Title: Neutron Responses of a Novel Multi-element Microdosimetric Detector and Its Potential for Dosimetry

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Abstract

A prototype multi-element gaseous detector based on THick Gas Electron Multipliers (THGEMs) has been designed and constructed. A THGEM generates a strong electric field within micro-holes of a sub-millimeter thick insulator, which makes electron multiplication possible without the traditional anode wire electrodes encountered in proportional counters. The wireless structure has been chosen to overcome the complicated fabrication and assembly process required for building multi-element microdosimetric detectors using the traditional proportional counter technology. The multi-element design was employed to enhance the neutron detection efficiency, particularly for weak radiation fields frequently encountered in radiation protection applications. The prototype detector consists of 21 cylindrical gaseous sensitive volumes, with equal heights and diameters of 17 mm, built in three alternating layers of tissue-equivalent plastic hexagons. The detector was filled with a propane-based tissue equivalent gas and its responses to various neutron fields were investigated using the ^{7}Li(p,n) neutron source at the McMaster Tandetron accelerator laboratory. Microdosimetric measurements were carried out for the proton energy range of 1.9 to 2.3 MeV and proton current of 50 μA. In this paper, the prototype detector structure is described. Preliminary results on the pulse height measurements and microdosimetric response of this novel detector are presented.

Keywords

Tissue Equivalent Proportional Counter, THick Gas Electron Multiplier, Microdosimetry, Multi-element Detector

1 Introduction

A proportional counter is a gaseous detector which provides a distribution of amplified signals proportional to the amount of energy released by individual ionization events within the gas. The low-pressure proportional counter, known as a Rossi counter [1], was developed in the early 1950s to measure microdosimetric quantities at the site size of a micrometer (μm). To model the energy deposited in volumes similar to biological cells, tissue equivalent materials are employed as the detector walls and filling gas. The traditional Tissue Equivalent Proportional Counter (TEPC) generally consists of a central wire anode surrounded by a spherical gas cavity in a conducting tissue equivalent A-150 plastic [2] of a specified thickness. Being capable of providing both spectrometric and dosimetric information, TEPCs are extensively used in experimental microdosimetry to measure the lineal energy spectrum which can be used to determine quality factors and hence the dose equivalent [3]. However, one inherent limitation of the TEPC-based instruments is low neutron detection efficiency which stems from the low elastic scattering cross section of hydrogen as the main fast neutron detection interaction mode in TEPCs. This is a major issue for radiation protection applications especially where monitoring weak neutron radiation fields is required.

A so-called "multi-element" structure, which utilizes stacks of alternative electrodes and insulators housing an array of gaseous cavities, can potentially increase the detection efficiency of a TEPC [4]. The idea of a stacking detector structure is closely related to the development of Gas Electron Multiplier (GEM) based detectors [5]. In contrast to traditional wire-based TEPCs, GEM detectors are wireless structures in which an avalanche electric field is produced using a micro-pattern hole-type structure. The standard GEMs typically consist of thin Kapton film substrates with double-sided metal laminates housing an array of chemically etched holes with 50 to 100 μm diameters. Applying a proper potential across the GEM accelerates electrons released in the gas through the holes where electron multiplication initiates.

Following previous publications [4, 6, 7], a prototype THick Gas Electron Multiplier (THGEM)

based multi-element TEPC has been designed and constructed for microdosimetry measurements in mixed neutron-gamma radiation fields. The THGEM was developed in 2002 by Periale *et al*. [8] and has a hole-structure similar to the standard GEM, but is approximately 10 times larger in diameter and insulator thickness. It offers a similar multiplication performance to the GEM with an inexpensive and more convenient fabrication process and permits achieving gains above 10^4 [9, 10]. Past studies on THGEM-based detectors mostly include particle tracking and imaging applications focusing on time and position resolution improvements [11, 12]. Yet, there have been no activities with the intention of detection efficiency improvement using these new detectors for monitoring weak neutron radiation fields.

This paper demonstrates the feasibility of constructing a multi-element TEPC with a stacked structure of THGEM electrodes and gives an accessible path to a modern microdosimetric detector with enhanced detection efficiency. Different components and technical considerations of the THGEM detector structure are described here. To evaluate the performance of the prototype detector, initial functioning tests were performed in mixed neutron-gamma radiation fields. Detector microdosimetric responses are discussed and the results are verified using the 0.5 and 2 inch commercial TEPCs.

