Design and function of an electron mobility spectrometer with a thick gas electron multiplier

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A B S T R A C T
The design and function of an electron mobility spectrometer (EMS) including a thick gas electron multiplier (THGEM) is presented. The THGEM was designed to easily be incorporated in an existing EMS to investigate the ability to detect tritium in air using a micropattern gas detector. The THGEM and a collection plate (anode) were installed and the appropriate circuitry was designed and connected to supply the required voltages to the THGEM-EMS. An alpha source (241Am) was used to generate electron-ion pairs within the gas-filled sensitive volume of the EMS. The electrons were used to investigate the THGEM-EMS response as a function of applied voltage to the THGEM and anode. The relative gas-gain and system resolution of the THGEM-EMS were measured at various applied voltage settings. It was observed a potential difference across the THGEM of +420 V and potential difference across the induction region of +150 V for this EMS setup resulted in the minimum voltage requirements to operate with a stable gain and system resolution. Furthermore, as expected, the gain is strongly affected not only by the potential difference across the THGEM, but also by the applied voltage to the anode and resulting potential difference between the THGEM and anode.

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1. Introduction
The presence of tritium, a short range (≈ 6 mm in air) and low energy beta emitter (E max, 18.6 keV) in the workplace of heavy water power reactors creates a challenging monitoring environment, especially if in the presence of gamma radiation and noble-gas radionuclides. The low detection efficiency of tritium and discrimination against other radiation types is an ongoing issue for all detector designs [1] but due to the high affinity of oxygen for electrons the efficiency of tritium detection in air using proportional counters or other micropattern gas detectors is further decreased. However, the motivation to develop a gas multiplication device as a tritium monitor stems from the principle that by incorporating tritiated air within the counting gas, both the counting efficiency and sensitivity can be maximized as well as the potential for gamma and noble-gas discrimination [2]. As part of this development work, an Electron Mobility Spectrometer (EMS) was recently constructed by Orchard and Waker [3] to look at electron mobility in various counting gases using a proportional counter to collect the electrons created within and drifted through the EMS, and was used to study the gas multiplication properties of proportional counters and their properties for measuring tritium in air.

Studies with the anode-wire configuration of the EMS yielded parameters such as the drift time of electrons, the pulse formation time in the gas multiplication region and relative gas-gain [3]. However, the use of an anode wire and its geometry within the EMS limited the ability to measure the drift time of electrons and pulse formation time independently. The use of a robust and easy to fabricate device that would provide a confined gas multiplication region [4] would reduce the uncertainty in timing measurements and for this reason a thick gas electron multiplier (THGEM) has been designed and integrated into the EMS of Orchard and Waker [3].

In this article the THGEM-EMS design and experimental setup are described and the THGEM-EMS response as a function of operating voltages is observed and compared to the anode-wire EMS configuration presented in [3]. The THGEM-EMS operating voltages are investigated using the ideal EMS operating conditions described in Orchard and Waker [3]. A set of systematic measurements were conducted and the relative gas-gain and system resolution as a function of applied voltages to the THGEM and induction region are presented.
2. Experimental design and method

The THGEM was first introduced in 2002 by Periale et al. [5] and was developed based on the gas electron multiplier (GEM) which was introduced in the mid 1990’s [6,7]. The THGEM is a proportional counter using a hole type structure and can be related to the category of micropattern gas detectors [8]. Initial studies using the THGEM for various detection purposes can be found in Breskin et al. [9] and Orchard et al. [10] and references presented within [9,10]. A THGEM is composed of an insulating sheet, such as FR4, which is coated on both sides with a conducting material, such as copper, and can be easily fabricated using standard printed circuit board (PCB) manufacturing techniques. The THGEM contains many sub-millimeter diameter holes generating a strong electric field within the holes when a voltage is applied across the conducting layers. The presence of the strong electric field within the holes generates an electron avalanche as electrons travel through the holes in the presence of a counting gas. The study and advancement of THGEMs in various detector applications is ongoing and references [11–16] represent a selection of recently reported investigations.

