Effects of the induction-gap parameters on the signal in a double-GEM detector

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Abstract

A study of a dual-GEM detector coupled to a strip readout anode is described. The effects of the induction electric field and GEM-to-anode gap are presented, for an operation in atmospheric pressure Ar/CO₂ (70/30) and Ar/CH₄ (95/5). Visible gain and anode signal pulse-shapes, measured with 5.9KeV x-rays, are presented for 1-6 mm wide induction gaps and for induction fields ranging up to 6kV/cm. The spatial distribution of the anode charge is provided for induction gaps of 2-12 mm. The results are useful for matching the detector parameters to the position recording circuit requirements.

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1. Introduction

The GEM (Gas Electron Multiplier) [1] consists of a thin insulator foil, metal-clad on both sides, perforated with a pattern of small holes. Applying suitable voltage across it, results in a very strong electric field within the holes, where the gas amplification process takes place.

Highly ionizing radiation permits conceiving detectors with single GEM amplification elements; high gains needed for the detection of low-ionization radiation are obtained with GEM preamplification foils preceding another type of gas multiplier, or by cascading multiple GEMs. 2D localization is obtained by coupling the last GEM in the cascade to a segmented anode readout circuit [2]. In a cascaded-GEM detector the charges generated in a given multiplication stage are driven towards the holes of the next GEM, under an appropriate electric field, which must be optimized to provide the transfer of a large fraction of the charges, with minimal losses of electrons to the GEM electrodes. The effects of electron transfer efficiency and transfer field optimization were exhaustively studied in [3, 4, 5].

In the multi-GEM detector we can define three different electron drift regions: the radiation conversion region, where the ionization electrons are created; the transfer region between successive GEMs and the induction region between the last GEM and the anode (see Figure 1). In the present work we have concentrated on the role and the optimization of the field in the induction region. Although GEM-based detectors have been widely studied, for particle tracking [6, 7], x-ray [8] and neutron [9, 10] imaging and in gas avalanche photomultipliers [11], the distribution of the detected charges on the position-recording anode is not well known. Usually, the trend has been to minimize the GEM-to-anode distance, reaching the smallest possible induction area; this is to cope with fast readout schemes consisting on thin anode strips connected to individual readout amplifiers [2]. However, more economical readout methods, e.g. charge division or delay-line readout, have opposite requirements; a broader distribution of the induced electron cloud on the anode circuit would result in a better interpolation of the localization information. We are currently developing a relatively large area (100x100mm$^2$) position-sensitive x-ray imaging multi-GEM detector with delay-line readout [12].

The aim of this work is to provide quantitative understanding of the dependence of the anode signal, namely pulse-height, rise-time and width, on the induction field and the GEM-to-anode induction gap. Since the delay-line works as a filter, pulses with either short rise-times or narrow width are strongly attenuated. The results of the present study should permit optimizing the GEM parameters for the delay-line readout method; selecting of the appropriate anode signals is expected to provide optimal signal transmission through the delay-line and
therefore good spatial resolution and homogeneous response over the full detector area. These will be reported in a separate article [12].

2. Experimental Setup

The detector setup, shown in Figure 1, consists of two GEM multipliers with overall dimensions of 30x30mm². The CERN-produced standard double-conical GEMs are made of 50 μm thick Kapton with 5 μm copper-clad on each side. The holes have a hexagonal pattern with a 140 μm pitch and 80 μm diameter (in Cu). The anode was either an 81% transparent metal mesh, used for pulse-height and time properties measurements, or a strip-electrode (50 μm wide strips, 200 μm pitch); both were placed at various distances from the second GEM. On the stripped anode, signals were recorded either from a single strip at its center or from the remaining interconnected strips of the full plane (see Figure 1). The window-and-drift cathode is made of a 6 μm thick aluminized Mylar; GEM electrodes are stretched on G10 frames. The drift and transfer gap widths are 3 mm and 2 mm, respectively.

