Study of Charge-Up Processes in Gas Electron Multipliers

P Hauer, S Urban, K Flöthner, M Ball and B Ketzer

Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany

E-mail: `hauer@hiskp.uni-bonn.de`

Abstract. GEM foils are known to collect charged particles on the polyimide part in its holes during the amplification process. This is accompanied by a change of the effective gain. The effect is commonly known as the "charge-up effect".

In order to study this effect, two complementary approaches were chosen. On the one hand, the effect is studied in an iterative simulation that is based on a finite element calculation of the electrostatic environment and Garfield++ which microscopically tracks charged particles. On the other hand, a dedicated test-detector was setup with a single GEM as an amplification stage. In this study, a special focus lies on the different GEM geometries, i.e. the difference between double-conical and single-conical GEMs.
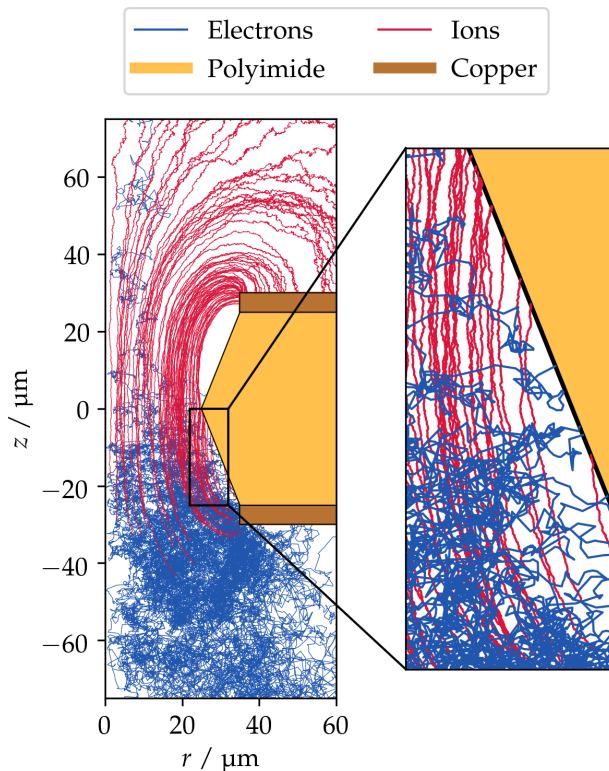
A quantitative comparison between simulated and measured values will be given. It can be concluded that the typical time-constant of the gain increase is in the order of 1×10^6 initial electrons per hole. For the specific case of a single-conical GEM, it can be shown that the orientation (tapered side pointing upwards or downwards) determines whether the gain increases or decreases.

1. Introduction

Gas Electron Multiplier (GEM) consist of a $50\,\mu m$ thick polyimide foil which is coated on both sides with $5\,\mu m$ thick copper foils [1]. In a photolithographic process, holes are etched into this foil stack. Standard GEM foils have an inner diameter of $50\,\mu m$, an outer diameter of $70\,\mu m$ and a pitch of $140\,\mu m$. If a suitable voltage is applied between both copper foils, strong electric fields are created inside of the holes (approximately $50\,kV/cm$). As a consequence, incoming electrons gain kinetic energy which is sufficient to ionize further gas atoms. Therefore, additional free electrons are created and can ionize further atoms. During this multiplication process, charged particles can get trapped on the polyimide part of the GEM as depicted in figure 1. Since the polyimide has a high resistance, charged particles remain there for a longer time and change the electric field locally. This is also known as the "charge-up effect". Many publications claim that the charge-up effect is responsible for a change of the effective gain in the beginning of a measurement but they do not give a full, quantitatively description of the process [2, 3, 4].

In the following chapters, the different approaches to study the charge-up effect will be explained. It starts with the description of the simulation procedure, which has an iterative structure. Afterwards, the setup of the test-detector will be explained which was used to investigate the charge-up effect experimentally. From both approaches, numerical values for key properties of the charge-up effect (e.g. the time constant) can be extracted and will be compared.

Figure 1. Simulated trajectories of electrons (blue) and ions (red) in a single GEM hole. The close-up view shows how particles end up on the polyimide (orange). For this simulation, a single electron was placed 100 μm above the GEM. A drift voltage of 400 V/cm lets the electron drift towards the GEM hole. The potential difference over the GEM was chosen to be 300 V. To extract electrons, a field of 2000 V/cm was applied below the GEM. The gas was set to a mixture of argon and carbon-dioxide (90:10).

