

# GTS - Garfield-based Triple-GEM Simulator

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**Abstract.** Triple-GEM detectors are gaseous devices used in high energy physics to measure the path of the particles which cross them. The characterisation of triple GEM detectors and the estimation of the performance for real data experiments require a complete comprehension of the mechanisms which transform the passage of one particle in the detector into electric signals, and dedicated MonteCarlo simulations are needed. In this work we will describe GTS (Garfield-based Triple-gem Simulator), a MonteCarlo code which has been developed to simulate the detector response to the passage of particles inside triple GEMs. The software takes into account the processes from the primary ionization up to the signal formation, e.g. avalanche multiplication and the effects of the diffusion in the gas volume. It uses a parametrization of the variables of interest meant to reproduce the same detector response (i.e. the charge distribution at the anode) as provided by Garfield++, a well known software that already performs this kind of simulation more detailed and therefore with a high CPU time consumption. In addition to the detector response, the simulation of the APV-25 electronics is implemented and the output is used to reconstruct the particle position with the Charge Centroid (CC) and the micro-Time Projection Chamber ( $\mu$ TPC) methods. A comparison of the simulated performance and the one collected in testbeams is used to tune the parameters used in GTS. Results in different conditions of incident angle will be shown.

## 1 Introduction

Gaseous Electron Multiplier (GEM) is a well know technology introduced by F. Sauli in 1997 [1] used to amplify the signal generated by ionizing particles interacting with the gas volume of the detector. The GEM foil considered in this paper consists of a copper coated (5  $\mu$ m) on a 50  $\mu$ m kapton foil, with holes of 50  $\mu$ m diameter and 140  $\mu$ m of pitch. Electrons entering these holes are accelerated and generate an electron cascade. Multiple stages of GEM foils allow to reach gain of about  $10^4$  with a very low discharge probability. The full design of a triple-GEM detector is given by a cathode, three GEM foils and an anode readout. Simulation of this technology is useful to understand the processes that play the main role in this detection technique.

An existing software Garfield++ [2], a toolkit for the detailed simulation of particle detectors based on ionisation measurement in gases and semiconductors, can perform a detailed simulation of a triple-GEM detector. It simulates step by step all the interactions of the ionizing particle, the interaction between the electrons and the gas mixture, as a function of the electric field. Since the simulation steps are small (about few  $\mu$ m) compared to the size of a

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triple-GEM (about 1 cm) and the number of electrons involved is large (about  $10^5$ - $10^6$ ) then the simulation of the space and time distributions of the signal at the anode can become quite expensive in terms of CPU time (10-20 hours per event). Examples of triple-GEM simulations performed with Garfield++ can be found in literature [3–5].

A fully parametrized simulation, GTS, is described in this work: it takes into account the primary ionization process, the generation of the avalanche in the GEM holes and the electron drift to the readout plane where the induction takes place. The description of the electronics is also taken into account. The results obtained from the simulation are compared with the experimental ones collected in a testbeam.

GTS is not a Garfield++ competitor but a complementary tool to measure the triple-GEM performance, *i.e.* the spatial resolution, in a faster way than the one proposed by Garfield++ through the parametrization of the main processes (multiplication and diffusion) in order to avoid the step by step simulation performed by Garfield++.

## 2 Setup description

The triple-GEM detector under study is defined by five electrodes (cathode, three GEM foils, and the anode) and four gaps used to define the drift properties of the electrons: a drift gap between the cathode and the first GEM of 5 mm, two transfer gaps between the GEM foils of 2 mm and an induction gap between the third GEM and the anode. A scheme of the detector is shown in Fig. 2 left.

A gas mixture of Ar+10%*i*C<sub>4</sub>H<sub>10</sub> fills the detector volume and defines its primary ionization properties, the electron drift and the gain of a GEM foil. The high voltage used on each GEM is 275 V, while the electric field in the different gaps is 1.5/2.75/2.75/5 kV/cm. The ionizing particles used in the simulation and in the testbeam are 150 GeV/*c* momentum muons with variable incident angle with respect to the detector surface. The used readout electronics is the APV-25 ASIC [6], a chip that samples the signal every 25 ns with a shaping time of 50 ns.

