MEASUREMENTS OF THE CHARGING-UP EFFECT IN GAS ELECTRON MULTIPLIERS

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ABSTRACT

Gas Electron Multipliers (GEM) are widely used as amplification stage in gaseous detectors exposed to high rates, e.g. in the Time Projection Chamber of the ALICE (A Large Ion Collider Experiment) experiment after its upgrade. The GEM consists of a polyimide foil which is coated by two thin copper layers. GEM foils are known to collect charges 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”.

This work presents two different methods to investigate the charge-up effect. Both methods were conducted with a single GEM as amplification stage. The first one is based on a current measurement while the second one relies on the analysis of $^{55}$Fe spectra over time.

Both methods combined give a quantitative result of the time constant on which the charge-up effect occurs. It can be shown that the characteristic time constant is of the order of $5 \times 10^5$ electrons/hole if the GEM voltage is set to 400 V. With the first method, two measurements at a GEM voltage of 350 V were conducted as well. Here, the time constant is approximately a factor ten higher.

Keywords Gas Electron Multiplier · GEM · Charge-Up Effect · Charging-Up Effect

1 Introduction

Detectors based on the Gas Electron Multiplier (GEM) [1] are widely used in particle physics experiments that require high position resolution over large areas in high-rate environments (e.g. COMPASS [2,3], LHCb [4], TOTEM [5,6], JLab Hall A [7] as well as ALICE [8,9] and CMS [10,11] after their upgrades). The GEM consists of a 50 µm thick polyimide foil which is coated on both sides with 5 µm thick copper layers. In a photolithographic process, holes are etched into this foil in a hexagonal pattern. Standard GEM foils have an inner diameter of approximately 50 µm, an outer diameter of approximately 70 µm and a pitch between two neighbouring holes of 140 µm. If a suitable voltage is applied between both copper layers, strong non-uniform electric fields are created inside the holes (of the order of 50 kV/cm). As a consequence, incoming electrons gain kinetic energy between collisions, which is then sufficient to ionize further gas atoms. Therefore, additional free electrons are created that can ionize further atoms. During this multiplication process, electrons and ions may diffuse to the polyimide part of the GEM and be adsorbed there as shown in figure 1. Due to the high resistivity of the material, the charges remain there for a rather long time. These new charges accumulate over time and dynamically change the electric field inside the hole. This is known as the “charge-up effect”. Many publications suggest that the charge-up effect is responsible for a change of the effective gain (e.g. in measurements with GEMs [3,12,13,14], in measurements with different micropattern gaseous detectors [15,16], as well as in simulations [18,19,20]), but often a quantitative investigation of the process is missing. In addition, several other effects have a similar signature as the genuine charging-up effect and may hence be misinterpreted as such.

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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 field 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++ (a C++ adaption of the Fortran-based framework Garfield [22]) was used. ANSYS® was used to calculate the electrostatic environment.

Especially the application of GEMs in Time Projection Chambers [8, 21], requires the gain to be stable over time. A quantitative understanding of the effect is hence indispensable.

In this work, two different methods will be presented that were used to investigate the characteristics of the charge-up effect experimentally. The first method makes use of a conventional X-ray tube where the amplified ionization currents are sufficiently large to measure them with a picoampere meter. For the second method, the peak position of the $K_\alpha$ line in an $^{55}$Fe spectrum is observed over time. Both types of measurement were conducted using a single GEM as amplification stage.

