precise simulation of the passage of particles through the gas due to the Magboltz model and support of complex nonuniform electrical fields that can be defined in ANSYS. The Garfield++ application simulates the remaining part of a GEM detector, not covered by Geant4: 3 GEM foils and readout.

In this project the Garfield++ toolkit is mainly chosen due to the detailed simulation of interactions of charged particles with gas. Necessary libraries (Heed, Magboltz model etc) are already integrated into the software. Fractions of mixture components can be changed easily and mixture properties are linked (as Penning transfer, drift velocity). Pressure and temperature can also be separately set. The characteristics of the initial electron are taken from the ROOT file from Geant4 application. This electron interacts with the gas and creates an avalanche. All secondary electrons are tracked and their properties are stored in the output ROOT file. For each secondary particle id of the initial electron, end-point coordinates, time and energy are saved. A fraction of avalanche electrons reaches the readout plane, their number represents the gain of the detector.

3.2 Discussion

A computational cost of Garfield++ simulation is hugely determined by the number of electrons composing avalanche. In the studied geometry, only a fraction of these electrons reaches the readout and forms a signal. Other particles are stopped by the surfaces of GEM foils. A distribution of the coordinate along the detector (z axis) is shown in the figure 2a. These data correspond to 2.7 keV energy of the initial electron and gas mixture consisting of 70% Ar and 30% CO_2 . It can be clearly seen that only $\approx 30\%$ of the electrons reach the readout and define a gain. Figure 2b helps to understand a mechanism of electron absorption in GEM foil near a hole. Some electrons directly hit the surface of foil (right peak). Although, a lot of particles have small energy and follow the electrical field lines and therefore hit the surface after going through the hole (left peak).

A gain of the detector is hugely influenced by the composition of gas mixture. Figure 3a shows how the gas gain exponentially decreases when the concentration of CO_2 rises in an argon based gas mixture. However, the ratio between the electrons reaching the readout and total avalanche size remains approximately the same (small drop from 32.6 % to 29.33 %), as it is visible in the figure 3b. The exponential decrease of the avalanche size can be explained by the fact that with more CO_2 in gas mixture more electrons are collected on the first and second foils.

A single-GEM geometry was used to study the time resolution of the detector. Time distribution of