The THGEM for this study was designed to be incorporated within the existing EMS described in Orchard and Waker [3]. The existing anode wire was removed and the THGEM along with a brass collection plate (CP) were installed. The THGEM was operated with a $HV_{EMS}$ of $-1600 \text{ V}$, at atmospheric pressure ($p$) with an electric field ($E$) strength of $\sim 274 \text{ V/cm}$ using P-10 (90% Ar, 10% CH₄) as the counting gas. These EMS operating conditions result in a $\alpha$ value of $0.36 \text{ V/cm/mm Hg}$ within the EMS gas sensitive volume, corresponding to the minimal electron attachment region for oxygen [3]. Fig. 1 is a schematic of the EMS and associated pulse processing electronics required for the operation of the EMS. Four high voltage supplies, $HV_{EMS}$, $HV_{SB}$, $HV_{THGEM}$ and $HV_{CP}$ were used independently to supply the required voltages to the EMS, the surface barrier (SB) detector, the THGEM and CP, respectively. The preamplifiers (PreAmp), amplifiers (Amp) and multichannel analyzer (MCA) were used to process the detected pulses. A mass flow controller (MFC) was used to flow gas continuously through the EMS sensitive volume (SV) at a rate of 50 cm$^3$/min. The dashed lines in Fig. 1 represent the additional electronics, an amplifier and a gate and delay generator (G&D), required to measure the transit time of electrons within the EMS by gating the MCA. The $^{241}\text{Am}$ alpha source (0.1 μCi, January 2011, Eckert & Ziegler) is used to generate electron ion pairs within the EMS sensitive gas volume. The electrons travel through the drift region of the EMS, and into the drift region of the THGEM. Gas multiplication occurs within the holes of the THGEM, and the collection plate is the anode where the emerging electrons from the THGEM holes are collected. The surface barrier detector is used to detect the alpha particles, and is used as a visual check to ensure the presence of charge carriers within the gas cavity. The surface barrier is also used as the trigger when the EMS is used to measure the transit time of electrons as described in [3].

The THGEM was designed using Altium Designer software and manufactured by Omega Circuits (Scarborough, Canada). The THGEM is a flat disc with a diameter of 41 mm composed of a 0.12 mm thick FR4 insulator. The active region of the THGEM is centered on the flat disc with a diameter of 17 mm and each side coated with copper, resulting in a total thickness for the active region of $0.17 \pm 0.01 \text{ mm}$. There are 293 holes within the active region each with a diameter of $400 \mu\text{m}$, pitch of $800 \mu\text{m}$ and a $100 \mu\text{m}$ rim. A schematic of the THGEM is shown in Fig. 2(a). Fig. 2 (b) is a schematic of the electric circuit used to create a voltage drop across the THGEM copper layers. This circuit design is based

![Fig. 1. Experimental setup of THGEM-EMS. The thick gas electron multiplier (THGEM) and collection plate (CP) were incorporated in place of the preexisting anode wire to study the THGEM properties. The $\alpha$ symbol represents the location of the $^{241}\text{Am}$ alpha source.](Image 60x87 to 276x371)

![Fig. 2. (a) Schematic design of THGEM used to incorporate within existing EMS. The active area (diameter of 17 mm) is defined by the copper layers centered on the THGEM. The overall diameter is 41 mm. Two copper electrical contacts (one on each side of the FR4) were extended from the active area to the holes located near the edge of the FR4 and used to connect the high voltage circuit as shown in (b). The EMS aperture grid (EMS AG) is located 1.7 mm above the THGEM and separates the EMS drift region and the THGEM drift region. The induction region is the 2 mm gap between the bottom of the THGEM and the surface of the collection plate (CP). (Diagrams not drawn to scale).](Image 329x130 to 545x399)
Thus, both the effects of the potential difference across the THGEM and induction region. It was observed that the number of events forming the alpha peak was constant and not dependent on the applied high voltages $V_{THGEM}$ and/or $V_{CP}$. An average count rate of $\sim 68$ counts per second (cps) was measured for the alpha peak. This represents about 2% of the $^{241}\text{Am}$ alpha source activity. This is as expected as the alpha source is located on the outside of the sensitive volume with a small cylindrical collimator with length 4.5 mm and diameter 7 mm within the source holder. Thus, only collimated alpha particles that reach the sensitive volume of the EMS will deposit the maximum energy and create electron–ion pairs that can be detected. All other contributions from scattered alphas will contribute to the low energy events of the observed spectrum labelled as background in Fig. 3.

The effects of the potential difference $\Delta V_{THGEM}$ and $\Delta V_{Ind}$ were investigated independently in order to observe the THGEM response in terms of the relative gain and system resolution of the measured alpha peak. It is expected the value of $\Delta V_{Ind}$ can affect the gain and resolution of the detected signals due to the loss of a small fraction of avalanche electrons to the bottom of the THGEM copper layer [15,17–19], thus the THGEM response is dependent on both $V_{THGEM}$ and $V_{CP}$. The THGEM gain was monitored daily to check for gain–drift by observing the alpha peak centroid position measured with the same high voltage settings prior to and after each measurement. The high voltage supplies and associated electronics were powered on in the morning and powered off after the completion of a set of measurements.