2 Detector Description

As presented schematically in Figure 1, for a single sub-element, the distinct gas regions provide three different functional areas: a) the conversion and drift region, b) the multiplication area and c) the charge collection gap. In this design, each A-150 layer serves as the cathode. The gas cavities in the Rexolite layers originally form conversion and drift gaps in which the electrons are produced by ionization and drift along the electric field from cathode to the THGEM layer. With the application of a high potential difference between the top and bottom of the THGEM, a strong electric field is produced inside the THGEM holes where electron multiplication happens. The

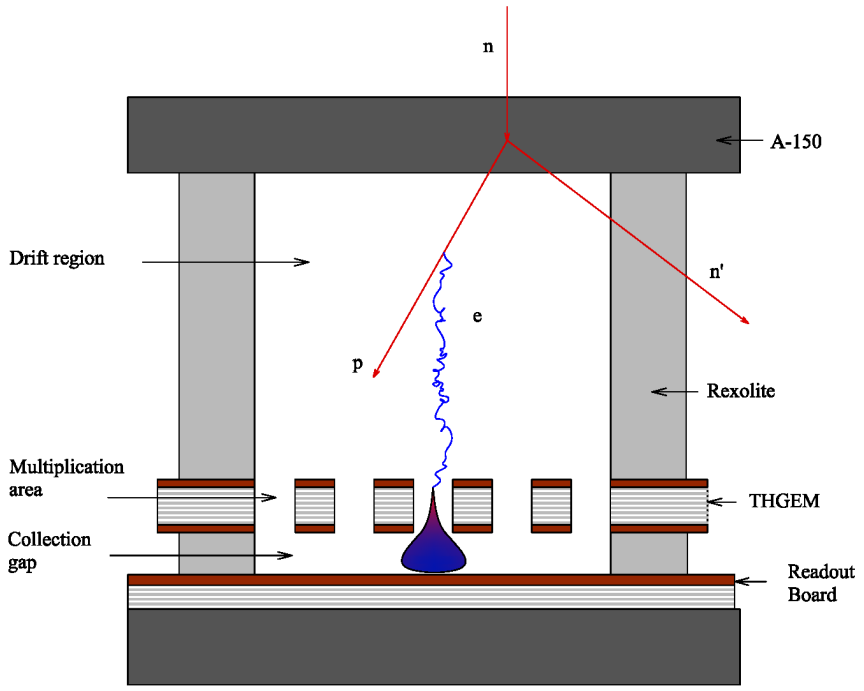

Figure 1: Schematic view of different functional gas areas in a single gas cavity of the prototype THGEM-based detector.

electric field strength inside the THGEM holes is large enough to initiate an electron avalanche. After multiplication, by the use of an efficient potential difference across the collection gap, the avalanche electrons leave the THGEM layer and are collected by a common collection electrode. The amplitude of the collected signal by the readout anode is linearly proportional to the total deposited energy of a single event.

The prototype multi-element detector layout consists of three alternating layers of Rexolite insulator (Rexolite 1422, C-LEC Plastics, Inc.) hexagons (see Figure 2). Each layer houses a hexagonal array of seven cylindrical gas cavity elements, known as the sensitive volumes, with equal heights and diameters of 17 mm so that the final detector structure consists of 21 counting volumes. To pump out the air and fill the sensitive volumes with the operating gas, a set of grooves is placed on the top and bottom of the Rexolite insulator. The wall thickness between each sub-element was kept at least 1 mm to satisfy the charged particle equilibrium condition for neutrons with the energies applied in this study. In each layer, the Rexolite insulator is sandwiched between a 1 mm

thick A-150 conducting plastic and a THGEM layer. The charge collection regions are located next to each THGEM layer and consist of common readout boards which are separated from the THGEM layer by employing an arrangement of ceramic spacers with a thickness of 1 mm.

Fabricated using the standard printed circuit board manufacturing techniques, the THGEM layout employed in this study is composed of 0.4 mm FR4 insulator coated with 0.05 mm of copper on both sides with a hexagonal pattern of 0.4 mm diameter holes and a hole pitch of 0.8 mm. After drilling, to have better shaped holes and avoid debris leftover during the drilling process, a combination of a mechanical brushing procedure using pumice stone followed by rinsing with high pressure water, and a micro etch chemical process was employed. The chemical contains approximately 10% nitric acid. Finally, THGEMs were washed with demineralized water and dried in an oven at 180 $^{\circ}C$ for 24 hours. This procedure helps to avoid high electric field values for sharp edges and have a better field uniformity.

