GEM simulation methods development

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Abstract

A review of methods used in the simulation of processes in gas electron multipliers (GEMs) and in the accurate calculation of detector characteristics is presented. Such detector characteristics as effective gas gain, transparency, charge collection and losses have been calculated and optimized for a number of GEM geometries and compared with experiment. A method and a new special program for calculations of detector macro-characteristics such as signal response in a real detector readout structure, and spatial and time resolution of detectors have been developed and used for detector optimization. A detailed development of signal induction on readout electrodes and electronics characteristics are included in the new program. A method for the simulation of charging-up effects in GEM detectors is described. All methods show good agreement with experiment. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

This article is an attempt to give a review of results of systematic work on the development of simulation methods for gas electron multipliers (GEM) [1]. A set of methods and simulations tools have been developed to simulate the main detector characteristics, and they can be used for detector optimization.

2. Simulation of GEM micro-characteristics

Our simulations of detector micro-characteristics such as primary electron collection efficiency - $\varepsilon_{\text{prim}}$ (also known as “detector transparency”), hole multiplication-$M_{\text{hole}}$, secondary electron collection efficiency-$\varepsilon_{\text{sec}}$, charge losses and effective detector gas gain-$M_{\text{eff}}$ are based on well-known simulation tools, namely the Maxwell [2] and Garfield [3] programs. Garfield’s Runge–Kutta drift subroutine is used for $\varepsilon_{\text{prim}}$ estimation. A primary charge takes part in the multiplication process only when it is moving along lines entering the hole region (see Fig. 1). The integral of the Townsend coefficient along all drift lines and over the cross-section of the periodic element (the periodic element of the foil geometry is shown in Fig. 2) yields the integral multiplication in the hole-$M_{\text{hole}}$. The most important features of the developed method are calculations of charge fractions on different detector electrodes (Fig. 3) and the estimation of their contributions to the total charges (directly collected and induced) which are measured on different detector electro-
For these calculations, Garfield’s avalanche routine is used. The secondary electron collection efficiency, $e_{sec}$, and an additional coefficient $r$, which is roughly equal to 2 (arising from the fact that the charge induced on the readout electrode by moving electrons is approximately equal to the collected charge) are the other components of the effective detector gas gain, $M_{eff}$, which can be
Fig. 3. Charge fractions from the avalanche on different detector electrodes and the dielectric surface, and total measured charges on different detector electrodes.

Fig. 4. Simulated effective gas gain for the G1 double conical GEM geometry measured in Ref. [4].
written as
\[ M_{\text{eff}} = e_{\text{prim}} M_{\text{hole}} e_{\text{sec}}. \]

The results of the effective gain simulation [5] are consistent with experimental data [4] (Fig. 4). The simulated dependence of measured charges on different detector electrodes versus the drift field value is also very close to the one measured in experiment (see Fig. 5). This fact is an additional proof of the method’s usefulness and can be used in detector optimization.

3. Dynamics of charging-up

From the avalanche calculations, we know where electrons and ions hit the kapton foil. The kapton foil is not a perfect insulator but capable of conducting small currents, which play an important role in the dynamics of the charging-up of the GEM foils. Apart from a constant current between

\[ Q_D \] is the charge measured in the drift electrode, \( Q_U \) is the charge in the upper GEM foil, \( Q_L \) is the charge in the lower GEM foil and \( Q_R \) is the charge seen by the readout electrode. Solid curves assume that charge deposited on the insulator will flow to the upper and lower GEM electrodes. Dashed curves assume the charge deposited on dielectric media does not move.

Fig. 5. Charge flow in a G4 foil as function of the drift field. \( Q_D \) is the charge measured in the drift electrode, \( Q_U \) is the charge in the upper GEM foil, \( Q_L \) is the charge in the lower GEM foil and \( Q_R \) is the charge seen by the readout electrode. Solid curves assume that charge deposited on the insulator will flow to the upper and lower GEM electrodes. Dashed curves assume the charge deposited on dielectric media does not move.

Fig. 6. The charge redistribution mechanism and an equivalent diagram of the charging-up effect. During the charging-up two main charge configurations are found. These configurations are responsible for the rise and fall time constants of the detector gas gain variation as shown in Fig. 8.
the two GEM electrodes, electrons hitting the foil will migrate towards the GEM electrodes and also towards ions hitting the foil elsewhere, thus generating additional currents. These currents are responsible for a potential gradient over the inside of the hole, which affects the field in the hole and hence also the location at which further electrons and ions will be deposited. As a result, the gain will change.

