SCIREA Journal of Environment
http://www.scirea.org/journal/Environmental
December 4, 2022
Volume 6, Issue 4, August 2022
https://doi.org/10.54647/environmental61318

Study on the wide range gamma dose rate response for a new type thick gas electron multiplier

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Abstract: We developed a novel Thick Gas Electron Multiplier (THGEM) film based on simulation results. With new substrate material and homemade industrial PCB technology, the film has good stability, the gain of monolayer reaches 2×10^4 and the working voltage range exceeds 150V. Although the detection efficiency of monolayer THGEM detector in high-energy gamma rays was only 0.2%, we measured high-energy gamma dose rates in the range of 0.3μGy/h to 8Gy/h (^{137}Cs and ^{60}Co) by switching between counting mode and current mode. The detector was not saturated at all even at very high dose rates in current mode. This study indicates that THGEM detector has a broad application prospect in the field of high-energy gamma detection, especially in the extremely high dose rate gamma radiation field, such as nuclear power plant radiation leakage accident.

Keywords: Thick Gas Electron Multiplier, Detection efficiency, Gamma dose rate, Wide range, Gain

The thick gas electron multiplier (thick GEM or THGEM) was first proposed by Breskin [1] and is based on a structural improvement of the GEM [2]. Compared with the GEM, the thick GEM has a higher durability, a higher gain and a lower cost, and thus, it has broader application prospects, such as X-ray imaging [3], track detection [4], neutron detection [5], etc. In addition to applications in high-energy particle detection, radiation imaging, etc., thick GEMs also show good application potential in the field of radiation protection, e.g., in the field of microdosage [6]. Relative to other radiation detectors of gas, thick GEMs have a shorter dead time, a larger dynamic range, a higher n/γ rejection ratio, and both position and energy resolutions, thereby exhibiting certain advantages in wide-range gamma dose rate measurement. Here, we describe a novel thick GEM-based γ dose rate detector and examine its performance under the irradiation of a wide range of γ dose rate.

1. Detecting efficiency of a thick GEM detector for γ-rays

1.1 Detection principle

When detecting uncharged particles, the particles are generally first transformed into electrons. The interaction between gamma-rays and the detector materials mainly includes the photoelectric effect, the Compton effect and the electron pair effect [7], which generated electrons involve continuous ionization or multiplication after them entering the sensitivity area of the detector. This interaction is acquired to reflect key information, such as the energy, fluence and position of the gamma-ray. The general structure of a thick GEM detector is shown in Fig. 1. It is assumed that γ-rays enter from the drift electrode and interact with conversion media, such as the drift electrode, working gas, etc., and that the resultant electrons (excited electrons) enter the drift region and collide with the working gas, ionizing or integrating through the pull of the drift electric field to generate more electrons (primary ionized electrons). Some of the primary ionized electrons enter the holes on the film and undergo avalanche multiplication under a stronger electric field in the holes. Partly of electrons ultimately escape from the hole and inductively collect by the collection electrode under the action of the collection region electric field. The induced signal generated by the collection electrode is read by an electronic system through a current or pulse, giving rise to the gamma-ray-related information.

