Simulation of gas avalanche in a micro pixel chamber using Garfield++

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ABSTRACT: A micro pixel chamber (µ-PIC), the development of which started in 2000 as a type of a micro pattern gas detector, has a high gas gain greater than 6000 in stable operation, a large detection area of 900 cm², and a fine position resolution of about 120 µm. However, for its development, simulation verification has not been very useful, because conventional simulations explain only part of the experimental data. On the other hand, some µ-PIC applications require precise understanding of the fluctuation of the gas avalanche and signal waveform for their improvement; therefore, there is a need to update the µ-PIC simulation. Hence, we adopted Garfield++, which is developed for simulating a microscopic avalanche in an effort to explain experimental data. The simulated avalanche size was well consistent with the experimental gas gain. Moreover, we calculated a signal waveform and successfully explained the pulse height and time-over-threshold. These results clearly indicate that the simulation of µ-PIC applications will improve and that Garfield++ simulation will easily facilitate the µ-PIC development.

KEYWORDS: Gaseous detectors; Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Time projection Chambers (TPC)

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1 Introduction

A micro pixel chamber (μ-PIC), the development of which started in 2000 as a type of a micro pattern gas detector, is a gaseous two-dimensional imaging detector with a fine pixel electrode based on the printed circuit board technology [1]. The pixel electrode of the μ-PIC with a pitch of 400 μm is placed on a polyimide substrate, as shown in figure 1 (left), and each pixel works as a proportional counter. To date, we developed a μ-PIC having a detection area of 10.24 × 10.24 cm² (256 × 256 pixels) [2] and 30.72 × 30.72 cm² (768 × 768 pixels) [3]. The characteristics of the μ-PIC are fine position resolution (RMS ∼120 μm), high gas gain (max ∼15,000), good gain uniformity (5% RMS), and stable continuous operation of greater than 1000 h with a gas gain of ∼6000 [4]. Detailed charged particle tracks can be obtained by a time projection chamber (TPC) using a μ-PIC. μ-PICs are employed in various applications such as for MeV gamma-ray astronomy [5, 6], medical imaging [7], neutron imaging [8], dark matter search [9], small-angle X-ray scattering [10], and gas photomultiplier [11]. Recently, high track precision is required by several applications. For that purpose, we developed a new data acquisition system for the TPC using the time-over-threshold (TOT) [12]. By the TOT-TPC, we can obtain high-quality tracks, shown in figure 1 (right).

Moreover, simulations of the application detectors are necessary for better accuracy, and require knowledge of waveform, gas gain uncertainty, and dependence on the anode voltage. However, for the development of a μ-PIC, verification using the simulation of gas avalanche has not been very useful, because the conventional simulation on the macroscopic scale explains only part of the experimental data. Therefore, we need to simulate the avalanche on the microscopic scale. Garfield [13], which is a simulator of gas detectors on the macroscopic scale, was updated to Garfield++ [14]. By employing Garfield++, we can trace the gas avalanche on the microscopic scale. Also, it supports several finite-element-method calculations for an electric field, which readily allows us to investigate the gas avalanche simulation. We fabricated a μ-PIC pixel electrode using Gmsh [15] and Elmer [16] and simulated the avalanche and signal waveform with a simulator of a μ-PIC using Garfield++. In this study, we report the first results of a gas avalanche simulation in a μ-PIC for comparison with past experiments.
2 Definition of geometry

We defined the geometry of the pixel electrode as a unit cell having an area of $400 \times 400 \, \mu m^2$, and generated a three-dimensional mesh using Gmsh. We constructed electrodes utilizing the measured values for a realistic simulation. The adopted and measured values are listed in table 1. The gas area above the electrodes had a depth of 1.5 mm for electron drift and was filled by Ar 90% + ethane 10% at a pressure of 1.0 atm. We periodically placed this unit cell in the electric field calculation and Garfield++ simulation. Initial electrons were generated at random positions in the area of $400 \times 400 \, \mu m^2$, at 1.0 mm above the electrodes. For calculating maps of the electric, potential, and weighting fields, we adopted Elmer. The drift electric field and cathode voltage were fixed at 1.0 kV/cm and 0 V, respectively. The dielectric constants of the gas, polyimide substrate, and copper electrode were 1, 3.5, and $10^{10}$, respectively. To define the electric field map in Garfield++, we used ComponentElmer class [17].