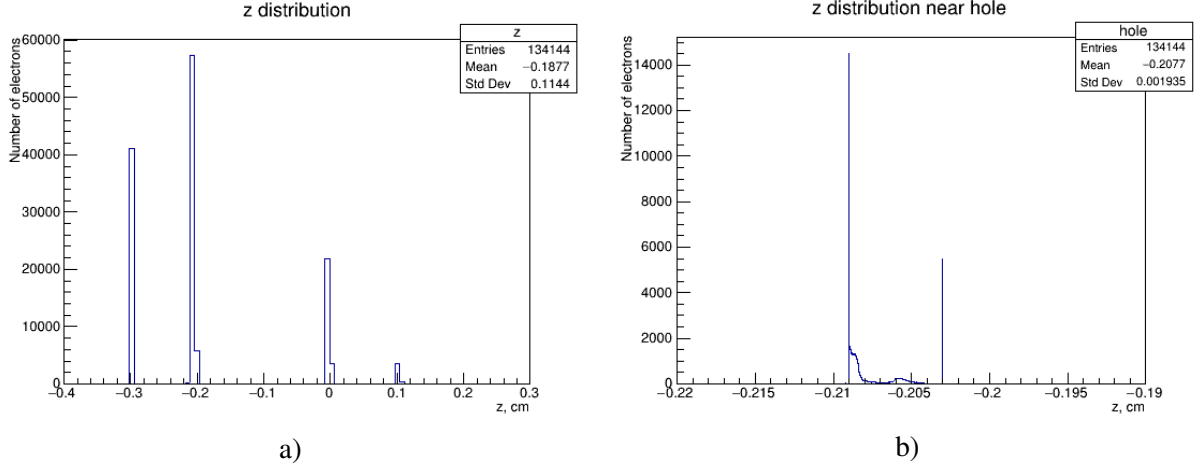


Figure 2: Distribution of z coordinate of the electrons in avalanche

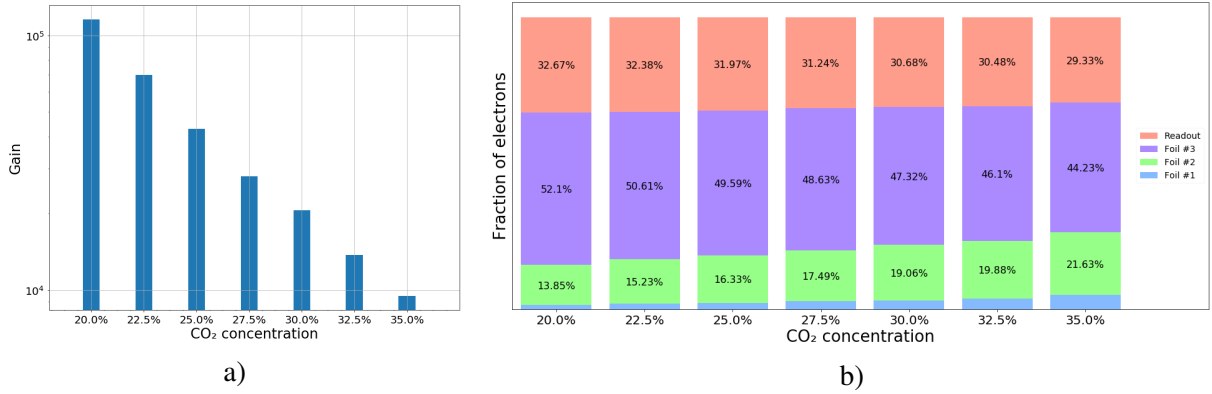


Figure 3: Dependency of detector gain on gas mixture composition

electron endpoints for a single avalanche is shown in the figure 4a. It consists of 2 peaks corresponding to electrons that are collected in the GEM foil and the readout. Typical full width at half maximum for these peaks is approximately 4 ns for studied geometry. However, the time distribution for electrons from 500 different avalanches (figure 4b) is much wider than an individual peak. This can be explained by the fact that peaks for different avalanches have significantly different mean value. It is defined by the time required to reach GEM-foil from the initial electron position. The Geant4 simulation shows that z-coordinate of the first ionization electron is almost uniformly distributed along the small gas gap (linear density of electrons slowly decreases but it is limited by the length of the gas gap).

The same single-GEM geometry was also used to analyze a movement of electrons and ions in the gas mixture. In the figure 5 distribution of both types of particles is shown in cylindrical coordinates. R coordinate is calculated as a distance from a center of the detector (center is defined as the nearest point to the gamma source). Narrow line at $z = -0.003$ for electrons and $z = 0.003$ for ions represents a direct hit of the surface of the foil by a particle. Particles can also be collected inside the hole, this mechanism creates repeating strips of bins. Each strip corresponds to a set of holes that are located at the same distance from the center.

Figure 6 shows a distribution of particles near the central hole of the detector. Big amount of both electrons and ions are collected near the edge of the hole. The simulation results show that nearly 7 % of electrons and 8 % of ions from the total number of particles hitting the GEM foil are collected in a small $2 \mu\text{m} \times 2 \mu\text{m}$ region around the edge of the central hole.

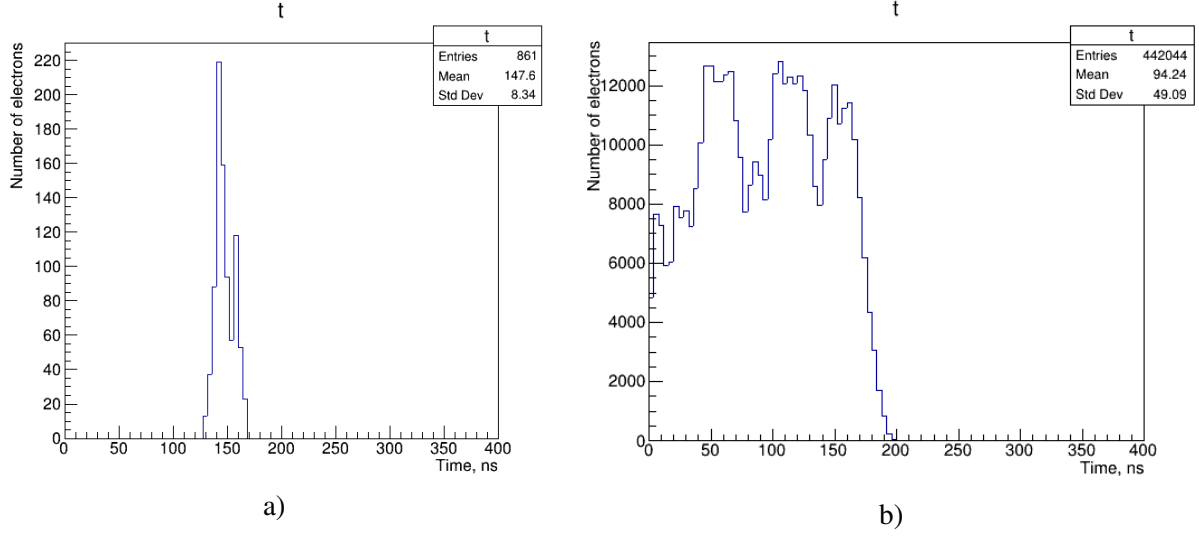


Figure 4: Time distribution of electrons from one avalanche (a) and 500 avalanches (b)