2 Setup

In order to measure the charge-up effect, a dedicated detector was set up with a single GEM foil as amplification stage. A sketch of the used detector is shown in figure 2. It consists of an aluminum vessel with a window on the upper side which can be used to irradiate the gas volume. The detector is constantly flushed with Ar/CO$_2$ (90:10) with a flow of 3 L/h. The total gas volume is approximately 4 L. It consists of a 25.7 mm long drift volume, in which photons of an X-ray source can convert. The drift field $E_{\text{drift}}$ is created by a double-sided drift foil and was set to 400 V/cm in all measurements. The used GEM foil with an active area of $10 \times 10 \text{cm}^2$ was produced at CERN with the so-called “double-mask-technique”. With this technique, a double-conical shape of the holes is achieved where the diameter of the holes in the polyimide (called inner diameter) is slightly smaller than the diameter of the copper holes (called outer diameter). Since earlier measurements report a strong influence of the hole shape on the characteristics of the charge-up effect [23], the outer and inner diameters of a few hundred holes were measured with an optical microscope. The deviations to the design values were small: $d_{\text{inner}} = (52.7 \pm 0.8) \mu$m, $d_{\text{outer}} = (72.8 \pm 0.9) \mu$m, where the uncertainties represent the RMS values of the measured distribution, and the superscripts “top” and “bot” refer to the top side (facing the drift electrode) and the bottom side (facing the readout electrode), respectively. The voltage across the GEM was set to be either 350 V or 400 V. An induction field $E_{\text{ind}}$ of 2000 V/cm extracts the electrons from the GEM and guides them to a pad plane, segmented in 100 pads of $1 \times 1 \text{cm}^2$ size. The induced signals can then be read out for example with a picoampere meter or can get amplified with a charge-sensitive amplifier, in order to analyze the pulse-height spectrum. The high voltage for each channel was supplied by a ISEG® EHS 8060n module. Each channel has a $1 \text{G} \Omega$ resistor to ground in order to set the ground reference for the system correctly, as the used high-voltage power supply can not sink currents.

The effective gain $G_{\text{eff}}$ is defined as the ratio between the readout current $I_{\text{readout}}$ and the ionization current $I_{\text{ionization}}$

$$G_{\text{eff}} = \frac{I_{\text{readout}}}{I_{\text{ionization}}}.$$

1 A 50 µm thick polyimide foil which is cladded on both sides with a 5 µm thick copper foil, i.e. as for GEMs, but without the hole pattern.
Temperature and pressure, as well as humidity and oxygen content of the gas, are constantly monitored. All these environmental parameters are measured in the gas system, directly after the detector. As an X-ray source, either a conventional X-ray tube (Mini-X by Amptek®) or an $^{55}$Fe source (with an activity of $\approx 11.5$ MBq) were used. Since the Mini-X needs some operational time until it delivers a constant rate, a shutter was used that was not opened until the X-ray tube operated stably (after 60 min).

With this setup, it is possible to investigate the charge-up effect especially with a focus on the characteristic time constant of the gain variations with respect to the initial rate of electrons. As a first assumption, it is reasonable to expect, for a given set of fields in the detector, that the time constant of the charge-up process depends linearly on the initial rate of ionization electrons. Since the used $^{55}$Fe source creates a rather small rate of ionization electrons compared to the Mini-X, a huge bandwidth (from a few fA up to pA) can be covered.

In order to assure that the measured gain variations are caused by the charge-up effect, several disruptive effects were carefully considered and ruled out. All measurements were conducted in a Faraday cage in order to reduce the influence of external noise sources on the signals. The voltage across the GEM was applied at least 24 h before a measurement was conducted. Additionally, the measurements were performed on different spots of the GEM in order to prove that the measured change of the effective gain is a local effect. The gas parameters (pressure, temperature, as well as oxygen and water content) were monitored during each measurement. For all measurements that were conducted with the Mini-X, a shutter blocked the X-ray beam from entering the detector until the rate of X-rays was stable. Therefore, the rate of ionization electrons was constant while the measurement took place.

### 2.1 Measurement method I – Current measurement

The first measurement method makes use of a picoampere meter (originally developed at TU München and further improved at Bonn University [24]) which is connected to the pad plane of the detector. In its most sensitive mode, the picoampere meter has a digital resolution of 0.5 pA and an absolute accuracy of 2 pA. Over a time interval of approximately 10 s, it measures 128 values and sends out the average value as well as the standard deviation (which yields the uncertainty of the average value when divided by $\sqrt{128}$, assuming that the fluctuations are purely statistical).