![Figure 1. Schematic view of $\mu$-PIC (left) and an example of a track obtained by a $\mu$-PIC TPC.](image)

![Table 1. Geometric parameters in the $\mu$-PIC electrode model.](table)

| parts     | parameters     | model     | measured          |
|-----------|----------------|-----------|-------------------|
| Anode     | pillar         | upper diameter | 70 $\mu m$       |
|           |                | lower diameter | 50 $\mu m$       |
|           | cap            | diameter    | 60 $\mu m$       |
|           |                | height      | 15 $\mu m$       |
|           | strip          | width       | 285 $\mu m$      |
|           |                | thickness   | 15 $\mu m$       |
|           |                |            | 15$^{+3}_{-0}$ $\mu m$       |
| Cathode   | strip          | width       | 340 $\mu m$      |
|           |                | thickness   | 15 $\mu m$       |
|           | opening        | diameter    | 256 $\mu m$      |
| Substrate | thickness      |            | 75 $\mu m$       |
|           |                |            | 75$^{+5}_{-0}$ $\mu m$       |
Figure 2. Avalanche size as a function of anode voltage (a) and dependence of fitted parameters on Penning effect rate (b, c). Filled circles are obtained by simulation with Penning effect rate of 0.0 (blue), 0.2 (magenta), 0.4 (red), and 0.6 (green). The blue solid line denotes the interpolated avalanche size with a Penning effect rate of 0.31. For comparison, the experimental gas gain is denoted by open squares (SN040426-1) and filled triangles (SN050921-1).

3 Simulation results

3.1 Avalanche in µ-PIC

First, we simulated the avalanche size by counting the electron-ion pairs generated in an avalanche by microscopic tracking. The filled circles in figure 2a denote the simulated avalanche size as a function of the anode voltage $V_a$ and Penning effect rate $r$. We fitted these plots with

$$A_r(V_a) = \exp(\alpha_r + \beta_r V_a),$$

(3.1)
at each $r$, and the dependence of the obtained $\alpha_r$ and $\beta_r$ on $r$ is shown in figures 2b and 2c, respectively. In the case of Ar 90% + ethane 10%, the Penning effect rate is 0.31 [18]. Hence, we interpolated $\alpha_r$ and $\beta_r$ under the assumption that the dependence of $\alpha_r$ and $\beta_r$ is a linear function of $r$. The calculated avalanche size using the interpolated $\alpha_r$ and $\beta_r$ is represented by the blue solid line in figure 2a. For comparison, the measured effective gas gain was represented by the open squares and filled triangles in this figure. The interpolated avalanche size is well consistent with the experimental gas gain. Hereafter, we fixed the Penning effect rate to 0.31. In the case of a proportional counter, the single-electron spectrum, which represents the uncertainty of gas gain, is described by Polya distribution

$$g(x) = \left(\frac{x(1 + \theta)}{\bar{A}}\right)^\theta \exp\left(-\frac{x(1 + \theta)}{\bar{A}}\right),$$

(3.2)

where $\bar{A}$ is the average gas gain, and the parameter $\theta$ gives the theoretical limit of energy resolution [19–21]. Figure 3 represents the single-electron spectrum of a µ-PIC obtained using the
Figure 3. Single-electron spectra of a µ-PIC with anode voltages of 460 V (left) and 560 V (right), and a Penning effect rate of 0.31. The filled circles are obtained using Garfield++ simulation, and the solid line is a fit utilizing the Polya distribution.

Figure 4. Number density map of an electron-ion pair generated (a) and center of gravity in each avalanche (b) at an anode voltage of 560 V.

Garfield++ simulation. The solid line in this figure was obtained by fitting with the Polya distribution. The Polya distribution can explain these spectra, although the electric field map of a µ-PIC is complex in comparison with that of a proportional counter. By fitting several single-electron spectra with different anode voltages, we obtained θ which was approximately 0.65, regardless of the anode voltage.