To simulate the movement of electrons and ions, the framework Garfield++ was used. ANSYS® was used to simulate the electrostatic environment.
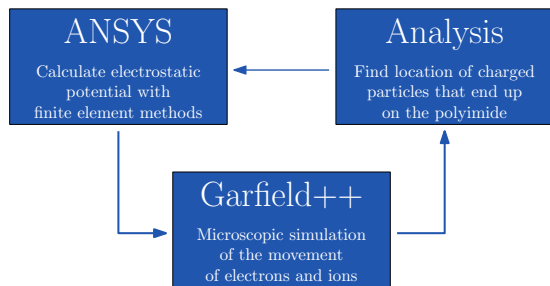
2. Simulations of the Charge-Up Effect

As briefly mentioned in the introduction, the simulations of the charge-up effect is based on an iterative approach that was published in [5]. However, new features were implemented to adjust the existing procedure [6]. The main idea of the simulation is to divide the polyimide part of the GEM into several slices where charges get applied step by step. The core of this system uses the finite element software ANSYS® [7] to calculate the electrostatic potential of a unit cell on a discrete mesh. Afterwards, the output is fed to a Garfield++ [8] program, which tracks the movement of electrons and ions microscopically. The third step is to analyze the trajectory of each particle and especially its end-position. If the end-position is on the polyimide, the corresponding charge gets included in the next calculation of the electrostatic potential in the next step.
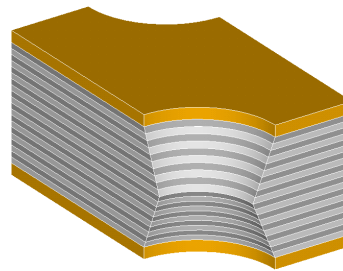
In this simulation, many parameters have to be chosen, e.g. the voltage that is applied to the GEM or the fields above and below the GEM. Certainly, they also influence the behavior of the charge-up effect, but this study focuses on the influence of different GEM geometries.

2.1. Workflow

A flowchart of the iterative workflow is depicted in figure 2. The simulation starts with the calculation of electric fields in an uncharged GEM. For this, a unit-cell is generated, as it is depicted in figure 3. The resulting field-maps can then be used by Garfield++ to simulate the electron avalanche and to track electrons and ions through the GEM. Afterwards, the end-position of every particle is analyzed with respect to the sliced polyimide part of the GEM. For this, the polyimide part is divided into 20 slices, as depicted in figure 3. The reason behind this subdivision is the strong z-dependency of the charge accumulation on the polyimide part (see e.g. figure 1). An angular dependence is neglected, since the hole has a rotational symmetry and therefore there is no preferred location where electrons and ions are getting trapped. Hence,

Figure 2. Iterative simulation procedure.

Figure 3. Sketch of a unit-cell of a GEM, where the polyimide part is divided into 20 slices.

to include surface charges in the next simulation step, the net-charge on each slice is calculated and multiplied by a constant extrapolation factor. The obtained charge distribution can then be added in the next calculation of field-maps and the process repeats.
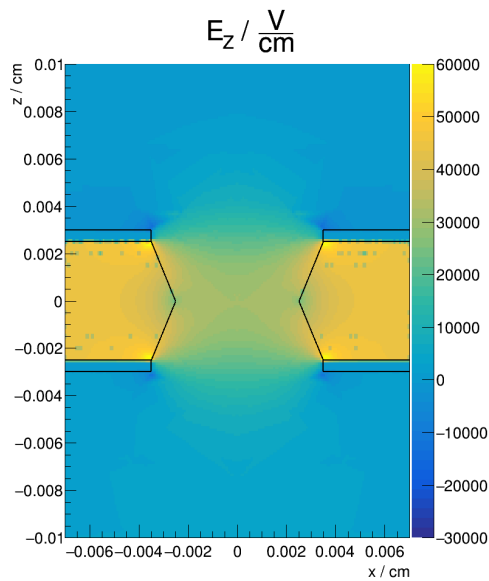
In order to decrease the computing time, an additional dynamic extrapolation factor can be introduced. It depends on the development of charge on each slice. If the total change of surface charges is small, a greater extrapolation factor can be used. This decreases the computational time by a factor of approximately six [6]. Nevertheless, the total CPU time to simulate the charge-up behavior of a GEM can easily take up to several days - depending strongly on the voltage across the GEM. E.g. one simulation for this work took approximately one day on an eight core machine (Intel Xeon E5 CPUs operating at 2.4 GHz).
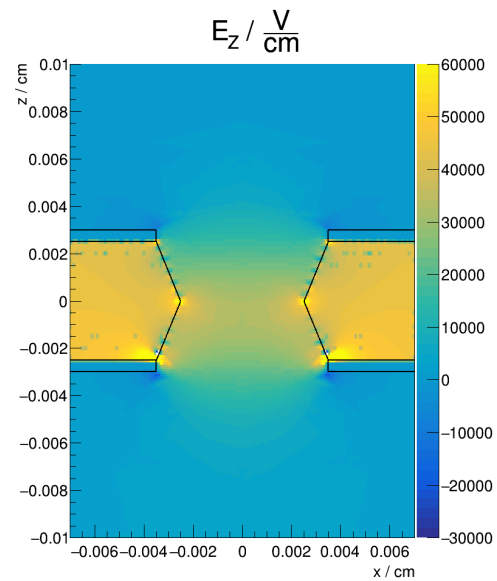
2.2. Results