A temperature-dependent behaviour of the picoampere meter is not taken into account, since the temperature variations during a measurement were rather small (smaller than 0.5 °C).

In order to create measurable currents, the Mini-X was used as irradiation source. Here, the GEM voltage was either set to 350 V or 400 V. The X-ray was collimated (see figure 2), however, different collimators were used for the measurements at different GEM voltages. It is very important that the collimator is perpendicular to the GEM surface, since a tilted X-ray beam would create a non-uniform profile of initial electrons. This would lead to many different overlapping time constants that are impossible to disentangle.
2.2 Measurement method II – Pulse-height spectrum analysis

The second measurement method is based on the pulse-height spectrum from an $^{55}$Fe source. In order to measure a pulse-height spectrum, the GEM voltage is set to 400 V and a single-channel charge-sensitive pre-amplifier (“Ortec 142” [27]) is connected to the pad plane, with the signals from the four innermost pads summed up. Afterwards, the signal is fed to the main amplifier (“Ortec 671” [28]) where the signal gets shaped (shaping time 3 $\mu$s) and amplified (course gain 300, fine gain 1.5). The shaped and amplified signal is then fed into a multi-channel analyzer (“MCA-8000A” [29]) which is connected to a computer. The spectrum can then be analyzed, more details will be given in section 3.2.

If the charge-up effect influences the gain of the GEM, the peak position of the $K_{\alpha}$ line will vary over time. Therefore, many spectra were recorded over a time period of several hours. Each spectrum had a measurement time of either one or five minutes. Since the rate of initial ionization electrons is small, the complete measurement took approximately 12 h. On this timescale, temperature and pressure variations may influence the gain behaviour significantly. Hence, the peak-position of the $K_{\alpha}$ line has to be corrected for these effects. In order to do this, many spectra were recorded after the gain has saturated. Due to variations of pressure $p$ and temperature $T$ in the laboratory, a correlation between the peak position of the $K_{\alpha}$ line and $T/p$ can be derived. A linear fit was applied to these data points and can then be used to correct for temperature and pressure variations.

Unfortunately, the effective gain of a single GEM at 350 V in Ar/CO$_2$ (90:10) is not sufficient to observe a clean spectrum. Therefore, this measurement type was only performed at a GEM voltage of 400 V.

3 Results

3.1 Measurement method I

The results from measurement method I are depicted in figures 3 and 4 which show the currents as a function of time for different currents of the X-ray tube and for two different GEM voltages (400 V in figure 3 and 350 V in figure 4). To each data set, a single exponential function of the form

$$I_{\text{readout}}(t) = I_{\text{sat}} - I_0 \cdot \exp\left(-t/\tau\right)$$

was fitted. $I_{\text{readout}}$ denotes the measured current on the pad plane, $I_{\text{sat}}$ the saturation current and $\tau$ the time constant of the charge-up effect. A summary of all key quantities is given in table 1.

On first sight, it can be seen from figures 3 and 4 that an increased rate of ionization electrons (due to a higher current of the X-ray tube $I_{X\text{-ray}}$) leads to a faster gain increase. Since the effective gain is different for different GEM voltages, the two measurements will first be analyzed separately. In order to compare all measurements, a new quantity – the number of electrons per hole – will be introduced later in this section.

For $U_{\text{GEM}} = 400$ V, two measurements were conducted where the rate of ionization electrons differs by a factor of approximately two (since the current of the X-ray tube $I_{X\text{-ray}}$ was decreased from 70 $\mu$A to 35 $\mu$A). To be more precise, the quotient between the saturation currents $I_{\text{sat}}$ can be used as a measure for the quotient of the ionization currents, since $I_{\text{ionization}} = I_{\text{sat}}/G_{\text{eff}}$

$$\frac{I_{\text{sat}}^{35\mu A}}{I_{\text{sat}}^{70\mu A}} = \left(\frac{I_{\text{ionization}}^{35\mu A}}{I_{\text{ionization}}^{70\mu A}} \cdot G_{\text{eff}}\right)^{-1} = \frac{I_{\text{ionization}}^{35\mu A}}{I_{\text{ionization}}^{70\mu A}} = 0.52 \pm 0.06 \text{ (syst.)}.$$  \hspace{1cm} (3)