The experimental data [7] were collected in several testbeams at CERN North Area within the RD51 collaboration [8].

## 3 Computation of inputs to GTS using the Garfield++ simulation

The simulation described in this work, is based on the idea described by Bonivento *et al.* [9], where the generation of the triple-GEM signal is divided into independent parts: ionization, GEM amplification, electron drift in each gap, induction and electronics readout. These processes have been simulated with Garfield++ and their output have been parametrized and used as input to the GTS simulation. The geometry description of the detector and its electric field map were performed with Ansys software [10]. Every process is considered independent. The Garfield++ results are shown in the following subsections.

### 3.1 Ionization

Charged particles crossing a gas mixture lose their kinetic energy and generate primary electrons. These electrons constitute the signal that a triple-GEM detector measures. The ionization process is determined by two factors: the kinetic energy of the particle and the gas mixture used. The ionization was simulated separately from the subsequent processes. Several muons were shot in a volume with 5 mm gap to extract the following variables: the number of electrons clusters and the number of electrons inside each cluster. The distributions of those

two quantities are shown in Fig. 1. The primary ionization follows a Poissonian statistic and the most probable value was parametrized to be used in GTS. The number of primary electrons inside each electron cluster was tabulated up to 100 electrons per cluster.

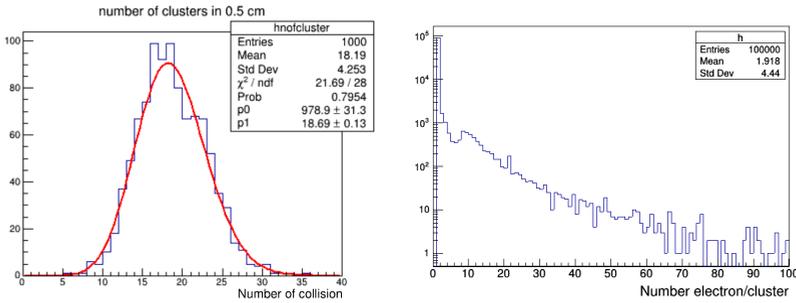


Figure 1: Left: distribution of the number of primary electrons (*i.e.* clusters) generated in the ionization created by 150 GeV/c muons in 5 mm  $Ar + 10\%iC_4H_{10}$ ; the histogram is fitted with a Poissonian distribution. Right: distribution of the number of electrons per cluster; the histogram is tabulated to be implemented in the simulation.

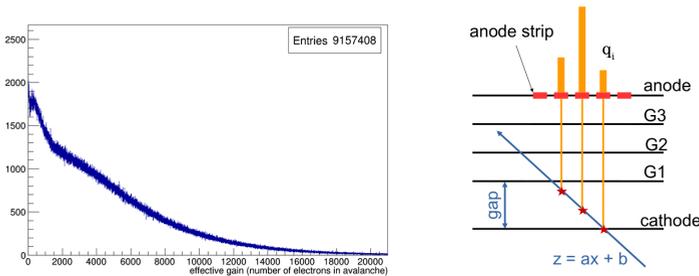


Figure 2: Left: effective gain for a triple-GEM. The histogram is the result of the full chain of simulations of the gain, collection and extraction efficiencies for the three GEMs. The contribution of *zero* effective gain is removed from the histogram. Right: sketch of a triple-GEM detector with the cathode, three amplification stages and the anode. Each strip measures time and charge and continuous strips are used for CC and  $\mu$ TPC reconstruction methods.