All measurements were carried out with a 5.9 KeV x-ray source. For measurements of anode spatial charge distribution, we used a narrow slit, 100 μm wide, in front of the source; both were mounted on a precise moving support and displaced along the detector window. The detector and the x-ray source were mounted on an optical bench and the slit was precisely aligned, parallel to the strip anode, with the help of a telescope.

All GEM electrodes were powered independently and the signals were read through decoupling capacitors. To study the anode signal properties we used three different amplifiers: a charge amplifier (Ortec 124, sensitivity=275mV/pC) recording the total anode charge; a current amplifier (VV44, MPI Heidelberg, with 6 ns time constant), recording the pulse-height and pulse-width of the ‘fast’ component of the signals and a very-fast current amplifier (ESN, 0.5 ns rise-time) recording the signal’s rise-time. Pulses were recorded with a digital oscilloscope (Tektronix TDS3052); pulse-height spectra were measured with a multi-channel analyzer (Amptek MCA8000A). The detector was operated in flow mode with Ar/CO₂ (70/30) and Ar/CH₄ (95/5) mixtures at atmospheric pressure. Characteristic gain curves are shown in Figure 2.

3. Methodology

The charge collection on the anode is defined basically by the induction field. The same induction field also modifies substantially the intrinsic gain of the second GEM, affecting the
electric field penetration from the GEM holes into the induction gap. Both effects lead to an increase of the anode charge with the induction field. Therefore we proceeded in the following normalization of the measurements: we recorded the charge signal on the anode as function of the induction field, normalizing it to the signal on the bottom electrode of the second GEM – BGEM2. The normalization signal was recorded on the BGEM2 electrode, while keeping a small reverse field (-200V/cm) across the induction gap, insuring full collection of the charges from the multiplication process on the BGEM2 electrode.

We measured the effects of the induction field on both the pulse-height and the pulse-shape properties, varying it from 0 up to 6kV/cm over four different induction gaps (1, 2, 4 and 6 mm). While varying the induction field, the other fields and voltages across the GEM electrodes were kept constant. For Ar/CO₂ (70/30): UGEM1=500V, UGEM2=450V; for Ar/CH₄ (95/5): UGEM1=UGEM2=405V, in both cases, the gain is about 2x10⁴ (see Figure 2).

The spatial distributions of anode-induced charges were measured while connecting the amplifier to a single, 50 µm wide, strip anode and displacing the collimated source across the anode. The width of the collimated beam, at the center of conversion gap, is 260µm. The scanning experiments were done for induction gaps of 2, 6 and 12mm.

4. Results

4.1. Charge Collection

Typical charge pulses on BGEM2 and on the mesh anode are shown in Figure 3, for Ar/CO₂ (70/30). The peak value of BGEM2 signal with a reverse induction field (Figure 3a) is used to normalize the gain measured on the anode (Fig 3b); note the fast rise and shape of the anode pulse, due to the absence of an ion component. Figure 4 shows the normalized charge (anode charge divided by the BGEM2 charge) for each induction gap.

These curves show how much the induction field can affect the visible gain through the deformation of the electric field in the last GEM, extending its amplification region towards the induction gap region. A similar effect was also observed for single- [3, 13] and double-GEM [14] in Ar/CO₂; it results in a real gain increase and not just in a modified electron transport property.

4.2. Rise-Time

Examples of fast signals recorded with the 0.5ns-risetime amplifier on the anode mesh are shown in Figure 5. Figure 6 shows the measured rise-time (10 to 90% of pulse maximum) for different induction gaps as function of the induction field. The measurements were done at
equal detector gain. Note that the bipolar pulse-shape is due to the differentiation by the fast amplifier.

For small induction fields we have inefficient charge collection due to losses of electrons on the BGEM2 electrode; the rise-time is longer due to lower electron drift-velocity. As we increase the field, between 2.5–4 kV/cm, the charge collection reaches saturation and the rise-time reaches a plateau for all four induction gaps. For higher fields the rise-time seems to converge to about 4ns.