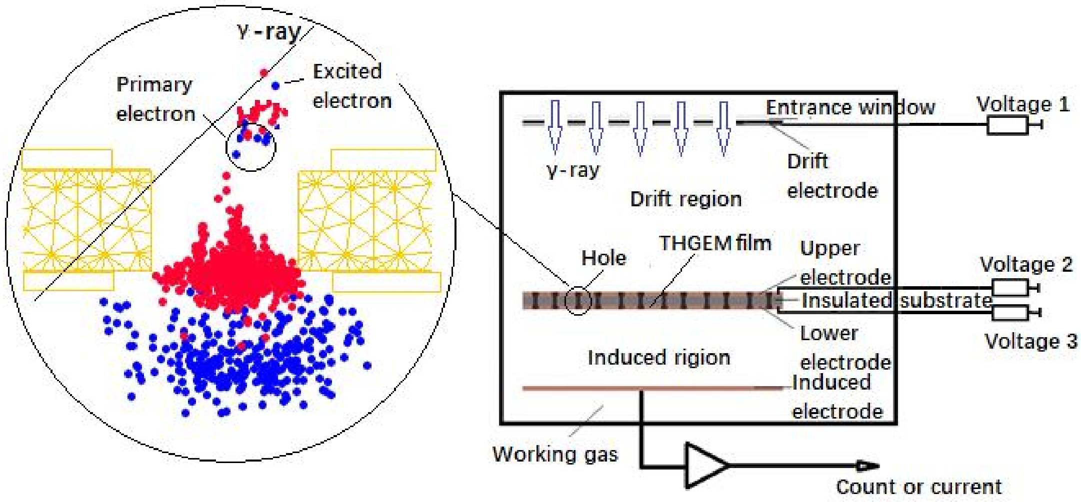

Fig. 1. Diagrams of a thick GEM detector structure and the working principle

According to the working characteristics of a thick GEM, only after entering the drift region can a gamma-ray-transformed electron enter the film hole and undergo avalanche multiplication. If a photon generates an excited electron in the drift region but the electron does not ionize enough primary ionized electrons or there are not enough primary ionized electrons entering the holes on the film, and the number of electrons after the avalanche multiplication is lower than the discrimination capability of the system, then this photon cannot be detected; only if an incident photon generates an excited electron that enters the drift region and generates sufficient primary ionized electrons in drift region, and if the signal of the primary ionized electrons passing through the film holes after avalanche multiplication reaches the system's discrimination threshold can the photon be effectively detected.

Assuming the number of primary ionized electrons generated by a single excited electron in the drift region is N_0, the entry efficiency of the primary ionized electrons to the hole of the film is η_1, the multiplication factor of the thick GEM is M, and the collection efficiency of the collection region on the primary ionized electrons passing through the holes of the film is η_2. Then, the number of electrons that are eventually collected or induced (N_c) is:

$$N_c = N_0 \cdot \eta_1 \cdot M \cdot \eta_2 \tag{1}$$

Additionally, assuming that the system's discrimination threshold is N_{TH} electrons, then the detection efficiency of a single photon (η) is comprised of two probability portions: the probability of generating excited electrons (η_0) and the probability at which N_c is greater than N_{TH}, i.e., the discrimination efficiency (η_{TH}):

$$\eta = \eta_0 \cdot \eta_{TH} \tag{2}$$

Thus, under ideal conditions:

$$\eta = \eta_0 \tag{3}$$

This outcome indicates that N_c is always greater than N_{TH}, which requires collecting or inducing as many electrons as possible and that the system noise be as low as possible; however, in practical applications the number of primary ionized electrons is associated with the working gas composition, the incident photon energy, and the track length of the sensitivity region with the hole entry efficiency. The electron entry rate and the multiplication factor are correlated to the electric field distribution and the structure and material of a thick GEM, so it is always the case that

$$\eta < \eta_0 \tag{4}$$

In this study, under the assumed ideal conditions, we first calculated the maximum detection efficiency of thick GEM on γ-rays, i.e., the probability at which a single γ-ray generates an excited electron in the sensitivity region of a thick GEM detector, and then designed or selected a thick GEM film with an appropriate sensitivity area based on the calculation.

1.2 Theoretical calculation

As shown in Fig. 1, the excited electron source of the drift region mainly has three parts: (1) the inner surface of the drift electrode; (2) the working gas in the drift region; and (3) the upper electrode. The first and third parts can be regarded as the interface of drift region, and the second part is the inside of drift region. In this study, we adopted the Monte Carlo method [8] and the gas discharge program Garfield++ to calculate the probability of the occurrence of excited electrons at the interface and the inside of drift region. Garfield++ is a software developed by CERN that was specially designed for the simulation of gas detectors and is characterized by its capability of simulating the behaviors of electrons in gases with an electric field, e.g., ionization, integration, diffusion, avalanche, etc., through various interface programs, such as Magboltz, Heed, SRIM, etc.; of these programs, Magboltz provides the necessary gas cross-section data for the Garfield++ calculation, Heed calculates the photoelectric conversion (PAI model) in the gas, and SRIM mainly calculates the ionization energy loss of the gas [9].