### 3.2 GEM amplification

A simulation of a GEM foil was performed in an independent framework to measure the products of the interaction of the electron in the electric field inside the hole: here the electrons are accelerated so much that they can ionize several times the gas. It is important to measure the number of electrons generated inside each hole but also the number of electrons that can be collected and extracted by a GEM. Some of the electrons drifting inside a GEM do not enter the hole and another fraction of the electrons generated inside the hole do not reach the next gap. The simulation of this portion of detector is used to extract the intrinsic gain of the GEM and its *transparency*. This simulation studied the drift of the electrons from 150  $\mu\text{m}$  before the foil up to 150  $\mu\text{m}$  after the amplification stage; this has been used

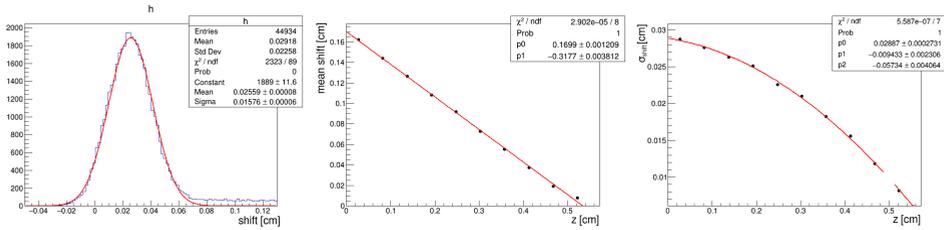


Figure 3: Left: distribution of the position shift, once an electron drifts in the transfer gap, is shown. Superimposed is the Gaussian fit used to measure the mean value and the sigma. Center and right: the motion of the electrons in the drift gap has been evaluated in these figures. The position distribution on the first GEM has been evaluated for electrons generated at several distances from the cathode. The drift gap has been divided in ten slices and each one of them a distribution has been fitted with a Gaussian. The mean value of the Gaussian functions as a function of the position in the drift gap is shown in the center; while the sigma of these distributions is shown in the right figure. The three plots have been evaluated with 1 T magnetic field.

to extract the GEM transparency, as the product of the collection efficiency (the probability to enter the hole) and the extraction efficiency (the probability to leave it). Together with the transparency, the number of secondary electrons generated by one electron entering the hole was extracted and fitted with a Polya distribution that well describes the fluctuations of the gain of a single GEM. The GEM transparency depends on the electric fields involved: the one between the previous electrode and the GEM and the one between the GEM and the next electrode. For this reason the transparency of each GEM foil has been measured separately. The product of the transparency and the intrinsic gain gives the extrinsic gain. The full detector gain can not be evaluated by the product of the three Polya distribution. Therefore a detailed simulation of the three GEM amplification stages was used to generate a distribution that fully describes the multiplication in a triple-GEM detector: one million of electrons have been simulated and for each amplification stage an intrinsic gain was sampled from the corresponding Polya distribution and transparency value, as shown in Fig. 2 right.

### 3.3 Electron drift

Drift properties such as transverse and longitudinal diffusion strongly depend on the gas mixture and the electromagnetic field. These values are well known in literature and a parametrization was performed based on the results of the Garfield++ simulation. A simulation of the electron drift was run for each gap and the distribution of the space shift was evaluated: *i.e.* ten thousand electrons were drifted from 150  $\mu\text{m}$  below the first GEM up to 150  $\mu\text{m}$  before the second GEM. A Gaussian fit was used to extract the mean value and the sigma of the distribution, see Fig. 3 left. The same procedure was followed for the other transfer gap and the induction gap. The drift in these gaps is performed by each electron generated before the first GEM. This method can not be used in the drift gap, where the primary ionization can take place in different positions and the path of each electron is different from the other one. Here a simulation of the electron drift was performed for different distances from the first GEM. A Gaussian fit has been used for each point to extract the mean value and the sigma as a function of the distance from the first GEM: Fig. 3 center and right show these results. The same studies have been performed for the time information.

## 4 GTS simulation and position reconstruction

The processes described in Sec. 3 define the details of a triple-GEM signal amplification and their parametrization from Garfield simulation. These were studied separately because they do not interfere at present setup conditions. Now the description of the GTS simulation is presented together with a simulation of the electronics and the position reconstruction.