In this case, the statistical uncertainty is negligible compared to the systematic uncertainty. The systematic uncertainty is estimated conservatively by dividing the maximum possible value ($I_{\text{sat}}^{35\mu A} = 2 \mu$A) by the minimum possible value ($I_{\text{sat}}^{70\mu A} = 2 \mu$A) and vice versa. A similar estimation of the systematic uncertainty will also be done for every other value presented in this work.

To test the assumption made in section 2.2 that the measured time constant of the charge-up effect $\tau$ depends linearly on the inverse ionization current, the value in equation 3 should be compared to the quotient of the time constants

$$\frac{\tau^{70\mu A}}{\tau^{35\mu A}} = 0.54 \pm 0.09 \text{ (stat.)}.$$ \hspace{1cm} (4)

Both values agree within the uncertainties. The statistical uncertainty was calculated with Gaussian error propagation, taking into account the fit uncertainties.
For $U_{\text{GEM}} = 350$ V, the same calculation can be done. Note that the current of the X-ray tube differs by a factor of three for these measurements. The results are

$$\frac{I_{\text{sat}}^{30 \mu A}}{I_{\text{sat}}^{90 \mu A}} = 0.28 \pm 0.06 \text{ (syst.)} \quad \text{and} \quad \frac{I_{\text{sat}}^{90 \mu A}}{I_{\text{sat}}^{30 \mu A}} = 1.77 \pm 0.015 \text{ (stat.)}.$$

Although the values do not agree within one sigma, the agreement can still be considered fair.

In order to compare the measurements with different voltage settings, a new quantity is introduced for normalization purposes: the number of initial electrons per hole $n_{\text{eph}}$. It describes the amount of ionization electrons that arrive at each hole during the time span of one time constant. Therefore, the formula to determine the number of initial electrons per hole from the measured values is given by

$$n_{\text{eph}} = \frac{I_{\text{sat}} \cdot \tau}{G_{\text{eff}} \cdot A_{\text{irr}} \cdot \rho_{\text{hole}} \cdot e},$$

where $A_{\text{irr}}$ denotes the irradiated area (the size of the beam spot), $\rho_{\text{hole}}$ the hole density of a GEM foil and $e$ the elementary charge. The hole density $\rho_{\text{hole}}$ of a standard GEM foil can be calculated by geometric considerations to be $58.91 \text{ mm}^{-2}$.

For further calculations, it is assumed that the X-ray beam enters perpendicularly to the surface of the GEM so that the irradiated area is equal to the opening of the collimator. For the measurements at $U_{\text{GEM}} = 400$ V, a collimator with an opening radius $r_{\text{coll}}^{400 \text{V}}$ of $(1.05 \pm 0.05) \text{ mm}$ was used, while a collimator with radius $r_{\text{coll}}^{350 \text{V}} = (0.75 \pm 0.05) \text{ mm}$ was used for the measurements at $U_{\text{GEM}} = 350$ V. The uncertainties are estimated; they do not include a possible bias of the measurement outcome by a penumbra of the X-ray beam.

The effective gain was determined by measuring the ionization current on the top side of the GEM, while the voltage across the GEM was set to $0$ V and the induction field to $0$ V/cm. With the ionization current and the measured saturation current, the effective gain can be calculated, see equation (1). The resulting values are $G_{\text{eff}}^{400 \text{V}} = 150 \pm 10$ and $G_{\text{eff}}^{350 \text{V}} = 45 \pm 5$, respectively. The uncertainties are purely systematic measurement uncertainties (mainly caused by the $2 \text{ pA}$ accuracy of the picoampere meter), the statistical uncertainties from the variation of the measured current values are negligible.