3. Results

When the transit time experimental setup is used (including the additional electronics represented by the dashed lines in Fig. 1) the surface barrier detector is used as the trigger signal limiting the measured count rate to $1.73 \pm 0.04$ cps as detected by the surface barrier. Fig. 4 displays and compares the data obtained using the transit time experimental setup, described in Orchard and Waker [3], with the anode wire and THGEM-EMS configurations. Both data sets displayed in Fig. 4 were obtained with a $V_{THGEM}$ of $-1600$ V. The data for the anode wire configuration (represented by squares in Fig. 4), was obtained with the anode

![Fig. 3. THGEM-EMS spectrum obtained with applied voltages of $V_{THGEM} = -1600$ V, $V_{THGEM} = -450$ V and $V_{CP} = 600$ V resulting in $\Delta V_{THGEM} = 409$ V and $\Delta V_{Ind} = 150$ V. The centroid and FWHM of the alpha peak was used to observe the relative gain and system resolution of the THGEM-EMS configuration.](image)

![Fig. 4. Comparison of the transit time measurements conducted with the THGEM and wire-anode EMS configurations. Error bars are smaller than the data points. The wire-anode data and fit are taken from Orchard and Waker [3] and are used to compare with the THGEM-EMS geometry data obtained with the same EMS operating conditions.](image)
voltage set to +500 V and was originally presented in [3]. For the THGEM-EMS configuration (represented by circles in Fig. 4), a potential of 410 V was applied across the THGEM and an induction field of 150 V. This THGEM-EMS measurement was conducted to compare the true transit time of electrons in P-10 gas measured with the previous wire anode EMS configuration to the new THGEM-EMS configuration. The true transit time represents the delay time setting on the G&D generator corresponding to the maximum count rate measured. As shown in Fig. 4, a small difference in the true transit time is observed as expected due to the different geometries between the two anode configurations. After fitting the data to a Gaussian, a true transit time of 4.0 ± 0.3 μs and 4.3 ± 0.4 μs was obtained for the wire anode and THGEM geometries, respectively. In the anode configuration the wire anode is located closer to the aperture grid of the EMS whereas in the THGEM geometry the CP is located a greater distance from the aperture grid. Thus, the total distance travelled by the electrons is slightly greater (~1–2 mm) in the THGEM configuration compared to the original wire anode setup. As shown in Fig. 4 the THGEM-EMS response is similar to the anode-wire EMS response indicating the performance of the THGEM-EMS geometry is comparable to the anode-wire EMS geometry presented in [3].

In order to investigate the THGEM operating voltage a series of systematic measurements were conducted to observe the effects of the applied high voltages (HV$_{\text{THGEM}}$ and HV$_{\text{CP}}$) on the gain and system resolution of the THGEM-EMS performance. The measurements conducted can be divided into two groups. (1) The applied high voltage to the anode (HV$_{\text{CP}}$) was varied at set ΔV$_{\text{THGEM}}$ values and the multiplication gain as a function of the induction voltage (ΔV$_{\text{Ind}}$) was observed. (2) The induction field (ΔV$_{\text{Ind}}$) was maintained at set values to observe how the gain and resolution depends on the applied ΔV$_{\text{THGEM}}$. For both systematic measurements, the voltage applied to the EMS, HV$_{\text{EMS}}$ was maintained at −1600 V. The results from these systematic tests were compared and used to identify the viable operating conditions for the THGEM in the EMS configuration. For all measurements the MCA was used to collect events and generate a spectrum. The spectral shape was consistent (as shown in Fig. 3) and the centroid channel number (C$_{\text{Centroid}}$) and FWHM of the alpha peak at each high voltage settings was obtained. The system resolution $R$ was calculated using [8]:

$$R = \frac{\text{FWHM}}{C_{\text{Centroid}}}$$

where $R$ represents the total resolution of the THGEM-EMS, which is a summation of effects due to alpha particle straggling, statistical fluctuations in the number of ions produced by the absorption of a fixed amount of energy, electric field deformities and fluctuations in the electron multiplication process of the THGEM [20].

If the applied HV$_{\text{THGEM}}$ was below the threshold electric field strength required for gas multiplication an alpha peak was not observed and the threshold HV$_{\text{THGEM}}$ was noted. Additionally, the error in $C_{\text{Centroid}}$ is represented by the standard deviation of the mean. The centroid value is proportional to the multiplication gain of electrons as they travel through the THGEM holes and was used to calculate the relative gain.