In order to visualize the impact of the charge-up effect on the electric field, its component in z-direction is depicted in figures 4 and 5. In figure 4, the electric field of an uncharged GEM is shown. Despite some rendering mistakes, the electric field does not show any peculiarities. In contrast to that, a clear structure on the polyimide is visible in figure 5, where the electric field in a GEM hole after the charge-up process is shown. The alternating pattern between very high (60 kV/cm) and very low (−30 kV/cm) electric fields can be explained with a "multipole-like" structure that evolves during the simulation. It happens, because two neighboring slices accumulate oppositely net-charges (e.g. the lowest layer accumulates a negative charge, while the second-lowest layer accumulates a positive charge). The reason for these "multipole-like" structures is probably the discretization of the system and it is questionable whether this model can be used to describe the charge-up behavior of a real GEM. A possible solution to this issue would be a continuous charge distribution along the polyimide part of the GEM. Unfortunately, with the current framework it is not feasible to go from the discrete system to a continuous one, since it is based on the finite element calculation of the electric field.

Nevertheless, it is possible to investigate the development of the effective gain during the charge-up process. For this, the generated field maps of each step are used. The effective gain is here defined as the number of electrons that end up below the GEM divided by the number of initial electrons. In figure 7, the gain development of a GEM with a double-conical shaped hole-geometry is depicted. It is clearly visible that the gain increases exponentially and saturates with a time-constant of $(1.14 \pm 0.04) \times 10^6$ e/hole. That means, after a few million initial electrons per hole, the gain saturates.

The same simulation was also performed with a single-conical GEM. Here, the orientation matters. Hence, the charge-up effect was simulated for both possible orientations. The results are depicted in figure 8 and figure 9. It is remarkable that the simulated gain does not increase, but decrease, in the case of a single-conical GEM, where the tapered side is on the top.

Figure 4. Electric field in z-direction for an uncharged GEM.

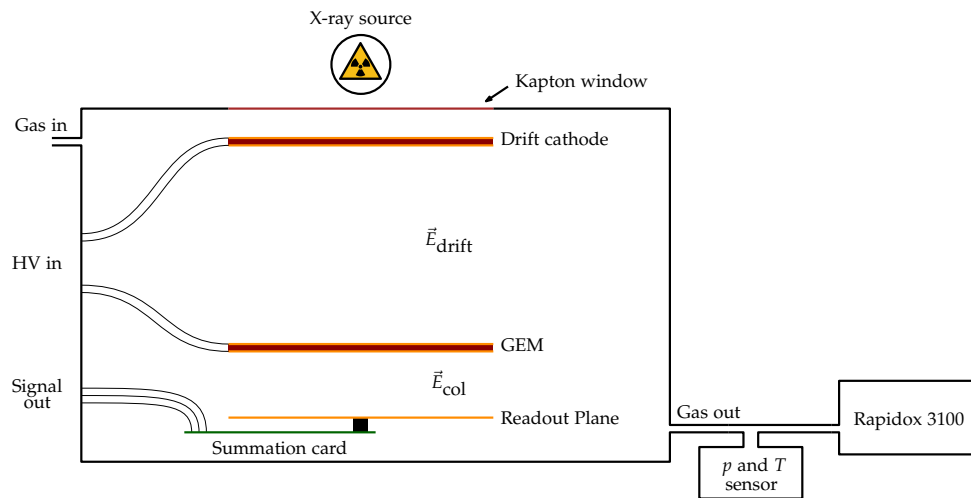**Figure 5.** Electric field in z-direction after the simulated charge-up process.

3. Measurements of the Charge-Up Effect

In order to verify the simulations experimentally, a dedicated test-detector was setup with a single GEM foil as an amplification stage. Before every measurement, the detector was opened up, so that humid air gets in contact with the GEM. This way, the charges on the polyimide are neutralized and the GEM can be used to investigate the charge-up effect. According to the simulations, not only a double-conical GEM was used but also a single-conical GEM in both orientations.

