A NEW FAST SIMULATION TOOL FOR THE MICROMEGAS DETECTORS

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Abstract. We propose a new simulation tool for the Micromegas detectors, in which the signal generated by electrons and ions is treated analytically. The description of this framework and a list of requirements are presented in this paper. We developed a prototype to verify the feasibility of this tool and we present some of the obtained results.

Key words: Simulation, Micromegas, gas detectors, avalanche, muons detector.

1. INTRODUCTION

Gas detectors were historically the first detector choice in high energy physics. The main motivations were essentially the possibility to create large sensitive areas with a competitive cost and the high sensibility. An integrated amplification mechanism allows the detection of a single particle and, adjusting appropriately the gases inside the sensitive area, it is possible to optimize the detection of specific classes of particles.

Because the downside of these detectors was mainly their low spatial resolution, different solutions must be used to reconstruct the incident particle trajectory, increasing the detector’s complexity and requiring complex electronics to drive it. These and other motivations drove a general trend to replace it, wherever possible, with comparable solid state detectors. The solid detector is lighter, has a micro-metric spatial resolution and needs lower power voltages to operate. These advantages come at higher cost and low sensitivity for less energetic particles.

Over the past years, a new class of hybrid detectors has been developed in order to incorporate the strong points of both classes of detectors and to minimize the weak points. The Micromegas detector integrates both a gas detector and an advanced electronic circuitry capable of achieving a spatial resolution lower than 100\,\mu m [1]. This detector is composed of a gas chamber which contains three regions, but only two of them are important in the signal generation (usually named drift and amplification region) and a PCB board filled with readout strips with a pitch of 250\,\mu m.
In figure 1, we shown a representation of a 2D Micromegas detector. The interactions of the incident particle take place in the drift region. An electric field of $\approx 1\text{ kV/cm}$ moves the generated electrons forward to the amplification region where a higher field of $40\text{ kV/cm}$ performs an avalanche amplification and generates an induction signal in the readout strips. The readout strips are sunken in an electrical insulator and protected from sparks by a set of resistive strips, so the readout strips collect only the induction signal and do not directly receive the electrons from the amplification avalanche.

This solution gives some remarkable benefits: it allows big sensitive areas with a moderate cost and provides a spatial resolution under $100\mu m$. Using advanced reconstruction techniques, like the $\mu$TPC method, and fast readout electronics ($t_s \leq 25\text{ ns}$), it is possible to fully reconstruct the incident particle trajectory at angles up to the full angular range [2]. Another benefit of this detector is the possibility to operate at higher rates, with an average inefficiency lower than 2% for tracks with $\theta = 0^\circ$ [3], where $\theta$ represents the angle between incident particle trajectory and the normal to the detector. Based on that, the Micromegas detector was chosen as the main tracking technology for the New Small Wheel [4] upgrade of the ATLAS Muon Spectrometer [5], performed for the high luminosity upgrade of the LHC.
New detector technologies, however, require new simulation frameworks. Existing simulation software utilized for solid detectors perform poorly when used to simulate gas detectors. This class of detector is, indeed, very sensible to the operating conditions like temperature, voltages, gas composition, small deviation from the nominal conditions could have significant effects on the detector’s output. A review of the existing software will be presented in the next section and a proposal for an alternative solution which will mitigate some problems of the current simulation tools.

2. EXISTING SOFTWARE TOOLS FOR SIMULATION OF GAS DETECTORS

2.1. GARFIELD

The first approach to an effective detailed simulation of drift chambers, TPC, and the multi-wires counter was done on 1984 with a software tool named Garfield [6]. The main advantage of this solution is that it is able to interface with other packages to perform some specific tasks. It connects with Magboltz [7] to calculate the characteristics of the detector gases for the given setup conditions. The interface with Heed [8] allows the detailed calculation of the scattering and photoionization processes. Another useful feature of Garfield is the interface with neBEM [9], a finite element analysis software which can calculate the electrostatic field for a given geometry, when analytical solutions are not feasible.

One of the weak points of Garfield is the programming language used to write it. Despite the fact that when it was developed, Fortran was the best suitable solution for scientific research, with a plenty of available libraries, nowadays it is preferred to write software using object oriented programming languages, like C++. For this reason, it is now much difficult to find the expertise needed to maintain legacy software and to implement new functionality like multi-processing and vectorization.

A port to C++ of the Fortran version was created by the same team and it was named Garfield++ [10]. This package is dedicated to the simulation of micropattern gaseous detectors and uses many of the Garfield’s principles, like the integration with Magboltz. While this solution reduces considerably the development time, using existing and validated solutions, it inherits the impossibility to use modern technologies for the most computing intensive elaborations, like the multi processes support and the impossibility to simulate complex geometries.