4.3. Pulse Width

Using the same set of induction gaps we measured the pulse-width with the 6 ns shaping-constant pre-amplifier, recording the pulse duration at 50% of its maximum. Figure 7 shows examples of pulses recorded for 2 and 6mm induction gaps, for equal detector gains. One clearly sees the effect of the induction field on both pulse width and height. We can notice on the pictures that varying the gap changes the pulse-shape but the area under the pulse stays constant for the same induction field. Figure 8 shows the pulse area versus the induction field, for different induction gaps; it is proportional to the total anode charge and its behavior for different induction fields follows very closely the normalized charge curve shown in Figure 4.

The pulse width, shown in Figure 9, results from the time required to collect the charge from the last GEM to the anode. The pulse width decreases with the field, following the increase in electron drift velocity; it reaches a plateau, different for each gap, at the drift velocity saturation.

If we normalize each point in Figure 9 to its respective induction gap, we obtain an indirect estimate of the collection velocity of the electrons; it is shown in Figure 10 for the induction gaps investigated. Except for the 1mm gap, all curves show similar behavior with saturation at about 5cm/µs, which are in good agreement with the electron drift velocity values found in the literature for Ar/CO₂ (70/30) [15, 16]. The different saturation value for the 1mm gap could be due to a larger relative field penetration, e.g. due to the 0.5 mm mesh opening.

4.4. Width of the Induced Charge

For this measurement we used the 1D strip-anode and measured the effect of the induction gap on the lateral size of the electron-cloud for Ar/CO₂ (70/30) and Ar/CH₄ (95/5) gas mixtures. Similar measurements were reported by other authors using different anode geometries [6] or gas mixtures [17]. The electric fields within the drift, transfer and induction
regions were kept constant at 1500, 2000 and 3000Vcm\(^{-1}\), and both GEMs were biased to provide equal total effective gains of 2\(\times\)10\(^4\) for both gas mixtures.

The measurement procedure consisted of moving the collimator and recording the corresponding charge spectra collected on the single-strip anode. We also recorded the charge spectrum from the surrounding interconnected strips, with the beam positioned far away from the isolated strip, in order to determine the total charge arriving at the anode plane. We used a gaussian fit to get the centroid for the 5.9keV peak. Figure 11 illustrates how the energy spectrum changes when the beam moves towards the strip. The slit is in front of the isolated strip at 10.6mm; the maximum fraction of the total charge is collected and the best energy resolution is reached.

Figure 12 shows the variation of the fraction of collected charge on a single-strip anode as a function of the source position, for different induction gaps in Ar/CO\(_2\) (70/30) and Ar/CH\(_4\) (95/5). The rms widths of these measured distributions (\(\sigma_{D\text{GEM}}\)), are given in Table 1. In the same table we also provide the calculated rms values for 6 keV x-rays, which include the contributions from the collimator width and alignment (\(\sigma=226\)\(\mu\)m), the photoelectron range (\(\sigma=212\)\(\mu\)m for both gas mixtures [18]) and the diffusion in the double-GEM detector, based on known diffusion coefficients [15, 16]. The last line in the table provides the calculated rms values for the case of infinitely small single-electron source, resulting solely from diffusion in the conversion, transfer and induction gaps. The experimental and calculated results are generally in agreement, indicating that other sources to the charge-distribution width, such as the GEM multipliers themselves and the electronic noise are negligible compared to the diffusion.

5. Conclusions

In this work we studied the effect of the induction field and the induction gap on the pulse height, the rise-time and the pulse width of fast anode signals in a dual-GEM setup in Ar/CO\(_2\) (70/30) gas mixture. We also studied the lateral width of the charge induced on the anode readout circuit in Ar/CO\(_2\) (70/30) and in Ar/CH\(_4\) (95/5).