With this information, the number of initial electrons per hole $n_{\text{eph}}$ can be calculated for each measurement. The values are given in table 1. It can be seen that the values for $U_{\text{GEM}} = 400$ V and the ones for $U_{\text{GEM}} = 350$ V, which were derived for very different rates of ionizing radiation, agree within uncertainties. It is remarkable that the values for $n_{\text{eph}}$ change by about one order of magnitude if the voltage across the GEM is changed from 400 V to 350 V. This may indicate that the time constant of the charge-up effect depends on the total charge rather than the initial number of electrons in a hole. However, taking the product of effective gain and initial number of electrons per hole as a measure for the total charge, there is still a discrepancy by a factor of 2.8 to 4.7 (see table 1). This can be taken as a hint that there is a residual dependency of the charge-up effect on the GEM voltage, in addition to the total charge.

### 3.2 Measurement method II

Two measurements by method II were conducted. As explained in section 2.2, the recorded spectra were analyzed. For this, a physics based fit-model was applied. It uses a superposition of four Gaussian-functions ($K_{\alpha}$, $K_{\beta}$ and their respective escape peaks) and in addition an error-function to describe the incomplete collection of charges. The peak centers were fixed relative to each other, as well as the widths of the Gaussian peaks. This can be done, since the energy of the lines and the energy dependency of the energy resolution are known. From the spectra, the centers of the $K_{\alpha}$ line can be extracted. Afterwards, the data points were corrected for changes in temperature and pressure (see section 2.2). For the first measurement (depicted in figure 5a) the relation

$$\mu_{K_{\alpha}}(T/p) = (11761 \pm 11) \cdot T/p - (2270 \pm 30)$$

was found, while for the relation for the second measurement (depicted in figure 5b) was found to be

$$\mu_{K_{\beta}}(T/p) = (17001 \pm 73) \cdot T/p - (3818 \pm 21).$$

$T/p$ is given in K/1013 Pa and the result is in MCA channel. The corrected results are depicted in figure 5, where the measurement time for one spectrum was set to one minute for figure 5a and to five minutes for figure 5b.

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\footnote{Since the beam is not perfectly collimated, a penumbra arises around the main beam spot. In this region, the rate of initial electrons is smaller compared to the main beam spot. Therefore, a longer time constant of the charge-up effect is expected in this region.}

\footnote{The relative energy resolution of a gaseous detector decreases proportional to $1/\sqrt{E}$, where $E$ denotes the energy of the incident particle.}
Therefore, the first uncertainty is statistical, while the second is systematic. In order to check the assumption that the \( \tau \) values for \( H \) and \( G \), the effective gain was used to estimate it.  

Table 1: Comparison of all measured values, obtained with the measurement method I. The uncertainty values for \( \tau \) and \( I_{\text{sat}} \) are given by the fit uncertainty. However, for the calculation of the uncertainty of \( n_{\text{eph}} \), the systematic measurement uncertainties (from \( I_{\text{sat}} \), \( G_{\text{eff}} \) and \( A_{\text{w}} \)) have to be taken into account, too (see formula 6). In order to do this, the maximum value of \( n_{\text{eph}} \), was calculated by dividing the maximal value for \( I_{\text{sat}} \) (e.g. adding 2 pA to it) by the minimal values for \( G_{\text{eff}} \) and \( A_{\text{w}} \) and vice versa for the minimal value of \( n_{\text{eph}} \).  