An aluminum vacuum chamber was designed and constructed to encase the entire detector assembly and house the high voltage and BNC signal connectors as well as a gas filling port. Designed to be used in neutron microdosimetry measurements, the assembled aluminum chamber is capable of keeping a steady pressure of several torr. This guarantees the reproduction of the measurements over an adequate data acquisition time. After assembling, the vacuum chamber was sealed and degassed using a rotary vane vacuum pump. Then, the detector was filled with propane-based tissue equivalent gas, consisting of 55% C_3H_8, 39.6% CO_2 and 5.4% N_2, at the pressure of 49.1 torr to simulate the energy loss pattern of charged particles in 2 μm of soft tissue.

3 Methods and Materials

The 1.5 MV double stage Tandetron accelerator at the McMaster Accelerator Laboratory was used as a radiation source to evaluate the counting efficiency and microdosimetric responses of the prototype THGEM detector in a mixed neutron-gamma radiation field. The Tandetron can

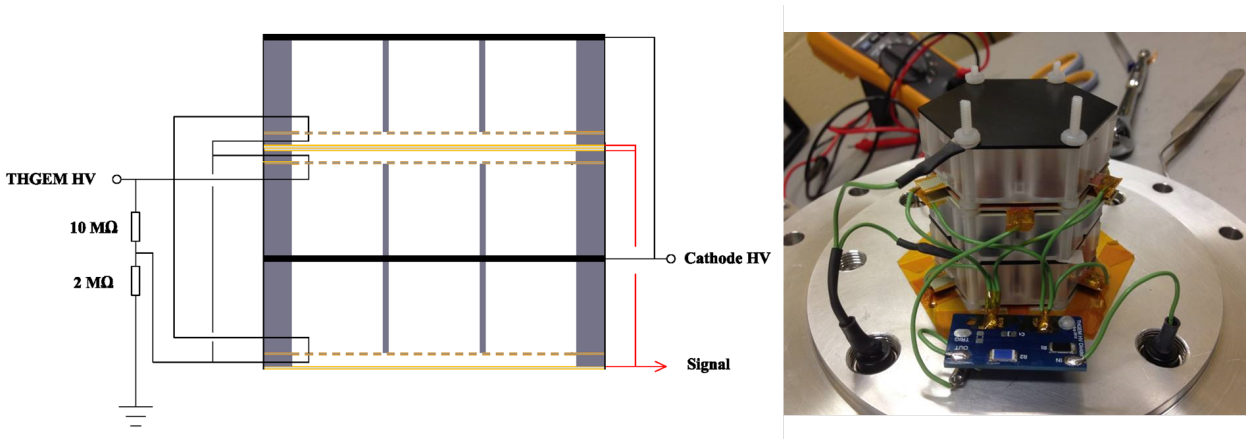

Figure 2: A schematic diagram of the bias voltage connections and a photograph of the multi-element THGEM detector within the aluminum casing.

accelerate protons up to 2.5 MeV with a maximum current of 1 mA. When energetic protons hit a thick lithium target at the end of the proton beam path, a wide-range continuous spectrum of neutrons is produced via the ^{7}Li(p,n)^{7}Be reaction with a threshold energy of 1.88 MeV. The Li target assembly is surrounded by an irradiation cavity which is designed to be used for medical and radiobiological studies such as *in vivo* neutron activation analysis [13]. The detector was placed inside the irradiation cavity centered on the beam path and about 30 cm away from the target.

The A-150 layers and THGEMs were biased by using two separate power supply units (Bertan Associates Model 305). A schematic diagram of the bias voltage connections to the different components of the prototype THGEM detector and a photograph of the detector within the aluminum casing are shown in Figure 2. In each layer, a negative high voltage was applied to the A-150 as the detector drift cathode, while the readout board was kept at ground potential to avoid high voltage on the signal feed through. By employing a custom made voltage divider circuit, the top and bottom layers of the THGEMs were biased to produce an avalanche electric field inside the THGEM holes and to direct the electron cloud to the collection readout board in each layer. The values of resistors were chosen as recommended by Orchard [7] to provide an efficient potential difference across the THGEM and collection gap. The output signal of the THGEM detector was connected directly to a