The simulation of an ionizing particle interacting with a triple-GEM starts from the ionization that generates the primary electrons in the drift gap. The inter-primary distance is randomized from an exponential function since the number of primary electrons follows a Poissonian statistics, see Fig. 1 left. For each primary, a certain number of secondary electrons are generated according to the distribution shown in Fig. 1 right. The transparency value is used to determine how many electrons survive to the first GEM and the effective gain distribution, shown in Fig. 2 left, to calculate the number of secondary electrons generated by each primary. The secondary electrons are randomly smeared in space and time in agreement with a Gaussian distribution whose mean value and sigma are those shown in Fig. 3. At the end, the final position of the electrons is used to determine the strip position for the readout and the signal generated by the electronics. Each electron reaching the anode is associated to the proper strip; its arrival time together with its charge is used to define the induced current. This is an approximation of the real induction process described by the Ramo [11] and Riegler [12] theorems. The induced current, shown in Fig. 4 top left, was used to determine the signal exiting the ASIC with the simulation of a pre-amplifier that integrates the charge and a shaper with integration time of 50 ns to determine the fraction of charge readout, see Fig. 4 mid-left and mid-right. A Gaussian noise was included for each channel, as well as threshold levels compatible with the testbeam condition.

Once the readout signal was generated strip by strip, the charge and time information were used to apply two reconstruction algorithms on clusters of contiguous strips: the charge centroid (CC) and the micro-Time Projection Chamber ( $\mu$ TPC). The CC performs a weighted average of the strips position with their charge as weight, while the  $\mu$ TPC uses the time information to measure the distance between the particle path and the anode: a bi-dimensional point is associated to each strip and a straight line fit is used to measure the particle position. A sketch of the two methods is shown in Fig. 2 right, while the formulas are described in Eq. 1:

$$x_{\text{CC}} = \frac{\sum_{i=0}^{\text{cl.size}} x_{\text{hit},i} q_{\text{hit},i}}{\sum_{i=0}^{\text{cl.size}} q_{\text{hit},i}} \quad ; \quad x_{\mu\text{TPC}} = \frac{\text{gap}/2-b}{a} \quad (1)$$

where  $a$  is the slope of the fitting line,  $b$  is the constant and  $\text{gap}$  is the drift gap thickness.

## 5 Tuning with experimental data

Despite the detailed simulation performed with Garfield++ used to implement the parameter in GTS, the simulated results differ from the ones measured in the experimental setup. The reason is due to some approximation applied in the GTS simulation and some known problem in the Garfield++ simulations [13, 14]. Four sentinel variables were used to tune the simulations: strip-cluster charge, strip-cluster size, CC and  $\mu$ TPC spatial resolution. A comparison of these values from the experimental results and the simulation has been performed for different incident angles. A  $\chi^2$  evaluation was used to measure the matching of the values.

A set of configurations was evaluated to minimize the  $\chi^2$  and the best results were obtained using a tuning factor on the gain and on the electron diffusion.

The results of the tuning are shown in Fig. 5.