Therefore, the first uncertainty is statistical, while the second is systematic. In order to check the assumption that the total charge per hole is relevant for the time constant of the charge-up effect, the effective gain was used to estimate it. Hence, the last column is a measure for the total charge per hole during one time constant of the charge-up effect.

| \( U_{\text{GEM}} \) / V | \( I_{X_{\text{ray}}} \) / \( \mu \text{A} \) | \( \tau \) / s | \( I_{\text{sat}} \) / pA | \( n_{\text{eph}} \) / e/\( \mu \) hole | \( G_{\text{eff}} \cdot n_{\text{eph}} \) / e/\( \mu \) hole |
|-----------------|-------------|---------|----------|----------------|------------------|
| 400             | 35          | 107 ± 13| 24.379 ± 0.007 | (5.3 ± 0.6 ±1.4 \( \pm _{1.2} \)) \( \times 10^5 \) | (7.9 ± 0.9 ±1.6 \( \pm _{1.3} \)) \( \times 10^7 \) |
| 400             | 70          | 58.0 ± 6.9| 46.758 ± 0.008 | (5.5 ± 0.6 ±1.3 \( \pm _{1.0} \)) \( \times 10^5 \) | (8.2 ± 1.0 ±1.6 \( \pm _{1.0} \)) \( \times 10^7 \) |
| 350             | 30          | 524 ± 27| 11.852 ± 0.008 | (8.3 ± 0.4 ±4.0 \( \pm _{2.3} \)) \( \times 10^6 \) | (3.7 ± 0.2 ±1.2 \( \pm _{1.0} \)) \( \times 10^8 \) |
| 350             | 90          | 92.6 ± 6.3| 42.452 ± 0.007 | (5.2 ± 0.4 ±1.8 \( \pm _{1.3} \)) \( \times 10^6 \) | (2.4 ± 0.2 ±0.5 \( \pm _{0.3} \)) \( \times 10^8 \) |
(a) First measurement with the $^{55}$Fe source. The recording time for each spectrum was set to 1 min. The reduced chi-square is $\chi^2_{\text{red}} = 3.57$. During the measurement, the oxygen content was almost constant at 30 ppm while the water content decreased from 21 ppmV to 19.5 ppmV. The pressure increased from 1014 hPa to 1018 hPa and the temperature decreased from 19.6°C to 19.2°C.

(b) Second measurement with the $^{55}$Fe source. The recording time for each spectrum was set to 5 min. The reduced chi-square is $\chi^2_{\text{red}} = 2.93$. During the measurement, the oxygen content was almost constant at 12.5 ppm while the water content decreased from 61 ppmV to 55 ppmV. The pressure decreased from 1034 hPa to 1028 hPa and the temperature decreased from 22.4°C to 21.5°C.

Figure 5: Temperature and pressure-corrected peak positions of the $K_\alpha$ line of an $^{55}$Fe source as a function of time.

Also this method shows a clear increase of the effective gain with time. Since the rate of initial ionization electrons is smaller compared to the values from measurement method I, the time constant is much longer. Furthermore, the second measurement (figure 5b) was conducted approximately 100 days after the first measurement (figure 5a). Since the activity of the $^{55}$Fe source decreased over time, it also reasonable that a longer time constant is determined.

In order to compare the results from both measurement methods, the number of initial electrons per hole $n_{\text{eph}}$ can be calculated for method II, too. Here, the formula

$$n_{\text{eph}} = \frac{I_{\text{ionization}} \cdot \tau}{A_{\text{irr}} \cdot \rho_{\text{hole}} \cdot e}$$  \hspace{1cm} (7)

holds, with the same quantities as defined for equation (6). For both measurements, the same collimator was used which has an opening radius of $(2.50 \pm 0.05)$ mm. $I_{\text{ionization}}$ is the ionization current, created by the conversion of X-ray photons that are emitted by the $^{55}$Fe source (here in units of electrons per second). This quantity can be derived by analyzing the pulse-height spectrum. In figure 6, two spectra are shown, where the first spectrum in figure 6a was recorded after the first measurement (figure 5a) and the second spectrum in figure 6b after the second measurement (figure 5b) took place. The ionization current $I_{\text{ionization}}$ can now be derived with the formula

$$I_{\text{ionization}} = \frac{A_{K_{\alpha}} E_{K_{\alpha}} + A_{K_{\beta}} E_{K_{\beta}} + A_{K_{\alpha e}} E_{K_{\alpha e}} + A_{K_{\beta e}} E_{K_{\beta e}}}{t_{\text{meas}} w_{\text{gas}}}$$  \hspace{1cm} (8)

where $A$ denotes the area under the respective peak and $E$ the energy of the line (in units of eV). For each spectrum, the measurement time $t_{\text{meas}}$ was set to 600 s. The mean ionization energy of an Ar/CO$_2$ (90:10) mixture $w_{\text{gas}} = 26.7$ eV [25].