### 3.1. Induction field voltage scan

The potential difference across the induction gap, ΔV$_{\text{Ind}}$, was varied by adjusting the applied HV$_{\text{CP}}$ while ΔV$_{\text{THGEM}}$ was set to a fixed value. A range of −70 V to 600 V was used for ΔV$_{\text{Ind}}$ by varying the applied HV$_{\text{CP}}$ from 520 V to 1300 V in increments ranging from 10 V to 50 V. The induction field scans were conducted at set ΔV$_{\text{THGEM}}$ values of 360 V, 410 V, 490 V and 590 V. At each ΔV$_{\text{THGEM}}$ a spectrum for a range of ΔV$_{\text{Ind}}$ values was collected and the $C_{\text{Centroid}}$ and FWHM values of the alpha peak for each spectrum were obtained. Fig. 5 is a plot of the $C_{\text{Centroid}}$ values as a function of ΔV$_{\text{Ind}}$ at the four selected ΔV$_{\text{THGEM}}$ values. An increase in the centroid is observed, as expected, as more electrons are extracted from the avalanche with increasing ΔV$_{\text{Ind}}$ [17]. At each ΔV$_{\text{THGEM}}$ the gain approaches a saturation value as the minimum required induction field value to extract all electrons from the avalanche is reached. The gain observed at negative ΔV$_{\text{Ind}}$ values indicates that the electric field lines generated across the THGEM holes extend into the induction region resulting in some electrons reaching the CP even at negative ΔV$_{\text{Ind}}$ values.

Fig. 6 displays the system resolution, $R$ as a function of ΔV$_{\text{Ind}}$ at selected ΔV$_{\text{THGEM}}$ values. A stable resolution is observed at ΔV$_{\text{Ind}}$ values greater than 100 V. Both Figs. 5 and 6 confirm the importance of the induction region as reported by others [4,9,13,15,19] and can affect the THGEM-EMS gain and system resolution. At set ΔV$_{\text{THGEM}}$ values a strong electric field in the induction region is required to efficiently collect electrons at the CP and to ensure a stable system resolution. Increasing the induction field further will improve electron collection; however, the system resolution, $R$, appears to plateau at values greater than ΔV$_{\text{Ind}} = 100$ V.

![Fig. 5. Gain, represented by the $C_{\text{Centroid}}$ Value, as a function of ΔV$_{\text{Ind}}$ at the four selected ΔV$_{\text{THGEM}}$ values. Error bars for the $C_{\text{Centroid}}$ data are smaller than the size of the data points shown in the figure.](image)

![Fig. 6. THGEM-EMS system resolution, $R$ as a function of ΔV$_{\text{Ind}}$ at the four selected ΔV$_{\text{THGEM}}$ values.](image)
3.2. THGEM potential difference scan

From the results presented above, the highest system resolution (lowest value of \( R \)) is observed when \( \Delta V_{\text{ind}} \) is set to 150 V or greater (Fig. 6) and the gain increases with increasing \( \Delta V_{\text{ind}} \) as shown in Fig. 5. To further study the THGEM-EMS performance \( \Delta V_{\text{ind}} \) was set to 150 V and \( \Delta V_{\text{THGEM}} \) was varied from 230 V to 640 V. These potentials were obtained by varying \( HV_{\text{THGEM}} \) from 200 V to 700 V in increments of 50 V, and maintaining \( HV_{CP} \) always at 150 V greater than \( HV_{\text{THGEM}} \). This procedure was repeated two more times at \( \Delta V_{\text{ind}} \) values of 350 V and 600 V. Again spectra were collected and the centroid and FWHM of the alpha peak extracted to observe the gain and resolution of the THGEM-EMS at constant \( \Delta V_{\text{ind}} \) values. During this experiment the total number of events under the alpha peak was monitored to verify the earlier observation of an average alpha peak rate of 68 cps. From this data set, an average count rate of 69 ± 2 cps for the alpha peak was measured. This result clearly shows the alpha peak count rate is consistent and independent of the applied high voltages, as long as \( \Delta V_{\text{THGEM}} \) is above the threshold value for electron multiplication and \( \Delta V_{\text{ind}} \) is maintained at a value where collection by the anode is not inhibited.