In the simulation calculation, we first established the unit model of the thick GEM detector (Fig. 2) and imported various files established in ANSYS, such as the geometric structure, electric field data, mesh division, etc., into Garfield++ for the simulation calculation through the interface function [10]. Based on the detector used in the experiment, the distance between the drift electrode and the upper electrode was set to 3 mm, the diameter of the film hole to 150 μm, the film thickness to 0.15 mm, and the distance between the collector and the lower electrode to 2 mm. The electrodes were all made of 10 μm thick copper, and both the upper electrode and the lower electrode have a small hole concentric to the hole on the film that is 290 μm in diameter. The exposed 70 μm insulating material was called the Rim ring [11], and the working gas was an argon-isobutane mixture at standard atmospheric pressure, in which argon accounts for 97% of the gas mass.

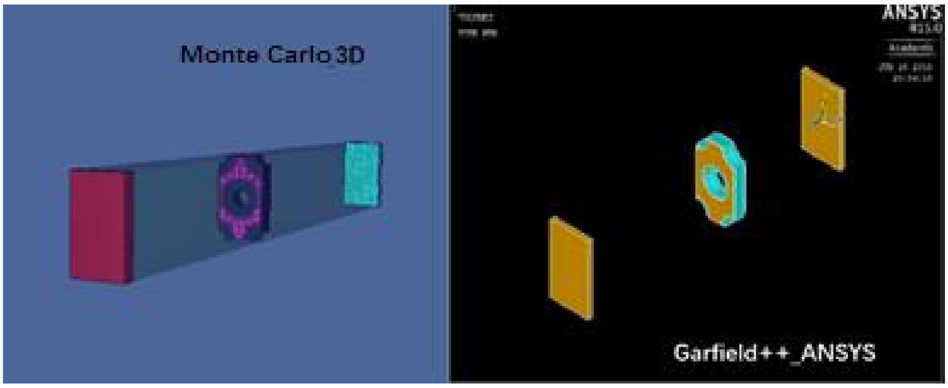

Fig. 2. Thick GEM unit model simulated through Monte Carlo and Garfield++

The probabilities at which the gamma-rays of ^{137}Cs and ^{60}Co generate excited electrons on the inner surface of the drift electrode, the upper electrode and in the gas in drift region were simulated, with the results shown in Table 1. The detection efficiency of the thick GEM detector for a single gamma-ray was approximately 0.2%.

Table 1. Probability at which excited electrons are generated at each area of the drift region

Gamma-rays	Inner surface of drift electrode	Upper Electrode	Gas in drift region	η_{0_total}
^{137}Cs	1.93×10^{-3}	1.11×10^{-5}	2.72×10^{-5}	1.96×10^{-3}
^{60}Co	2.12×10^{-3}	1.18×10^{-5}	4.73×10^{-6}	2.14×10^{-3}

Assuming the gamma dose rate of the ambient radiation level is 0.1 μGy/h, the fitted coefficient K of the ^{60}Co radiation was 5.342 pGy.cm^2 based on the conversion coefficient K from the fluence ($\emptyset$) to the monoenergetic photon free air KERMA (K_a) [12], using the following equation:

$$K = \frac{K_a}{\emptyset}\ (\text{pGy.cm}^2) \tag{5}$$

We obtained the fluence rate at approximately 5 cm^{-2}. s^{-1}; for the detector to quickly obtain a photon response, e.g., within 5 seconds, the detection area must be larger than 20 cm^2 based on the calculated detection efficiency.

2. Performance characteristics of the new thick GEM film

Based on the calculation described above, we chose a thick GEM film 36 cm^2 in area and 0.15 mm in thickness, as shown in Fig. 3, in which the right panel shows an enlarged view via electron microscopy. The diameter of the hole was 150 µm and that of the concentric hole on the copper layer was 290 µm. The distance between the holes was 400 µm.