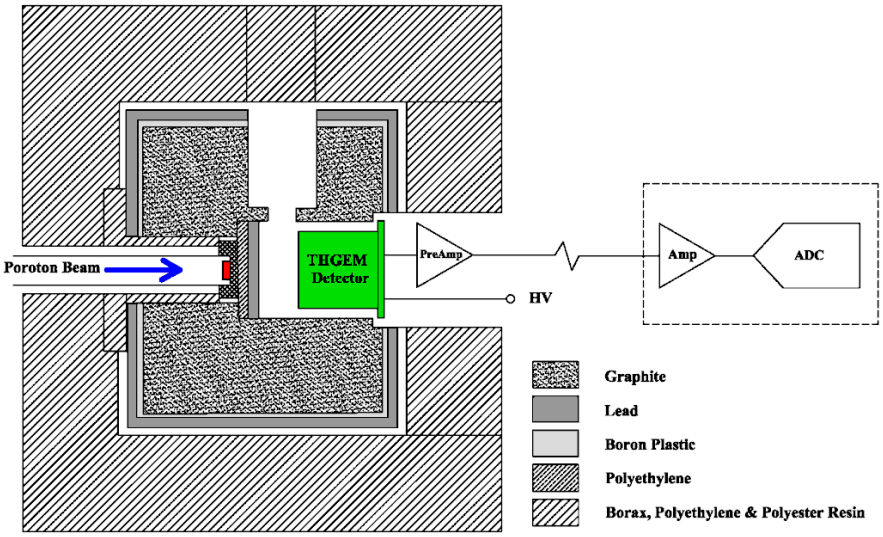

Figure 3: The arrangement of the measurement setup with THGEM detector.

low-noise charge sensitive preamplifier (Model A1422, CAEN) located as close as possible to the detector. To process pulse signals from the detector, the preamplifier output signal was fed into a commercial digital pulse processing system (Model DSPEC, Ortec). The DSPEC supports up to 16k channels. The gain setting and THGEM operating high voltage were chosen so that all of the events can be entirely covered in one spectrum. To compare the result with the standard data, the commercial 2 inch and 0.5 inch TEPCs (the standard single wire LET proportional counters with the internal diameter of 5.08 and 1.27 cm respectively, available from Far West Technology Inc.) were used in this study. The layout of the experimental arrangement is depicted in Figure 3.

After data collection, the pulse height spectrum was calibrated in terms of the lineal energy, y. Lineal energy is a principle microdosimetric variable which is desired to be measured in experimental microdosimetry [14]. According to ICRU 36, lineal energy is defined as the energy imparted by a single event in a volume divided by the volume mean chord length $\bar{l}$ and is presented in units

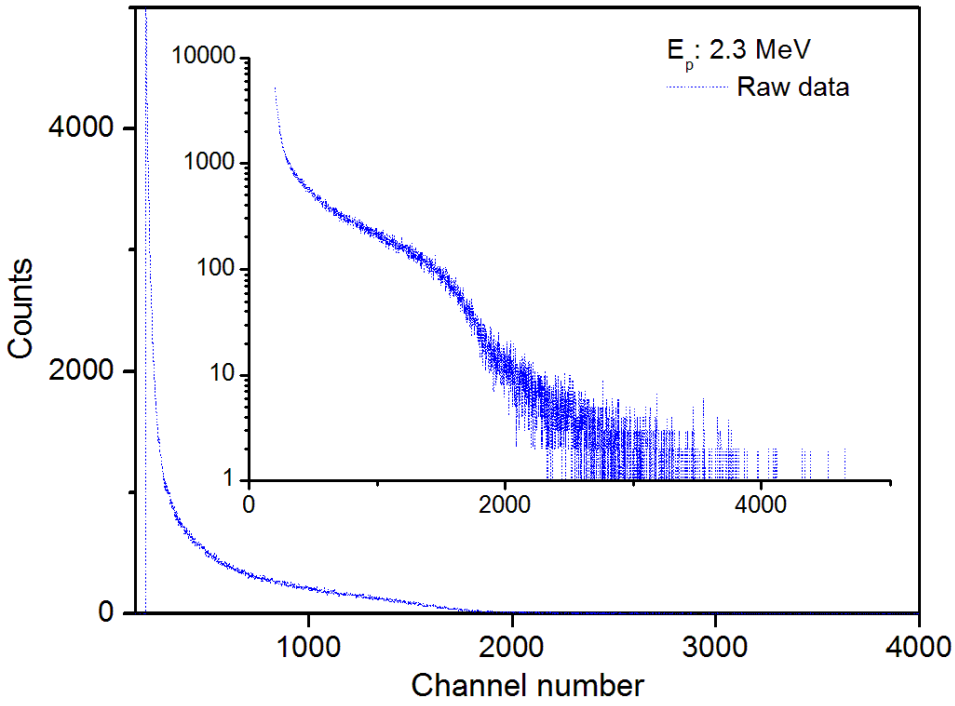

Figure 4: The pulse height spectrum obtained using the prototype multi-element THGEM detector at a THGEM bias voltage of 650 V and for a proton energy of 2.3 MeV.