3.1. Setup of the Test-Detector

A sketch of the used test-detector is shown in figure 6. The total gas-volume is approximately 4 L. It consists of a 25 mm long drift volume, in which photons of an X-ray source can convert. The drift-field is created by a double-sided drift-foil and is set to be 400 V/cm. The voltage across the GEM was chosen to be 350 V and corresponds to the simulated value. However, the voltage was applied at least 24 h before the measurement started, to prevent the influence of polarization effects. To be even more certain that the observed changes of the effective gain are not locally, the measurement was repeated on different spots of the GEM. A collection field of 2000 V/cm extracts the electrons of the GEM and guides them to a pad-plane. The induced signals can then be read-out for example with a picoampere-meter. The detector is constantly flushed with Ar/CO_2 (90:10) with a flow of approximately 3 L/h. Additionally, the temperature and the pressure are constantly monitored, as well as the humidity and the oxygen content. As an X-ray source, a conventional X-ray tube (Mini-X by Amptek) was used. With it, different rates of initial electrons can be created by changing the current of the X-ray tube. It is known that this device needs some operational time until it delivers a constant rate. Therefore, a shutter was used that was not removed until the X-ray tube operates stable.

Here, the effective gain can be defined as the current on the padplane divided by the current of initial electrons. Since the current of incoming electrons is constant, the current on the read-out can be used as a measure for the effective gain.
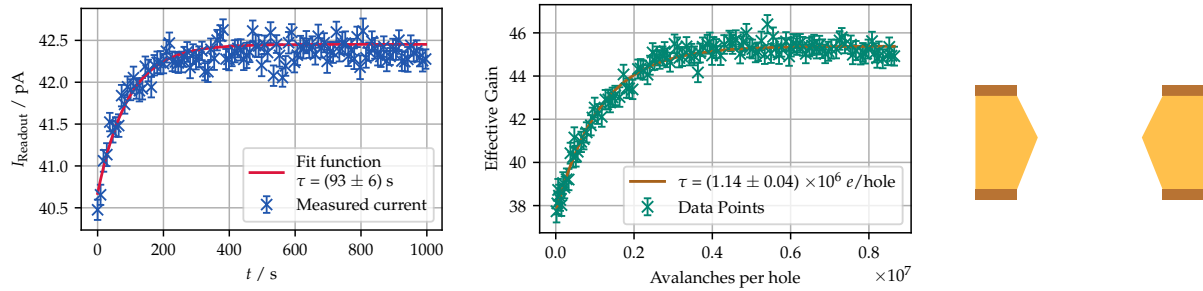
Figure 6. Sketch of the used test-detector.