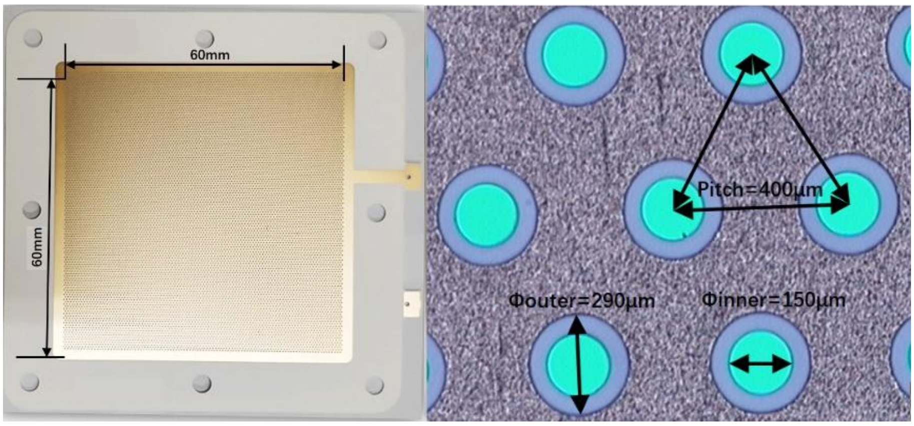

Fig. 3. External view and configuration of new thick GEM film

The new thick GEM film used an improved insulating matrix material based on a previous study [13] so that the film had a lower starting voltage and a wider operating voltage range, having a gain of 2.0×10^4 in a single layer film (Fig. 4). In addition, the energy resolution of the film under the operating voltage of 600 V was 26.5% (Fig. 5), which is comparable to that of the majority of thick GEM films reported previously [14, 15]. Moreover, the base material of the film only has slight water absorption, which is conducive to the stable operation of the detector.

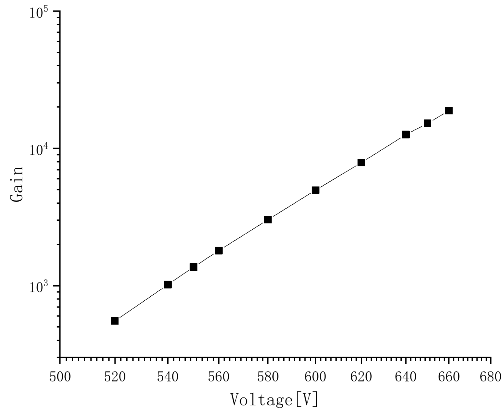

Fig. 4. Monolayer film gain curve of the new thick GEM

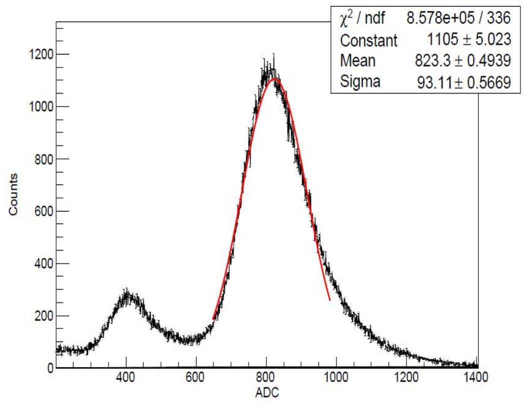

Fig. 5. Energy resolution of the new thick GEM film

3. Wide range γ dose rate measurement

The measurement of the gamma dose rate is generally performed by converting the current or counting signal generated by the detector into a fluence rate of the gamma-ray and then converting the fluence rate to the dose rate. Therefore, by experimentally measuring the correspondence relationship between the current or the counting signal and the fluence rate or the dose rate of the detector, the dose rate response of the detector can be scaled.

Under low dose rate gamma-ray irradiation, the thick GEM detector only produces low-magnitude signals, generally at the order of pA[16]. If the current measurement method is adopted, the requirement for the system stability and current measurement accuracy are very high, as they are susceptible to environmental interference. By adopting a count measuring system consisting of a preamplifier and a main amplifier that have low bandwidth requirements, we were able to accurately measure the low-range gamma dose rate. We used a thick GEM detector, an 572A main amplifier (made by ORTEC of USA), an 142H preamplifier (made by ORTEC of USA) and a scaler to set up the gamma counting test system, i.e., the counting mode, the components of the test system are shown in Fig. 6.