The rise-time of the fast signal varies by only about 20% for induction gaps ranging from 1-6mm. On the other hand, both the induction field and the gap width have strong effect on the current pulse shape; nevertheless, the area under the fast pulse is fairly constant and as expected, follows the detector visible gain curve. The pulse width values saturate for fields above 3.5kVcm\(^{-1}\) and, except for the 1mm induction gap, their values are proportional to the induction gap. The induction field within the 1mm induction gap, also has an exceptionally
strong influence on the charge gain of the dual-GEM detector. Both effects are due to electric field penetration, resulting from the large anode mesh opening compared to the induction gap size.

The measured lateral spread of charges induced by a collimated x-ray beam in Ar/CO₂ (70/30) and Ar/CH₄ (95/5), for different induction gaps, are generally in rather good agreement with those expected from electron diffusion calculations.

The results of this work are relevant for optimizing the geometry of position encoding electrodes and readout systems of GEM detectors. An immediate application was the optimization of the delay-line readout circuit parameters in a currently studied two-dimensional 100x100mm² GEM detector, as discussed in a different work [12].

Acknowledgments

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References


### Tables

Table 1: Measured and calculated rms values of the induced charge distribution on the anode by 6keV x-rays, and calculated rms values for a point-like single-electron source, for different induction-gap widths and gas mixtures.

<table>
<thead>
<tr>
<th>Induction Gap</th>
<th>(2\text{mm})</th>
<th>(6\text{mm})</th>
<th>(12\text{mm})</th>
<th>(2\text{mm})</th>
<th>(6\text{mm})</th>
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</thead>
<tbody>
<tr>
<td>Measured (\sigma_{DGEM}) ((\mu m))</td>
<td>340</td>
<td>485</td>
<td>510</td>
<td>454</td>
<td>781</td>
</tr>
<tr>
<td>Calculated (\sigma_{DGEM}) (for our 6keV x-rays) ((\mu m))</td>
<td>356</td>
<td>393</td>
<td>443</td>
<td>578</td>
<td>617</td>
</tr>
<tr>
<td>Expected (\sigma) (for ideal single e(^{-})) ((\mu m))</td>
<td>175</td>
<td>242</td>
<td>317</td>
<td>487</td>
<td>533</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1: A schematic view of the experimental setup. The detector is irradiated with 5.9 KeV x-rays from a collimated $^{55}$Fe source. The signals are read from the anode, which is either a mesh or a stripped plane, placed 1-12mm away from GEM2.

Figure 2: Charge gain of double-GEM in Ar/CO$_2$ (70/30) and Ar/CH$_4$ (95/5), measured by recording the charge pulses on the bottom side of GEM2, with a reversed induction field EI. The values of the conversion-and-drift field, ED, and the transfer field, ET, are marked in the figure.

Figure 3: Charge pulses recorded from (a) the bottom of GEM2, with a reversed induction field and (b) from the anode mesh under 3kV cm$^{-1}$ induction field and 2mm induction gap. The shape difference is due to the ion component present in (a) but not in (b).

Figure 4: Normalized amplitude of anode charge pulses as function of the induction field, measured in Ar/CO$_2$ (70/30) for four different induction gaps. The lines are drawn to guide the eye. The induction field strongly affects the actual GEM2 gain by modifying the field in the GEM vicinity.

Figure 5: Current anode pulses recorded with a fast amplifier (0.5ns rise time), in Ar/CO$_2$, for a 2kV cm$^{-1}$ induction field. (a) 2mm induction gap and; (b) 4mm induction gap. Note the different time and amplitude scales.

Figure 6: Anode-pulse rise-time, measured in Ar/CO$_2$ (70/30) with a fast pre-amplifier (0.5ns risetime), as a function of the induction field, for different induction gaps. The lines are drawn to guide the eye.