2.2. GEANT4

Geant4 is a software tool used to perform the simulation of particle detectors in high energy physics [11]. It has a complete physics library set and it is intensely
used at LHC experiments to model their complex detector geometries. Due to the completeness of the geometry primitives available in Geant4, this software is used at ATLAS experiment as the main simulation framework [12]. Unfortunately, this framework can not be directly used for the simulation of gas detector: Geant4 is limited to the study of the particle energy loss and, by default does not have an integration with other packages specialized in gas characterization.

3. A SEMI-ANALYTICAL APPROACH

In this section, we will present our proposal for a semi-analytical approach which it is worth taken into account. Our aim is to create a solution which combines the strong points of the software presented above and, at the same time, improve some weak points. The simulation of the electron amplification avalanche in Garfield is performed by an electron basis: every electron of the avalanche is simulated individually. While Garfield produces very accurate results, it results computationally expensive, considering often we are just interested about the macroscopic generated signal. Another desirable feature would be a full compatibility with existing used geometry primitives: Geant4 became a de facto standard at LHC and most of the detector’s geometry is built using this framework.

In the Micromegas detector, the signal collected on the readout strips is an induction signal caused by the movement of the electrons in the amplification region. To calculate the signal we need to use the Shockley-Ramo theorem [13], which allows calculating the induction signal generated by multiple moving charges in a complex system composed of multiple readout electrodes. The current induced on the $k$ electrode has the form:

$$I_k(t) = \sum_i q_i \cdot \frac{E_k}{V} \cdot v_i$$

where $q_i$ and $v_i$ are, respectively, the charge and the speed of the moving electron, $E_k/V$ is the weighting field given by the $k$ electrode when its voltage is set to 1 V and other electrodes are grounded. This formula considers the position and speed of every electron in the avalanche. It is very important to remark that, because an avalanche is composed by $\approx 10000$ electrons it results far too computationally expensive.

A more efficient solution to this problem can be implemented if we combine the Shockley-Ramo with the Townsend theory [14]. This way, we can obtain an analytical solution for the signal generated by the avalanche amplification [15]:

$$I_{kn}(t) = q_0 v_n \frac{E_z(x_0 + v_n t)}{V_k} \exp(\alpha v_n t)$$
I_{kp1}(t) = q_0 v_p \frac{E_z(x_0 + v_p t)}{V_k} \exp(\alpha v_n t - \alpha v_p t - 1) \tag{3}

I_{kp2}(t) = q_0 v_p \frac{E_z(x_0 + v_p t)}{V_k} \exp(\alpha d - \alpha v_p t - 1) \tag{4}

where the total current induced on strip $k$-th by electrons and ions is:

$I_k(t) = \begin{cases} 
I_{kn}(t) + I_{kp1}(t) & \text{for } 0 \leq t < t_n \\
I_{kp2}(t) & \text{for } t_n \leq t < t_p 
\end{cases}$ \tag{5}

This formulation allows us to calculate analytically the induced current for any given readout electrode of the Micromegas, knowing the gas Townsend coefficient $\alpha$ and the drift speed of electron and ions ($v_n, v_p$), the weighting field $E_z/V_k$ generated by every $k$ readout electrode and the distance $d$ between the mesh the readout plane.

To calculate the gas coefficients ($\alpha$ and $v_n, v_p$) we decided to interface with Magboltz until a more modern solution will become available. Magboltz will calculate the $\alpha$ coefficient and the electron drift velocity $v_n$ while, for the ion counterpart, $v_p$ we needed to fall-back to the Langevin theory to get an adequate estimation [16, 17].

The last element we need to calculate is the weighting field generated by every strip. The determination of such fields would require the use a finite element software. While this is a very versatile solution, allowing a precise field calculation for arbitrary geometries, it is possible to use a simpler analytical expression for the weighting field [18]:

$$
\frac{E_x}{V_k} = \frac{1}{2D} \left( \frac{\sin \left( \frac{\pi x}{D} \right)}{\cosh \left( \frac{\pi x + W/2}{D} \right) - \cos \left( \frac{\pi x}{D} \right)} - \frac{\sin \left( \frac{\pi x}{D} \right)}{\cosh \left( \frac{\pi x - W/2}{D} \right) - \cos \left( \frac{\pi x}{D} \right)} \right) \tag{6}
$$

$$
\frac{E_y}{V_k} = 0 \tag{7}
$$

$$
\frac{E_z}{V_k} = \frac{1}{2D} \left( \frac{\sinh \left( \frac{\pi x + W/2}{D} \right)}{\cosh \left( \frac{\pi x + W/2}{D} \right) - \cos \left( \frac{\pi x}{D} \right)} - \frac{\sinh \left( \frac{\pi x - W/2}{D} \right)}{\cosh \left( \frac{\pi x - W/2}{D} \right) - \cos \left( \frac{\pi x}{D} \right)} \right) \tag{8}
$$