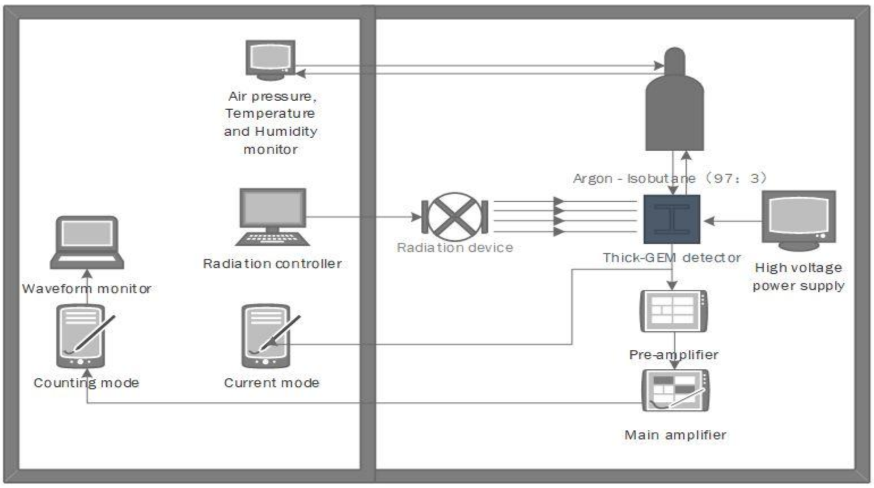

Fig. 6. Schematic diagram of the gamma dose rate measurement system

In the counting mode, the main amplifier amplifies the signals of the preamplifier and transmits them to the counting system of the console, which is composed of a scaler and a waveform monitor, in which the scaler sets up the discrimination threshold and the read time interval, so the number of pulses in a period of time that exceeds the discrimination threshold can be recorded and is connected to the waveform monitor to enable synchronous monitoring while preventing the "pseudo count" of the scaler derived from a certain sudden interference.

Under high dose rate gamma-ray irradiation, due to the limited bandwidth of the system, an anode-induced current reading system comprised of the detector and the KEITHLEY-6517B current meter was adopted, i.e., the current mode. In this mode, the preamplifier and the main amplifier in the counting mode were excluded, while the other parts remained unchanged. The collection electrode of the thick GEM detector was directly connected to the input electrode of the ammeter, and the background subtraction measurement method was utilized; i.e., prior to each irradiation, the background current (leakage current) detected by the thick GEM was recorded, and after irradiation, the ammeter obtained the net current generated by the irradiation by automatically subtracting the background current.

In the measurement system, the chamber and preamplifier of the thick GEM detector were placed on a mobile platform. The γ-ray beam of ^{60}Co or ^{137}Cs, calibrated and extended uncertainty is less than 5%, was perpendicular to the plane of the thick GEM film. The working gas of argon-isobutane (97:3) was used, while the working voltage was provided by a

NDT1470 module (Made by CEAN of Italy) with a small ripple. Based on the voltage gain curve, the working voltage between the electrodes of the thick GEM films was set to 600 V.

4. Experimental testing and analysis

4.1 Stability of the measurement system

The stability of the measurement system must be validated before the formal simulation. Under the counting mode shown in Fig. 6 and a radiation of 50.07 mGy/h from ^{137}Cs, the readings over two hours were continuously recorded and plotted in Fig. 7, showing that in the first half hour, the count rate of the thick GEM detector was gradually increasing. The cause of the increase in the first half hour was unclear. In one case, it was attributed to the influence of moisture on the film surface [11], in which it took approximately 5 hours for the thick GEM film to condition.