of keV/μm. The mean chord length in a cylindrical volume (with equal height and diameter) that results from the random interception of the site by a straight line is equal to 2/3 of the diameter.

4 Microdosimetric Measurements and Dose Responses

Figure 4 shows a pulse height spectrum of the prototype multi-element THGEM detector for a THGEM bias voltage of 650 V at a proton energy and current of 2.3 MeV and 50 μA respectively. The corresponding lineal energy spectrum along with 0.5 and 2 inch TEPC responses are presented in Figure 5 after gamma-ray component subtraction. To create the lineal energy spectrum for each data set, the corresponding lineal energy of each detected event was calculated using a proper calibration line and redistributed into equal logarithmic bins with a resolution of 60 bins per decade. For the vertical axis, the number of counts in each logarithmic bin, N(y), was multiplied

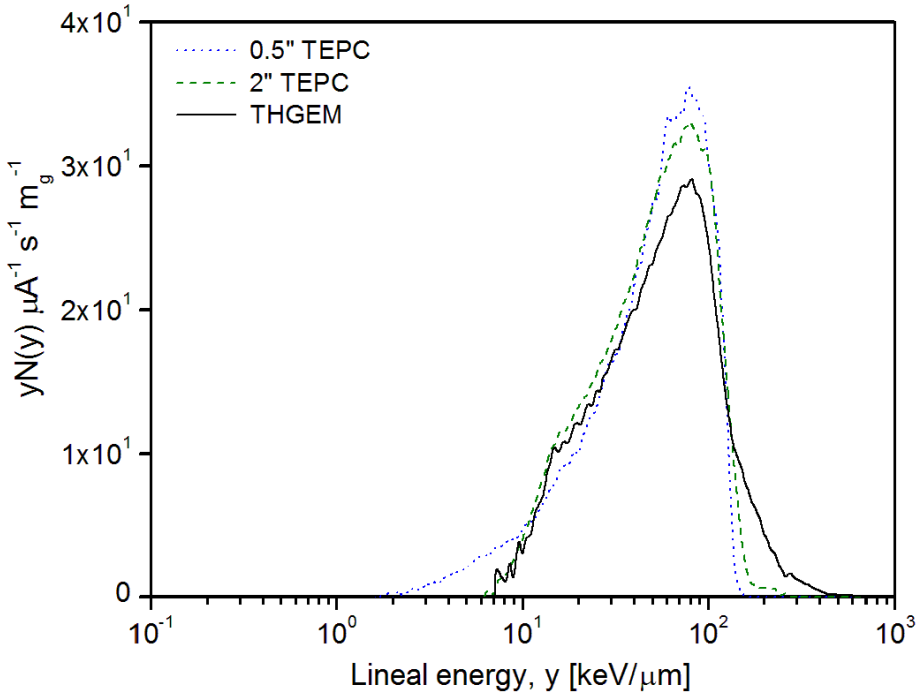

Figure 5: The lineal energy spectra obtained using the prototype multi-element THGEM detector and commercial TEPCs after gamma-ray component elimination.

by the corresponding lineal energy such that the area under the curve between two values of y is proportional to the fraction of dose in that region. For the 0.5 inch TEPC data, the lineal energy was calibrated with a built-in ^{244}Cm alpha source. For the prototype multi-element detector and 2 inch TEPC, which do not have a built-in calibration sources, the proton recoil peak of the 0.5 inch TEPC and a pulser calibration line were used to convert the pulse height information into the lineal energy spectra. For comparison, all spectra are normalized by the total proton charge, μC, incident on the lithium target and by the mass of the counting volume gas, m_g. From the lineal energy spectrum, it is apparent that the neutron response of the prototype detector is consistent with the standard TEPCs with a comparable energy resolution for the neutron peak. When compared to the standard TEPCs, the minimum detectable lineal energy shifts toward higher values from 2 keV/μm for the 0.5 inch TEPC to about 6 keV/μm for the prototype THGEM detector. This mainly stems from a lower signal-to-noise ratio for the prototype detector. To calculate the neutron absorbed dose from