4. REQUIREMENTS

In this section, we present the requirements needed in order to create a valid and versatile solution. The focus is on the needs of both advanced and starter users. For the first ones we decided to give the possibility to deeply customize the simulation parameters, while for the beginners, we decided to have a user-friendly default
setting, allowing to perform a simulation with fewer commands.

4.1. GEANT4 INTEGRATION

The first requirement is to use the Geant4 framework. This allows us to integrate perfectly with the infrastructure existing in the various experiments and to use the complete physics library available. Another important requirement is to use all code conventions existing in Geant4, giving other developers the possibility to modify our solution to better fit their needs. As we said before, Geant4 is not able to simulate the avalanche amplification and the induction signal. For this reason, some modules must be developed and integrated with the existent infrastructure.

4.2. DETECTOR CUSTOMIZATION

We decided to emphasize on the level of customization for the detector. It must be possible to set all the parameters of the Micromegas detector, like the size of the amplification region, the dimensions, the pitch of the readout electrodes, the size of the active area and many others. Another very important aspect is the capability to customize the attributes of the gas mixture. An ideal solution would be to specify any combination of gases but as a first step, it would be enough to be able to define the gas temperature, pressure, and ratios of Ar:CO$_2$. The last elements the user can modify are the value and direction of the electric fields.

4.3. BATCH MODE

Due to the degree of customization required in the previous demand, it is important to be able of creating some batch script. Geant4 provides a basic scripting language and we can use it for the detector customization, given the fact that we created a full command set covering all the attributes that can be introduced by the user.

4.4. ROOT EXPORT

ROOT is a software platform used in high energy physics to perform data storage and analysis. One of the key advantages of this platform is the possibility to store a huge quantity of data in space efficient root files. A desirable feature of our solution would be the capability of saving the simulation setup and results into root files, so they can be analyzed later in time.

5. PROTOTYPE RESULTS

To test the feasibility of our solution a prototype was created and tested with several configurations. The base configuration is composed by a Micromegas de-
tector with a 5 mm active drift region with an electric field of 0.6 kV/cm and an 128 µm amplification region with a field 39 kV/cm. The X strips have a size/pitch of 200 µm/250 µm while the Y strips have a size/pitch of 80 µm / 250 µm. The gas has a pressure of 1 atm at 20 °C and it is a mixture of Ar:CO₂ with the ratio 93 : 7.

In figure 3 we illustrate the peak in current induced on the X readout strips by a primary electron created in the drift region which enters in the avalanche section. In figure 4 it is possible to see the detector response to a set of different particles at different energies. Another thing we would like to remark is the different detector response when the composition of the gas is altered, as shown in figure 3. In figure 5 it is presented the charge collected by the detector when hit by 50 muons at 1 GeV.

![Figure 2](image.png)

**Fig. 2** – Current peak induced on the X readout electrodes by a 1 GeV incident muon.
6. SUMMARY AND CONCLUSIONS

In this article, we discussed the existing solutions for gas detector simulation used in high energy physics. The advantages and disadvantages of every solution were analyzed.

A new semi-analytical application was proposed. The theoretical framework was discussed and a prototype was created and tested in a common setup.

The preliminary results of the tests performed with our prototype are comparable with theoretical predictions and with the experimental measurements.

To fully validate our simulation tool we plan to perform an extensive set of benchmarks, in which we would like to study: the spatial resolution, gas gain, detector efficiency and overall performance. This study is mandatory before the public release of our fast simulation tool for the Micromegas detectors.

Fig. 3 – Plot measuring the pack current for a variable set of gas ratio. Lower levels of CO$_2$ produce higher avalanche amplification.
Fig. 4 – Detector response to different particle at different energies.

Fig. 5 – This histogram represents the total charge collected by every strip on X direction by a bunch of 50 muons spread on the detector surface (gun distance 50 cm).
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REFERENCES

13. S. Ramo, Proceedings of the IRE 27(9), 584–585 (1939); https://doi.org/10.1109/JRPROC.1939.228757.