According to Eqs. (1) and (2), when the thick GEM detector begins to work, η_1, η_2 and η_Δ are unstable, especially for the thick GEM film under a flowing working gas, in which the impure gas (including water vapor) has a great impact on the hole entry efficiency and the electron transmittance of the primary ionized electrons. This outcome affects the gain level so that the probability of exceeding the discrimination threshold is lowered. The stabilization time depends on the water absorption of the thick GEM film (or its ability to absorb impure gas). The matrix of the film used in this study only had a low water absorption, enabling the film to condition in a shorter period of time. After half an hour of working time, the count rate kept decreasing for approximately one hour and then stabilized; this outcome was caused by the charging-up effect that has also been observed in other studies [17].

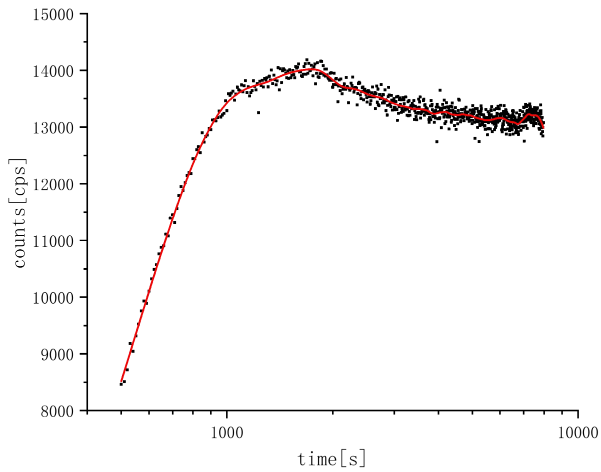

Fig. 7. The measurement system's stability

In summary, to obtain a stable result, the thick GEM film needs to be operated for at least 1.5 hours before a reading is taken; if the reading is taken in half an hour; i.e., ignoring the charging-up effect, the maximum error is approximately 5%.

4.2 ^{137}Cs and ^{60}Co dose rate response curves under the counting mode

The counting system is mainly used to measure the low-dose rate ^{137}Cs and ^{60}Co, with a range of 0.3 μGy/h - 10 mGy/h. Due to the limited bandwidth of the counting system, when the counting rate is over 13 kHz (approximately 5 mGy/h), the system exhibits nonlinearity. The nonlinear error (d_N) can be calculated using the following equation:

$$d_N = \frac{\Delta N}{N_i} \times 100\% \tag{6}$$

where $\Delta N = N_i - N_a$, N_i is the expected value, and N_a is the measured value. It was calculated that at 10 mGy/h the nonlinear errors of ^{137}Cs and ^{60}Co were 29.13% and 20.04%, respectively.

The figure shows that the thick GEM detector manifested a good linearity when dose rate was below 5 mGy/h, while the thick GEM detector manifested the maximal nonlinear error when the dose rate was approximately 10 mGy/h. At a dose rate point of 3 mGy/h, the fluence rate of ^{137}Cs and ^{60}Co were 267824 cm^{-2}.s^{-1} and 155997 cm^{-2}.s^{-1}, respectively, according to Eq. (5), indicating that the detection efficiencies of the detector in measuring the ^{137}Cs and ^{60}Co gamma-rays were 10×1.0^{-3} and 1.4×10^{-3}, respectively, which were lower than their respective simulated values (η_0). Based on Eq. (2), for the ^{137}Cs and ^{60}Co gamma-rays, the calculated η_{TH} values were 51.7% and 63.6%, respectively.