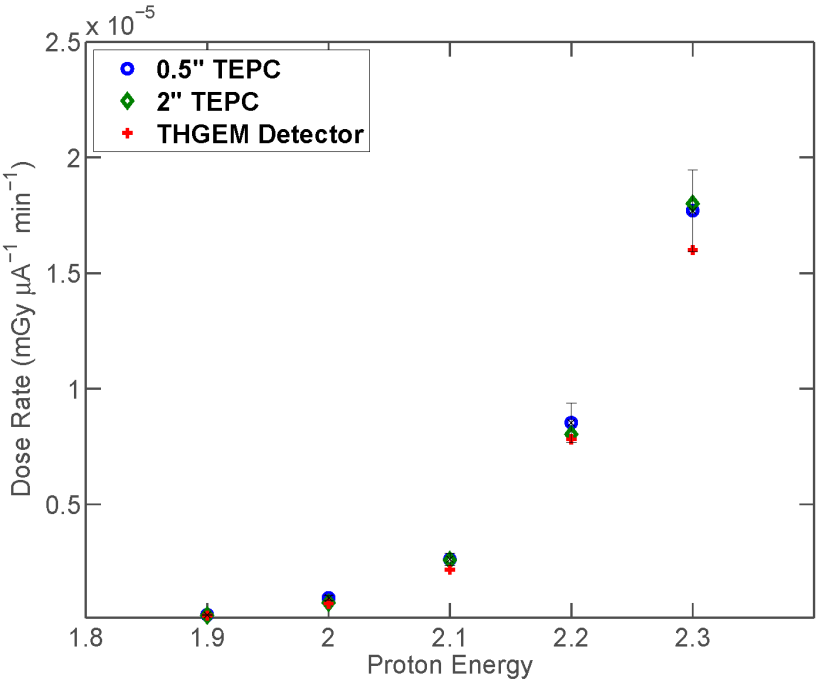

Figure 6: Measured dose rates obtained from the prototype multi-element THGEM detector, 0.5 and 2 inch standard TEPCs at different proton energies.

each spectrum, the gamma-ray component was fitted with a standard gamma-ray microdosimetric spectrum from ^{137}Cs and subtracted from the entire spectrum. Then, the area under the yN(y) curve was determined by integrating the remaining neutron component. The integrated area is proportional to the neutron dose through the following equation

$$D(Gy) = \frac{total\ deposited\ energy}{gas\ mass} = \frac{1.6 \times 10^{-16}(J/keV)\ \bar{l}_m(\mu m) \sum\ y\ N(y)}{m_g(kg)} \quad (1)$$

The measured neutron absorbed dose rates for the prototype multi-element THGEM detector and the standard TEPCs are summarized in Table 1 for the proton energy range of 1.9 to 2.3 MeV. For comparison, the results are plotted in Figure 6 and all measurement results are quoted in $mGy/\mu A^{-1}min^{-1}$ for convenience.

Table 1: The measured neutron absorbed dose rates for the prototype detector and standard TEPCs.

	Proton Energy (MeV)				
	1.9	2.0	2.1	2.2	2.3
0.5 inch TEPC	2.21E-07	9.49E-07	2.62E-06	8.53E-06	1.77E-05
2 inch TEPC	1.99E-07	7.48E-07	2.59E-06	8.03E-06	1.80E-05
Multi-element THGEM Detector	1.83E-07	7.04E-07	2.17E-06	7.82E-06	1.60E-05

Values are in $mGy\ \mu A^{-1}\ min^{-1}$ $\pm$ 10%

5 Conclusion

A novel prototype multi-element THGEM detector was designed and successfully constructed. The prototype detector utilizes a multi-layer structure of alternative THGEM electrodes and Rexlite insulators seeking two main objectives: to enhance neutron detection efficiency and to overcome the complicated fabrication and assembly process required for building a multi-element microdosimetric detector based on wire electrodes. The multi-element THGEM detector is a prototype and the adequate detection efficiency for monitoring weak neutron fields can be achieved by optimizing the number of sub-elements. To evaluate the overall performance of the THGEM-based detector, initial microdosimetric measurements were carried out in a mixed neutron-gamma radiation field. As shown, the detector is capable of measuring neutron dose rates within an acceptable range of uncertainty and gives similar spectral information compared to standard TEPCs.

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