For studying the occurrence of avalanches, we generated 1000 seed electrons and then traced the secondary electrons. Figure 4a shows the number density map of points of the secondary electrons generated at an anode voltage of 560 V. As shown in the figure, the majority of the avalanche is formed in a limited area below 80 µm from the anode. Figure 4b shows the number density map of the center of gravity in each avalanche. The center of gravity of the avalanches is concentrated above the anode at approximately 5 µm. The distances between the anode and center of gravity of the avalanches are nearly the same, even when the anode voltage is changed. Therefore, the signal waveform with the exception of charge is insensitive to the anode voltage. On the other hand, we also studied the termination points of all electrons. Two percent of the electrons in the avalanche are terminated on the substrate, whereas the remaining drift to the anode. Therefore, the electron
collection efficiency of a $\mu$-PIC is 98%. This result is approximately consistent with the results of a previous simulation [22], which state that most of the electrons reach the anode and the remaining drift to the substrate.

3.2 Signals and time-over-threshold

Next, we simulated the induced current using the weighting field of the anode. We used the ion mobility data established in [23]. Figure 5 shows a sample single-electron signal. This signal waveform consists of two components. The first, caused by electrons, is a sharp spike with a pulse width of approximately 1 ns. The second, caused by ions, represented by the red line in figure 5, exhibits a slow decay time. Furthermore, the charge of the ion component is approximately 9 times higher than that of the electron component. In the case of an avalanche at $5 \mu m$ from the anode of a proportional counter with an anode radius of $30 \mu m$ and a cathode radius of $128 \mu m$, the charge of the ion component is 8.4 times higher than that of the electron component, which is almost equal to the avalanche of a $\mu$-PIC. On the other hand, because of complications of the electric field map of a $\mu$-PIC, the ion component takes various pulse shapes, which depend on the ion transportation paths. Therefore, the formulation of the signal waveform is difficult.

To simulate the signal output of a $\mu$-PIC, we simulated 2000 single-electron signals as waveform templates. Using this template, we calculated the signal waveform of a $\mu$-PIC as follows:

1. Create seed electrons with a Gaussian distribution having mean $E/w$ and sigma of $\sqrt{fE/w}$, where $E$, $f$, and $w$ are the deposit energy, the Fano factor, and $w$ value of gas, respectively.
2. Define the uncertainty of arrival time by using the longitudinal diffusion of each seed electron.
3. Define the average avalanche size $\bar{A}$ with a Gaussian distribution having a sigma of $\sigma_A$ for each pixel because of the fluctuation in $\mu$-PIC gain uniformity.
4. Obtain the avalanche size $A$ using a Polya distribution with mean $\bar{A}$ and $\theta$ of 0.65 for each seed electron.
5. Select a waveform from 2000 signal templates and multiply it by $A$. 

![Figure 5. Signal waveform sample for single-electron. The blue and red line are induced by electrons and ions, respectively.](image)
Figure 6. Emulated signal waveform with 16 ns ASD (a) and 80 ns ASD (b). Experimental waveform (c) measured by utilizing X-ray irradiation of MnKα (5.89 keV) from ⁵⁵Fe. The experimental pulse height is well explained by this signal emulator.

6. Obtain the output signal of a μ-PIC by summing the single-electron signals for all seed electrons.

7. Simulate the readout circuit and compare it with the experimental data.

As a readout, we use an amplifier-shaper-discriminator (ASD) chip having a time constant of 16 ns [24], designed for the ATLAS Thin Gap Chamber, or a redesigned ASD having a time constant of 80 ns [25]. We built the readout emulator with the responses obtained by the spice simulation of 16 ns and 80 ns ASD ICs. Figure 6a represents the emulated signal waveform by this method under the assumptions $E = 5.89$ keV, $w = 26$ eV, $f = 0.17$, $\bar{A} = 3000$, $\sigma_{\bar{A}} = 7\%$, and an ASD time constant of 16 ns. The emulated signal waveform with 80 ns ASD is shown in figure 6b. From these figures, the emulated pulse heights of 16 ns ASD and 80 ns ASD are 11 mV and 23 mV, respectively, and the ratio of the pulse height is approximately 2.2. Figure 6c shows an example of a waveform measured by using the X-ray irradiation of MnKα (5.89 keV) from ⁵⁵Fe. The experimental pulse heights obtained by 16 ns ASD and 80 ns ASD are approximately 10 mV and 20 mV, respectively. By comparing the experimental data and simulation results, we found that the emulated pulse height is well consistent with the experimental pulse height, as well as the difference in pulse height caused by the ASD time constant. However, the emulated signal waveform has a slightly long tail, which is not observed in the experimental waveform.