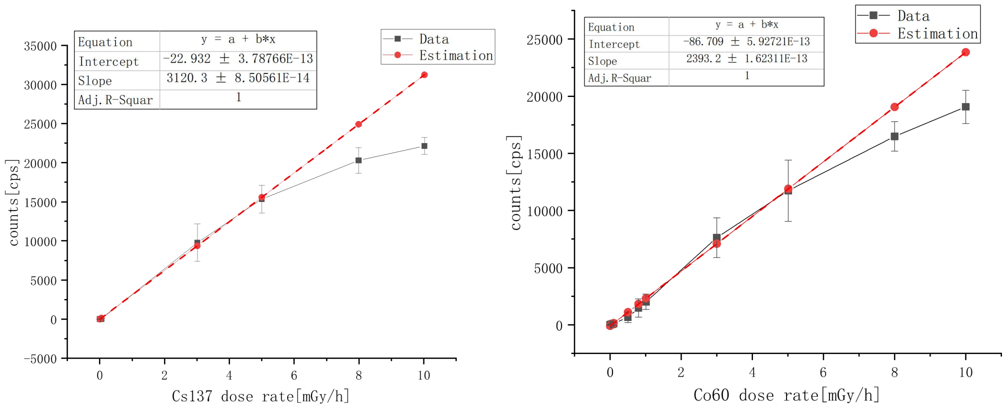

Fig. 8. Thick GEM detector dose rate-count rate response curve

4.3 ^{137}Cs and ^{60}Co dose rate response curves under the current mode

At over 10 mGy/h, we conducted the measurement using the current mode and found that for both ^{137}Cs and ^{60}Co, a good linearity was observed, the current sensitivity was 0.1 nA/mGy.h^{-1}. At the same dose rate, the current of ^{137}Cs was slightly higher than that of ^{60}Co, which was similar to that under the counting mode. Limited by the irradiation conditions, the detection limit for ^{137}Cs was 80 mGy/h. For ^{60}Co, in the dose rate range of 10 mGy/h ~ 8 Gy/h, the current showed a linear relationship from 1.38 nA to 1666.2 nA (Fig. 9), with a maximum fluence rate of 4.2×10^6 mm^{-2}/s, which is higher than that of GEM detectors of the same type by one order of magnitude [18].

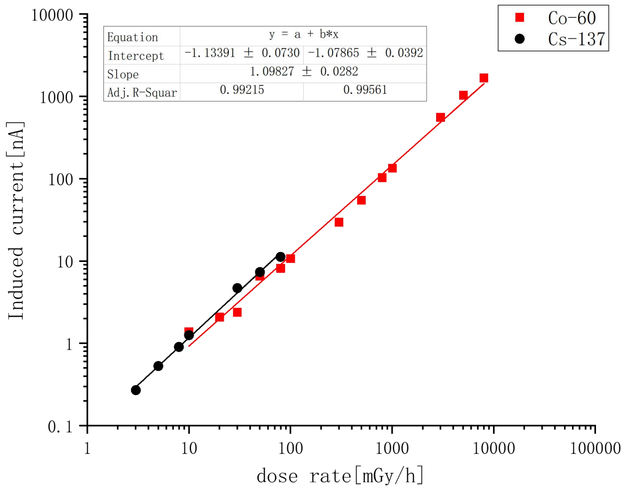

Fig. 9. Thick GEM detector dose rate-current response curve

4.4 Dose rate response at different operating voltages

The working voltage of the thick GEM film is closely associated with the gain. Assuming that the effective gain of a thick GEM detector is G, then based on Eq. (1), we have:

$$G = \frac{N_c}{N_0} = \eta_1 M \eta_2 \tag{7}$$

For a signal to be detected, it must meet the requirement of $G \cdot N_0 > N_{th}$. In the test, we kept the electric fields in the drift region and collection region constant at 1 kV/cm and 2.5 kV/cm, respectively, i.e., keeping η_1 and η_2 constant but varying the operating voltage between the upper and lower electrodes. At this time, the gain increased exponentially as the voltage increased (Fig. 4). At a constant threshold, the probability (η_{TH}) at which $G \cdot N_0$ is greater than N_{TH} changed exponentially, which can be verified by the experiment , as shown in the Fig. 10, the counting rate or current will eventually drop if the voltage is too high.