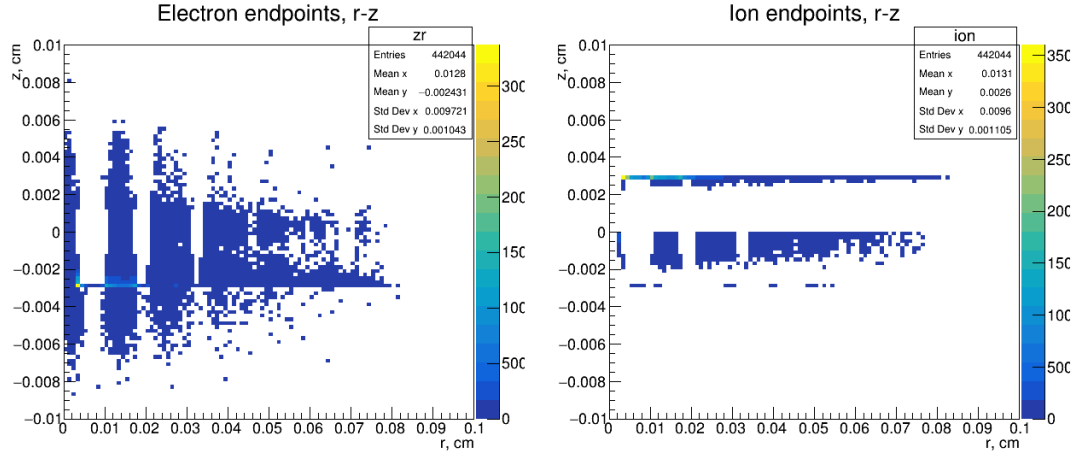


Figure 5: RZ histogram for electrons and ions

4 Conclusion

The developed project can be used to simulate a performance of single- and triple-GEM detectors and to calculate different properties of occurring processes. Electron distributions obtained through the Geant4 stage are suitable for further simulation in Garfield++. Some changes in the physical model could help to improve a similarity of experimental and model data, such as Auger electrons emission at 3.2 keV and photon absorption. However, in the current state, this application can be used to simulate different detector properties, for example, time resolution. The Garfield++ stage simulates the electron avalanches in the detector with a good resemblance with experimental data. Distributed computing should be used to calculate a big amount of events due to the high computational cost of the simulation with the studied geometry and electrical field.

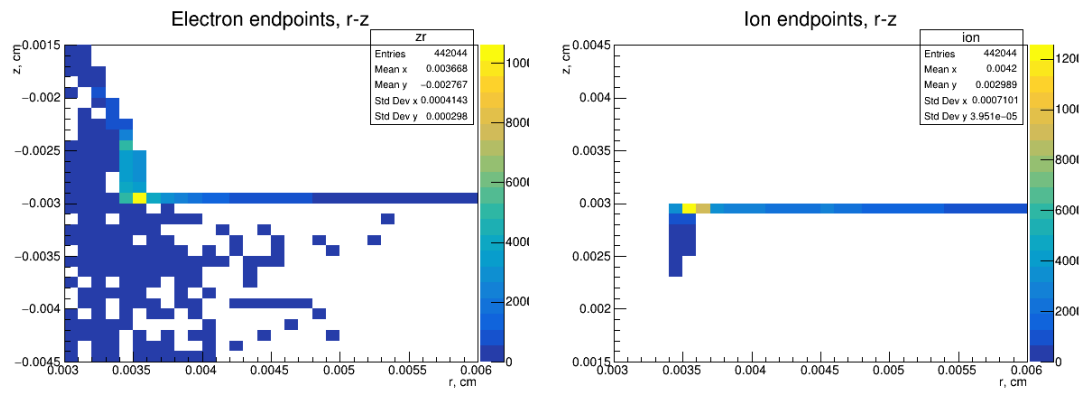


Figure 6: RZ histogram for electrons and ions near a hole