Finally, we simulated the TOT distribution as a function of deposit energy using the hit pixel number of TOT-track images. One TOT hit pixel was defined by $400 \mu\text{m} \times 10$ ns, which is the readout clock of the track encoding system [26]. Hence, the TOT hit pixel number represents an area of track images as shown in figure 1 (right). By measuring the gamma-ray irradiation of ¹³⁷Cs (662 keV), we obtained figure 7a with a TPC volume of $7.5 \times 7.5 \times 14$ cm$^3$, a gas gain of 24000 (10 by a GEM [27] and 2400 by a μ-PIC), a pressure of 1.5 atm, a drift velocity of 3.2 cm/μs, an ASD time constant of 80 ns and threshold of $-15$ mV. The TOT distribution of the electrons in the experimental data has two components. The first consists of fully contained events, which stop and deposit all energy in the effective volume of TPC, and the second consists of electrons above 200 keV, which escape from TPC. At 40 keV and 100 keV, the typical TOT hits for fully contained electrons are about 500 pixels and 1500 pixels, respectively. Because an electron above 200 keV, which becomes the escape event, runs longer than tens of keV electrons, the TOT hit of escape events is larger than that of fully contained events. For simulating TOT tracks, we built a simulator of a μ-PIC TPC using Geant4.9.0-p01 [28, 29] with a TPC volume of $10 \times 10 \times 14$ cm$^3$, a
Energy [keV]
0 20 40 60 80 100 120

TOT [pixel]
0 500 1000 1500 2000 2500 3000 3500 4000

Escape Events
Fully contained

Figure 7. Dependence of the TOT hit pixels as a function of deposit energy: a) experimental data, and b) simulations based on Geant4. Each TOT distribution has two components: fully contained events and escape events.

transverse diffusion of $\sigma_{\text{trans}} = 450 \mu m/\sqrt{\text{cm}}$, and a longitudinal diffusion of $\sigma_{\text{long}} = 350 \mu m/\sqrt{\text{cm}}$. As initial particles, we generated electrons at random positions in the TPC volume with a flat energy spectrum below 200 keV in random directions. Then, we obtained the energy deposit of electrons, calculated signals at each pixel, emulated the digital pulses, and compared the simulated tracks with the experimental TOT tracks. The simulated TOT distribution shown in figure 7b has also two components, and the number of simulated TOT hits is nearly equal to that of the experimental data at each deposit energy. Therefore, we can say that this simulator describes the TOT distribution well, and is a precise simulator for $\mu$-PIC applications.

4 Summary

For a more precise study of $\mu$-PIC and its applications, we simulated gas avalanches at a microscopic scale using Gmsh, Elmer, and Garfield++. The simulated avalanche size was well consistent with the measured gas gain, and the single-electron spectrum of $\mu$-PIC was described by a Polya distribution. By tracking the secondary electrons, the avalanches were confirmed to form at a distance below 80 $\mu m$ the anode. The electron collection efficiency was about 98%, which is approximately consistent with previous simulation results. We also obtained the waveform of a seed electron incident. The induced current consisted of a sharp spike caused by electrons and a slow pulse caused by ions. The charge ratio of the electron component to the ion component was similar to that of a proportional counter. Moreover, for comparison with the experimental data, we created a readout emulator of ASD ICs. The pulse height dependence on the time constant of the preamplifier was explained well by this readout emulator. Finally, with the Geant4 and ASD emulator, we could approximately explain the TOT hits distribution. From these results, it is clear that a simulation based on Garfield++ can explain a $\mu$-PIC. Garfield++ gives a signal waveform, gain uncertainty, and TOT distribution to $\mu$-PIC TPC applications. Furthermore, the Garfield++ simulation will facilitate the $\mu$-PIC development because the design of pixel electrode structure using computer simulation can be studied.
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