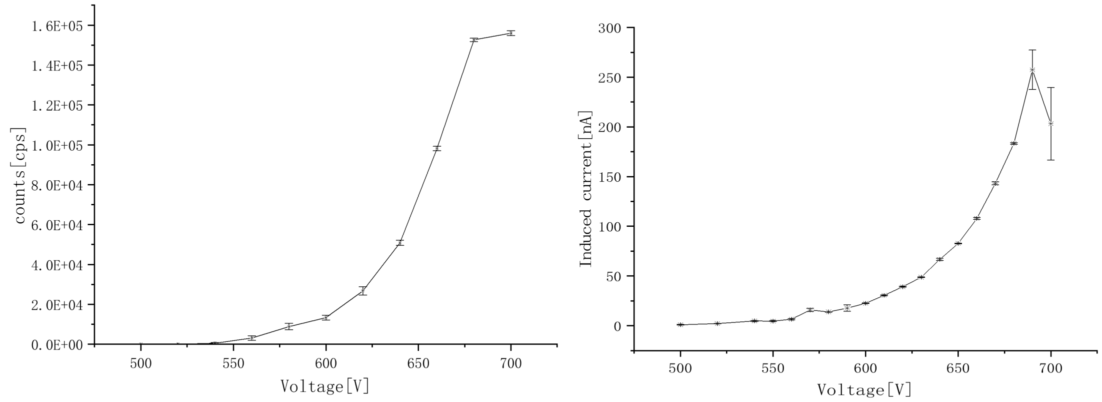

Fig. 10. Change of the count rate with the interelectrode voltage of the film

As can be seen from the figure, the voltage should not be too high or too low. To select the appropriate value, we also tested the dose rate response curve at varying interelectrode voltages of the film and verified the linear relationship between the dose rate and the count rate or current under different gains (Fig. 11). The results show that at different operating voltages the count rate or current assumed a linear relationship with the dose rate. At lower gamma dose rates, if a higher operating voltage is chosen, the detection efficiency can be improved and the lower range can be extended.

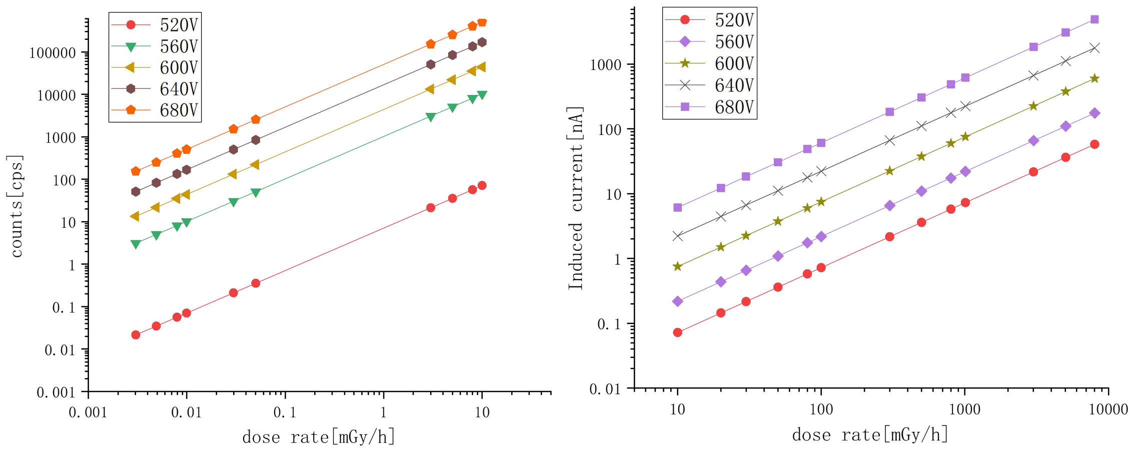

Fig. 11. Dose rate response curve of a thick GEM detector under gamma irradiation at different operating voltages

5. Conclusion and prospects

Based on the simulation results, a new type thick GEM detector was designed, which can measure the gamma dose rate from 0.3uGy /h to 8Gy/h. In the experiments, the counting model and the current model were designed to test low range and high range of gamma dose rate respectively, which effectively solved the problems of large current error in low range and insufficient counting ability in high range. This paper also studied the response of gamma dose rate under different working voltages, and adjusted the response curve of the dose rate by selecting different working voltages. Through the research in this paper, it can be seen that this new thick GEM detector maintains a good linearity in a very wide range of gamma dose rate, especially showing a broad application prospect in gamma measurement with ultra-high dose rate.

Acknowledgments

The authors would like to acknowledge *Institute of High Energy Physics, Beijing, China* for providing some experimental apparatus.

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