If all quantities are inserted into equation (7), the values

$$n_{\text{eph}}^{\text{first}} = (5.06 \pm 0.21) \times 10^5 \text{ e/hole} \quad \text{and} \quad n_{\text{eph}}^{\text{second}} = (4.9 \pm 0.4) \times 10^5 \text{ e/hole}$$  \hspace{1cm} (9)

can be calculated. They are in good agreement within their uncertainties. It is now also possible to compare these values to the ones presented in table 1. Also here, a good agreement is achieved if they are compared to the measurements at 400 V.
Figure 6: Two spectra — each with a measurement time of 600 s — were taken after their respective charge-up measurement in order to calculate the ionization current. A physics-motivated fit-model was applied. The uncertainty for each data point is assumed to be $\sqrt{N}$ where $N$ is the number of counts in this channel.

4 Conclusion and Outlook

In this work, the charge-up effect of GEM foils was investigated quantitatively using two different measurement methods. For the first method, a conventional X-ray tube was used which provides a high rate of ionization electrons. The second method relies on the analysis of many $^{55}$Fe spectra, where the used $^{55}$Fe source created a small rate of ionization electrons. Nevertheless, when a GEM voltage of 400 V was applied, the resulting time constant on which the charge-up effect occurs is of the order of $5 \times 10^5$ e/hole for both measurement methods. The measurements also show that the time constant of the charge-up effect depends reciprocally on the initial rate.

Since a GEM voltage of 350 V is not sufficient to observe a clean $^{55}$Fe spectrum, only the first method could be used at this voltage. Here, a time constant of around $7 \times 10^6$ e/hole was determined. This discrepancy is reduced to a factor of about 3 when the total charge in the hole is used for normalization instead of the initial number of electrons entering the hole. This may indicate that there is a residual dependency of the charge-up effect on the GEM voltage, in addition to the total charge.

In the future, we plan to investigate the influence of the GEM voltage on the time constant of the charge-up effect in more detail. Moreover it is interesting, whether the external fields — drift field and induction field — also influence the behaviour. As previous publications have claimed to observe different behaviours for different hole shapes (e.g. single-conical holes), it is interesting to investigate the charge-up effect for these foils as well. In addition, a comparison to simulations is foreseen.