3.2. Results

The measured current on the pad-plane I_{Readout} is depicted in figure 7 as well as a single exponential fit function. This measurement was conducted with a double-conical GEM foil. As in the simulations, the gain increases in the beginning and saturates afterwards. The time-constant in this measurement is $(93 \pm 6)\,\mathrm{s}$. In order to compare this value to the simulated value of $(1.14 \pm 0.04) \times 10^6\ e$/hole, the rate of the initial electrons, as well as the irradiated area have to be known. Both quantities were estimated and the resulting value is calculated to be $(0.9 \pm 0.1) \times 10^6\ e$/hole. The deviation between simulation and measurement is therefore in the order of $20\,\%$.
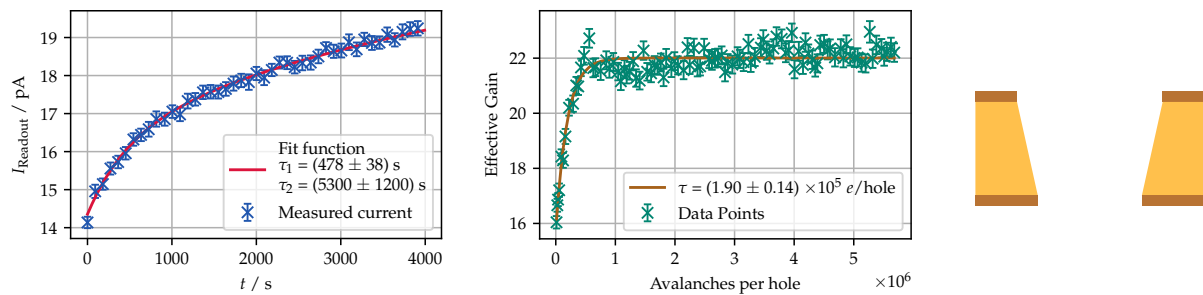
However, also the charge-up process of a single-conical GEM was investigated. As explained, both orientations were used since a different gain development is expected. The results are depicted in figure 8 and figure 9. Again, a clear change of the effective gain over time can be observed. As expected from the simulations, the effective gain increases, if the tapered side of the GEM hole is pointing downwards and the effective gain decreases, if the tapered side is on the bottom. A significant difference to the measurements of the double-conical GEM is that it is not sufficient to fit the data points with a single exponential function. To overcome this issue, a sum of two exponential functions were used to describe the data. The reason for this is yet unknown. A possible explanation for this may be that the collimator of the X-ray tube does not collimate the beam to an isotropically irradiated beam spot, but rather to a spot with a high intensity and a ring of lower intensity around it - a "penumbra". To prove this assumption, further measurements have to be conducted.
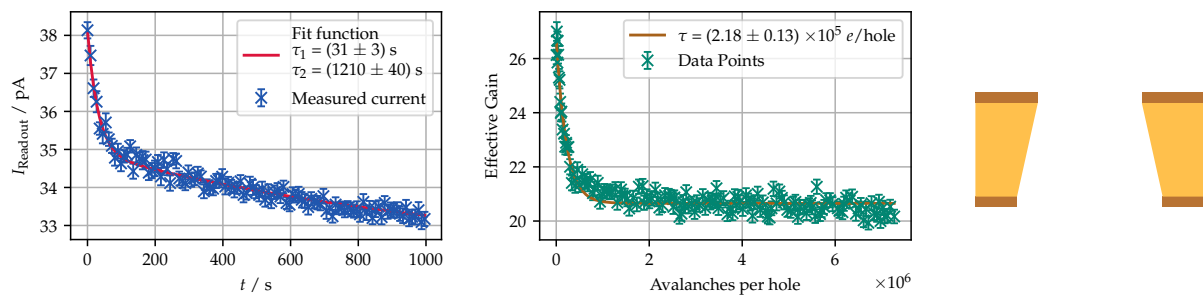
4. Conclusion and Outlook

The simulations of the charge-up effect with the iterative approach, where charges get accumulated on slices, can be used to predict the effective gain development in a GEM qualitatively. Nevertheless, a "multipole-like" structure evolves during the simulation. Still, a characteristic time-constant can be extracted, in which the charge-up effect changes the effective gain. It can be compared to an experimentally determined time-constant. In the case of a double-conical GEM, the time-constant can be estimated with a small deviation of only $20\,\%$. It is remarkable that the simulations also correctly predict the effective gain development for the single-conical GEMs, especially where the tapered side is pointing downwards and the gain decreases.

Figure 7. Measured (left) and simulated (middle) gain development in a double-conical GEM (right).

Figure 8. Measured (left) and simulated (middle) gain development in a single-conical GEM with the tapered side on the bottom (right).

Figure 9. Measured (left) and simulated (middle) gain development in a single-conical GEM with the tapered side on the top (right).

As mentioned previously, the "multipole-like" structures in the simulations occur because the polyimide is divided into several slices. A better approach would be to apply a continuous charge distribution. Also, different voltage settings (e.g. increased GEM voltage) should be investigated in order to understand the charge-up effect in more detail. To match the time-constant between simulations and measurements in this case, further measurements have to be carried with an improved collimator. Since the contact with ambient air seems to neutralize the charges on the polyimide, upcoming measurements will investigate the influence of an increased humidity in the detector gas on the charge-up effect.

6

References

[1] Sauli F 1997 A new concept for electron amplification in gas detectors *Nucl. Instr. and Meth. A.* **386** 531-34

[2] Altunbas C et al 2002 Construction, test and commissioning of the triple-GEM tracking detector for COMPASS *Nucl. Instr. and Meth. A* **490** 177-203.

[3] Simon F et al 2007 Development of tracking detectors with industrially produced GEM foils *IEEE Trans. on Nucl. Sci.* **54 6** 2646-52.

[4] Croci G 2007 Study of relevant parameters of GEM-based detectors *Master's Thesis (Università degli studi di Milano - Bicocca)*

[5] Correia P M M et al 2014 A dynamic method for charging-up calculations: the case of GEM *JINST* **9** P07025

[6] Urban S A 2016 Development of QA procedures for large-area GEMs *Master's Thesis (University of Bonn)*

[7] **URL:** *https://www.ansys.com* 2019

[8] Schindler H, Veenhof R 2019 Garfield++ – simulation of ionisation based tracking detectors **URL:** *http://garfieldpp.web.cern.ch/garfieldpp/*