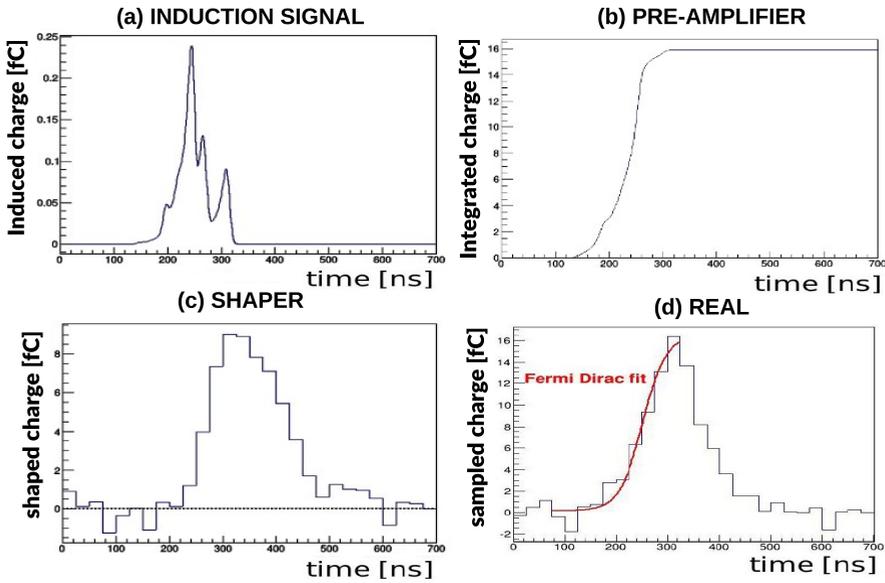


Figure 4: Top left: induced current on a single strip in a single particle simulation. Top right: shape of the current after the pre-amplifier simulation on a single strip. Bottom left: shape of the current after a shaper simulation with a RC-CR circuit having an integration time of 50 ns. Bottom right: example of the signal measured by a real event from an experimental setup to be compared with the previous picture.

## 6 Conclusion

A detailed parametrized simulation of a triple-GEM detector has been performed starting from Garfield++ simulation. The simulation takes into account also the effects of the electronics and a tuning procedure of the data. This new approach exploits a parametrization of the Garfield++ output to reduce significantly the computational time up to few seconds to generate the charge and time distribution of the electron at the anode. With this parametrization of the distributions obtained with the Garfield++ simulation, tuned to better reproduce the real test beam data, we are able to describe satisfactorily the GEM detector response. Therefore, this tool can be used to quickly emulate the response of other possible detector configurations.

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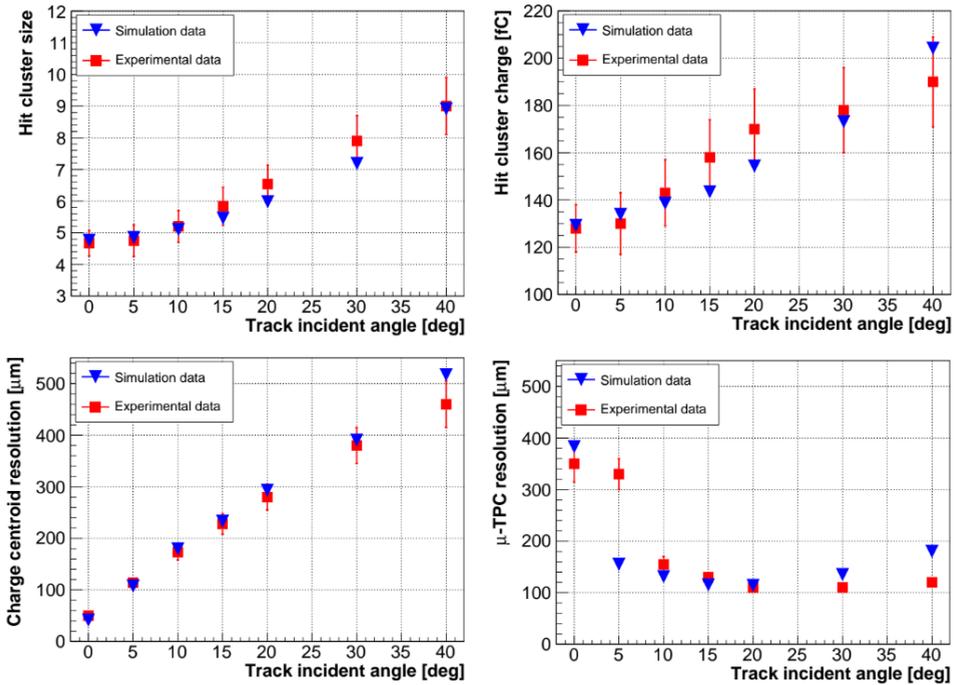


Figure 5: Experimental and simulated results for the four sentinel variables as a function of the incident angle: cluster charge (top left), cluster size (top right), CC resolution (bottom left) and  $\mu$ TPC (bottom right). The tuning values have been already applied in the shown set of results.

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