Figs. 7 and 8 display the relative gain and system resolution obtained as function of \( \Delta V_{\text{THGEM}} \) with a constant \( \Delta V_{\text{ind}} \) value of 150 V, 350 V and 600 V. The trends in both figures indicate a value of about 400 V or greater across the THGEM results in adequate system resolution and signal amplitude to conduct measurements with the THGEM-EMS. For higher signal amplitude one can simply operate the THGEM at higher \( \Delta V_{\text{THGEM}} \) values. Given the resolution due to the alpha source geometry and energy straggling within the EMS are constant during all experiments, the observed changes in the system resolution shown in Figs. 6 and 8 are only due to the THGEM response as a function of the applied potential difference voltages \( \Delta V_{\text{THGEM}} \) and \( \Delta V_{\text{ind}} \). Observing the trends in Figs. 5–8 the minimum operating conditions for the THGEM in the EMS configuration are \( \Delta V_{\text{THGEM}} \approx 420 \text{V} \) and \( \Delta V_{\text{ind}} \) value of 150 V. This corresponds to an applied \( HV_{\text{THGEM}} \) of 460 V and a \( HV_{CP} \) of 610 V.

4. Discussion and conclusion

A THGEM was designed and assembled within an existing EMS. Initial work was conducted to ensure the EMS performance was consistent between the wire anode and THGEM configurations (see Fig. 4). Since the same EMS operating conditions (\( HV_{\text{EMS}} \), gas flow rate and \( E/P \) value) were used to compare the two configurations, the same drift velocity of the electrons in the EMS drift region is expected and as shown in Fig. 4, the transit time measurements indicate similar performance between the THGEM and wire anode geometries. Using the ideal operating conditions for the EMS, reported by Orchard and Waker in [3], the voltages associated with the THGEM and collection plate (CP) within the EMS were investigated to observe the THGEM-EMS gain and system resolution trends. The relative gas-gain and system resolution as a function of THGEM and CP applied voltages were calculated in order to observe the THGEM gas multiplication response. The series of measurements were conducted to investigate the THGEM response to the applied high voltages to the THGEM and CP individually and in combination. The combination of these applied voltages varies the resulting potential difference across the THGEM and the induction region. The results indicate a strong relationship between the THGEM and CP applied voltages on the overall THGEM-EMS response. From the results, the gain observed at the upper \( \Delta V_{\text{THGEM}} \) and \( \Delta V_{\text{ind}} \) values, is greater than the gain obtained with the wire-anode geometry presented in Orchard and Waker [3].

The consistent spectral shape as shown in Fig. 3 was used to obtain the relative gas-gain and system resolution as a function of applied voltages by extracting the centroid and FWHM of the alpha peak. Two sets of measurements were conducted to observe the THGEM-EMS response. From the results presented the minimum potential across the THGEM, \( \Delta V_{\text{THGEM}} \), and induction field, \( \Delta V_{\text{ind}} \). Required are 420 V and 150 V, respectively, for the highest system resolution. Increasing the potentials further increases the gain while the system resolution plateaus. An important observation from this work is the strong dependence of the gain on the induction region electric field as shown in Figs. 5 and 7, and the influence of the induction field on the system resolution (Figs. 6 and 8). These results indicate the THGEM performance is strongly affected by the induction gap conditions as expected [19]. A focused study on the thickness of the induction region in combination with the applied \( HV_{CP} \) will provide additional information on the THGEM gain dependence on the induction region conditions within the EMS. Additionally, a study focusing on the THGEM geometry such as the thickness relative to the hole diameter and/or pitch would also provide additional insight on the THGEM-EMS overall performance.
Another observation during these investigations was a slight increase in gain as a function of daily operating time. We believe this is due to a small temperature increase of the EMS components and sensitive volume air by the applied high voltage circuits, but did not verify this with a systematic study. Since the higher the $\Delta V_{THGEM}$ the greater the risk of generating sparks or arching across the THGEM holes [21], the optimum $\Delta V_{THGEM}$ value should be carefully selected and maintained at the minimum required value with acceptable gain and system resolution.

The investigations presented in this article have provided a quantitative analysis of the THGEM-EMS geometry dependence not only on the potential across the THGEM, $\Delta V_{THGEM}$, but also on the conditions of the induction region, $\Delta V_{Ind}$. From the results the minimum requirements for operating the THGEM-EMS geometry with a 2 mm gap in the induction region were deduced. Further experimental and simulation studies on the gas-gain and system resolution of the EMS with a THGEM or THGEMs in cascade will provide fundamental information on the operating conditions to maximize gas-gain for the advancement of gaseous THGEM detectors. Future work with the THGEM-EMS includes introducing a delay line readout circuit [22] to measure the drift velocity of electrons within the EMS drift region in various counting gases, including P-10 and tissue equivalent gases and the system response in the presence of air for the advancement and investigation of measuring tritium in air using micropattern gaseous detectors.

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