Figure 7: Fast pulses recorded with 6ns shaping-time amplifier on the anode in Ar/CO$_2$ (70/30) for (a) 2mm gap and (b) 6mm gap for 1.5 and 3kV cm$^{-1}$ induction fields. The pulses were recorded at constant detector gain of 2x10$^4$. 
Figure 8: Pulse area as a function of the induction field, for several induction gaps, in Ar/CO₂ (70/30). The line is drawn to guide the eye.

Figure 9: Pulse-width measured with a 6ns shaping-time pre-amplifier, as function of the induction field, for different induction gaps. The lines are drawn to guide the eye.

Figure 10: Electron collection velocity in Ar/CO₂ (70/30), for different induction gaps, versus the induction field. The lines are drawn to guide the eye.

Figure 11: Charge pulse-height spectra recorded in Ar/CO₂ (70/30) on a central single-strip anode, for three different positions of the x-ray collimated source. At 10.6mm the source is in front of the strip, yielding the maximal charge and the best energy resolution.

Figure 12: Charge distributions on the anode; they are represented by the fraction of total charge collected on a single anode strip as function of the source position, for different induction gaps, in Ar/CO₂ (70/30) (a-c) and Ar/CH₄ (95/5) (d-e).
Figure 1
Figure 2
Figure 3

a) \( EI = -200\text{V/cm} \)

b) \( EI = 3\text{kV/cm} \)

20mV; 2us/div
\textbf{Ar/CO}_2 (70/30)
UGEM1 = 500V UGEM2 = 450V
ED, ET = 3kV/cm
Drift Gap = 3mm
Transfer Gap = 2mm

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Figure 4}
\end{figure}
Figure 5

(a) $I_{\text{gap}} = 2\text{mm}$  
$E_\text{I} = 2\text{kV/cm}$  
25mV; 4ns/div

(b) $I_{\text{gap}} = 6\text{mm}$  
$E_\text{I} = 2\text{kV/cm}$  
5mV; 20ns/div
Figure 6

**Ar/CO₂ (70/30)**
UGEM1 = 500V UGEM2 = 450V
ED, ET = 3kV/cm
Drift Gap = 3mm
Transfer Gap = 2mm

<table>
<thead>
<tr>
<th>Induction Gap</th>
<th>Rise-Time [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1mm</td>
<td></td>
</tr>
<tr>
<td>2mm</td>
<td></td>
</tr>
<tr>
<td>4mm</td>
<td></td>
</tr>
<tr>
<td>6mm</td>
<td></td>
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</tbody>
</table>

**Induction Gap**
- □ 1mm
- □ 2mm
- △ 4mm
- ▽ 6mm

**Induction Field [kV/cm]**

**Rise-Time [ns]**

Figure 6
Figure 7
Figure 8

Ar/CO₂ (70/30)
UGEM1 = 500V
UGEM2 = 450V
ED, ET = 3kV/cm
Drift Gap = 3mm
Transfer Gap = 2mm
Figure 9

Induction Field [kV/cm]

Pulse Width [ns]

Induction Gap
- □ 1mm
- ○ 2mm
- ▲ 4mm
- ▽ 6mm

Ar/CO₂ (70/30)
UGEM1 = 500V
UGEM2 = 450V
ED, ET = 3kV/cm
Drift Gap = 3mm
Transfer Gap = 2mm
Electron Collection Velocity [cm/µs]

Induction Gap
- ■ 1mm
- ○ 2mm
- ▲ 4mm
- ▼ 6mm

Ar/CO₂ (70/30)
UGEM1 = 500V
UGEM2 = 450V
ED, ET = 3kV/cm
Drift Gap = 3mm
Transfer Gap = 2mm

Figure 10
Figure 11
Figure 12
Figure 12

(c) Ar/CO\(_2\) (70/30)
Induction Gap = 12mm

FWHM = 1200µm

(d) Ar/CH\(_4\) (95/5)
Induction Gap = 2mm

FWHM = 1070µm
Figure 12

Ar/CH₄ (95/5)
Induction Gap = 6mm

FWHM = 1840 μm

Charge Fraction on Strip [%]

Beam Position [mm]