We describe this feedback mechanism with the help of an equivalent electrical diagram, to try and explain the changes in effective gain during and after charging up. When irradiation of the GEM starts, the electrons and ions hit the kapton as illustrated in the top half of Fig. 6. The ions tend to end up near the lower GEM electrode, which is already positively charged, while the electrons concentrate in the upper, negatively charged half of the GEM. Thus, the deposits enhance the field inside the GEM and therefore also the gain.

The voltage at the point where the charge is injected can be explained within the proposed equivalent diagram by a simple equation, as a function of time

\[ V(t) = I_0 R (1 - \exp(t/\tau)) \]

![Fig. 7. Equivalent diagram response on applied irradiation.](image)

The effective gas gain variation due to the charging-up of the GEM dielectric for the G16 foil geometry measured in Ref. [6]. Zero time is the moment when the particle rate is switched on, and the vertical line shows the time when the particle rate is switched off.

![Fig. 8. The effective gas gain variation due to the charging-up of the GEM dielectric for the G16 foil geometry measured in Ref. [6]. Zero time is the moment when the particle rate is switched on, and the vertical line shows the time when the particle rate is switched off.](image)
where \( \tau = RC \), \( R \) and \( C \) are the resistivity of the hole’s surface and the capacity for the point under study.

The voltage behavior can be explained (see Fig. 7) as reaction of the \( RC \) circuit on the step-function front of \( I(t) \).

For the double conical geometry G16 studied in Ref. [1] the charging-up mechanism can be explained in the following way: at the start of the process (when the particle rate is switched on) the initial charge configuration (top half of Fig. 6) defines the rise time of the gain change. This stage takes place when the variation of the gain is small (up to 5–10% of the gain value).

During the next step a saturation of the process occurs when multiple feedback keeps the value of the gain at the level of the maximum variation. The value of the gain in these points is defined by the charge configuration shown in the bottom half of Fig. 6. The discharge of the system and the fall time for the process when the particle rate is switched off will also be defined by this final charge configuration.

### Table 1

Gas electron Multipliers (GEM) geometry

<table>
<thead>
<tr>
<th>Foil#</th>
<th>( P ) (( \mu m ))</th>
<th>( D ) (( \mu m ))</th>
<th>( d ) (( \mu m ))</th>
<th>( T ) (( \mu m ))</th>
<th>( s ) (( \mu m ))</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>200</td>
<td>110</td>
<td>100</td>
<td>75</td>
<td>18</td>
<td>Rec.</td>
</tr>
<tr>
<td>G4</td>
<td>120</td>
<td>65</td>
<td>30</td>
<td>50</td>
<td>5</td>
<td>Hex.</td>
</tr>
<tr>
<td>G16</td>
<td>200</td>
<td>140</td>
<td>80</td>
<td>50</td>
<td>15</td>
<td>Rec.</td>
</tr>
</tbody>
</table>

\( P \) is the structure pitch, \( D \) and \( d \) are the external and inner diameters of the hole, \( T \) is the thickness of the dielectric and \( s \) the thickness of the copper.

![Fig. 9. A typical simulated event for a single-GEM configuration. Large ionization corresponds to production of \( \delta \)-electrons.](image-url)
The results of the simulation are in good agreement with experiment [6]. The simulation dependence is shown by the solid line in Fig. 8 while the points are measured values. The simulation of the charging-up is in good agreement also for other detector geometries [7] (4 types were studied), e.g., for a practically cylindrical G1 geometry the gain variation was negligible, as was also found experimentally (Table 1).

4. Simulation of the spatial resolution of the detector

We have developed a program that simulates a complete GEM detector: an ionization gap, one or more GEM foils and transfer gaps, an induction gap and readout strips. HEED is used to generate the ionization deposits [8]. We apply noise and electronics transfer functions to the signal shape calculated by the program and then derive the space and time resolution [9].

Fig. 9 shows an event with ionization deposits and electron trajectories. Fig. 10 shows the coordinate resolution estimated from a sample of 20000 such events.

5. Conclusion

A review of methods for the accurate modeling of GEM characteristics has been given. Practically all the main detector characteristics can be calculated and are in good agreement with measurements. The developed methods and simulation tools can be used for detector characteristics optimization in the micro- and macro-parameter regions.

![Fig. 10. Simulated spatial resolution of the detector for the centroid method.](image)
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References