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References

[1] F. Sauli — GEM: A new concept for electron amplification in gas detectors. In Nucl. Instr. and Meth. A vol. 386, pages 531 - 534. 1997.
[2] B. Ketzer — Micropattern gaseous detectors in the COMPASS tracker. In Nucl. Instr. and Meth. A vol. 494, pages 142 - 147. 2002.
[3] C. Altunbas et al. — Construction, test and commissioning of the triple-GEM tracking detector for COMPASS. In Nucl. Instr. and Meth. A vol. 490, pages 177 - 203. 2002.
[4] G. Bencivenni et al. — A triple GEM detector with pad readout for high rate charged particle triggering. In Nucl. Instr. and Meth. A vol. 488, pages 493 - 502. 2002.
[5] M. G. Bagliesi et al. — The TOTEM T2 telescope based on triple-GEM chambers. In Nucl. Instr. and Meth. A vol. 617, pages 134 - 137. 2010.
[6] M. Bozzo et al. — Design and construction of the triple GEM detector for TOTEM. In IEEE Symposium Conference Record Nuclear Science vol. 1, pages 447 - 450. 2004.
[7] K. Gnanvo et al. — Large size GEM for Super Bigbite Spectrometer (SBS) polarimeter for Hall A 12GeV program at JLab. In Nucl. Instr. and Meth. A vol. 782, pages 77 - 86. 2015.
[8] B. Ketzer — A time projection chamber for high-rate experiments: Towards an upgrade of the ALICE TPC. In Nucl. Instr. and Meth. A vol. 732, pages 237 - 240. 2013.
[9] C. Lippmann — A continuous read-out TPC for the ALICE upgrade. In Nucl. Instr. and Meth. A vol. 824, pages 543 - 547. 2016.
[10] D. Abbaneo et al. — GEM based detector for future upgrade of the CMS forward muon system. In Nucl. Instr. and Meth. A vol. 718, pages 383 - 386. 2013.
[11] C. Calabria — Large-size triple GEM detectors for the CMS forward muon upgrade. In Nucl. Instr. and Meth. A vol. 273-275, pages 1042 - 1047. 2016.
[12] F. Simon et al. — Development of Tracking Detectors With Industrially Produced GEM Foils. In IEEE Transactions on Nuclear Science vol. 54, pages 2646 - 2652. 2007.
[13] B. Azmoun et al. — A Study of Gain Stability and Charging Effects in GEM Foils. In 2006 IEEE Nuclear Science Symposium Conference Record vol. 6, pages 3847 - 3851. 2006.
[14] M. V. Nemallapudi — Gain of a Single Gas Electron Multiplier. Master’s Thesis at University of Arkansas. 2012. [https://scholarworks.uark.edu/etd/533/](https://scholarworks.uark.edu/etd/533/).
[15] M. Pitt et al. — Measurements of charging-up processes in THGEM-based particle detectors. In Journal of Instrumentation vol. 13, March 2018.
[16] D. Shaked Renous et al. — Gain stabilization in Micro Pattern Gaseous Detectors: methodology and results. In Journal of Instrumentation vol. 12, September 2017.
[17] M. Alexeev et al. — The gain in Thick GEM multipliers and its time-evolution. In Journal of Instrumentation vol. 12, September 2017.
[18] P. M. M. Correia et al. — A dynamic method for charging-up calculations: the case of GEM. In Journal of Instrumentation vol. 9, July 2014.
[19] P. M. M. Correia et al. — Simulation of gain stability of THGEM gas-avalanche particle detectors. In Journal of Instrumentation vol. 13, January 2018.
[20] M. Alfonsi — Simulation of the dielectric charging-up effect in a GEM detector. In Nucl. Instr. and Meth. A vol. 671, pages 6-9. 2012.
[21] M. Berger et al. — A large ungated TPC with GEM amplification. In Nucl. Instr. and Meth. A vol. 869, pages 180 - 204. 2017.
[22] R. Veenhof — Garfield, recent developments. In Nucl. Instr. and Meth. A vol. 419, pages 726-730. 1998.
[23] F. Sauli — The gas electron multiplier (GEM): Operating principles and applications. Nucl. Instr. and Meth. A vol. 805, pages 2 - 24. 2016.
[24] D. Schaab et al. — High resolution picoamperemeters for high voltage applications. Poster at DPG Spring Meeting, Münster. 2017.
[25] F. Sauli — Principles of operation of multiwire proportional and drift chambers. In Academic Training Lectures, CERN. 1977.
[26] Ortec 142 — Online Manual. Retrieved from [https://iseg-hv.com/en/products/detail/EHS](https://iseg-hv.com/en/products/detail/EHS) December 2, 2019.

[27] Ortec 142 — Online Manual. Retrieved from [https://www.ortec-online.com/products/electronics/preamplifiers/142a-b-c](https://www.ortec-online.com/products/electronics/preamplifiers/142a-b-c) December 2, 2019.

[28] Ortec 671 — Online Manual. Retrieved from [https://www.ortec-online.com/products/electronics/amplifiers/671](https://www.ortec-online.com/products/electronics/amplifiers/671) December 2, 2019.

[29] MCA8000A — Online Manual. Retrieved from [https://www.amptek.com/products](https://www.amptek.com/products) December 2, 2019.