Nuclear Instruments and Methods in Physics Research A 757 (2014) 67–74

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Monte Carlo design study for thick gas electron multiplier-based multi-element microdosimetric detector

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ARTICLE INFO

Article history:
Received 5 July 2013
Received in revised form
24 April 2014
Accepted 26 April 2014
Available online 9 May 2014

Keywords:
THick Gas Electron Multiplier
Microdosimetry
Multi-element detector
Monte Carlo simulation
Geant4

ABSTRACT

To accomplish enhanced neutron dose response with high detection efficiency, a set of multi-element microdosimetric detectors were designed using THick Gas Electron Multiplier (THGEM). THGEM generates a strong electric field within microholes of a sub-millimeter thick insulator, which makes electron multiplication possible without the traditional anode wire electrodes. Owing to the absence of wire electrodes, the newly designed neutron dosemeters offer flexible and convenient fabrication in contrast to the traditional multi-element tissue-equivalent proportional counters. In order to investigate the dependence of the neutron dosimetric response and detection efficiency on detector design, five designs with a different number of gas cavities and an identical outer diameter of 5 cm were created. For each design, a Monte Carlo simulation was developed using the Geant4 code to calculate the deposited energy spectrum in the gas cavities for mono-energetic neutron beams ranging from 10 keV to 2 MeV. From the simulation results, the microdosimetric and the absorbed dose responses of each multi-element design were consistent with the responses of the conventional single cavity detector. The quality factor and the dose equivalent responses were subsequently obtained and showed reasonable agreement with the ideal values for neutron energies above 300 keV while underestimating in the lower energy region. The neutron detection efficiency of each design was analyzed in terms of the neutron counts per incident fluence and the counts per dose equivalent. As the number of the multi-element cavities increased, both efficiencies increased greatly. The efficiency of the highest cavity density with 61 × 9 multi-elements was on average 5.6 times higher than that of the single cavity design. The 37 × 7 design could be chosen as a reasonable compromise between the two conflicting requirements, high efficiency and convenience in fabrication.

1. Introduction

Accurate real-time neutron dosemeters are vital in radiation protection for survey and monitoring of unknown radiation fields. The primary dose quantity aimed to measure is neutron ambient dose equivalent H*(10), which is defined at 10 mm depth in the ICRU (International Commission on Radiation Units and Measurements) sphere for specific irradiation conditions [1]. Given the neutron energy range of interest often exceeds ten decades, particularly for reactor neutron fields, while fast neutrons are in general not easy to detect, the moderator-based instruments [2–5] have been most popular due to their high efficiency to date. Their underlying principle is that through scatterings with a spherical or cylindrical moderator, incident fast neutrons are slowed down to the thermal neutron energy region and then counted by a central thermal neutron detector such as a BF_3 or ^{3}He counter. A well designed moderator-based instrument modifies the incident neutron spectrum in a similar way to the ICRU sphere. However, a fundamental limitation is that the dose calibration relies on the number of detected thermal neutrons rather than taking into account the energy deposited in a tissue equivalent material. Therefore, it is not surprising that the ambient dose equivalent response, i.e. ratio of the dosemeter reading to the true ambient dose equivalent value, of moderator-based instruments deviates significantly from the ideal response in energy regions outside of the calibrated energy. Particularly, the instruments significantly over-respond in the keV region while under-respond in the region above 5 MeV. Another shortcoming is the heavy weight of the polyethylene moderator, which make them inconvenient to handle [6,7].

To overcome the fundamental limitation of the moderator-based instruments, many groups employed microdosimetric tissue-equivalent proportional counters (TEPCs) [8–11] which collect the pulse height spectrum of the energy deposition event inside a tissue-equivalent gas cavity to simulate the energy deposition distribution in a micrometric tissue volume. The pulse height spectrum is calibrated in terms of the lineal energy [1], which is a microdosimetric quantity

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http://dx.doi.org/10.1016/j.nima.2014.04.063
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defined as the deposited energy in a volume by a single event divided by the mean chord length and is directly coupled to linear energy transfer (LET). The mean chord length is defined as the mean length of the random interceptions of a micrometric site by a straight line and is given by 2/3 of the diameter for a spherical or cylindrical (with equal height and diameter) micrometric site. For a collected lineal energy spectrum, the absorbed dose is conveniently determined by integrating the spectrum. Moreover, the mean quality factor can be extracted when the quality factor is incorporated in the lineal energy distribution [12]. The mean quality factor weights the absorbed dose with the average biological effect relative to ^{60}Co radiation. Therefore, TEPC-based instruments have a sound physical foundation in determining the dose equivalent [13,14]. TEPC-based neutron monitors were applied for measuring neutron dose distributions at nuclear power plants, proton therapy accelerators, aircraft, etc. [9–11,15–18].

In spite of their outstanding feature in determining dose equivalent, the TEPC-based instruments generally suffer from low neutron detection efficiency, which is a critical issue for monitoring weak neutron fields. The efficiency limitation is in some sense unavoidable since the elastic scattering cross section of hydrogen, the main fast neutron detection interaction in TEPC, is much lower than the thermal neutron cross sections of the ^{10}B(n,α) and ^{3}He(n,p) reactions, used in moderator-based instruments. A simple way to overcome the efficiency limitation is to increase the detector sensitive volume. For example, to obtain an efficiency comparable to a SNOOPY dosemeter [19,20], a representative moderator-based instrument having an efficiency of 800 [counts/μSv], a TEPC with a diameter of about 28 cm is required [21]. Although it is technically not challenging to manufacture such a large size of TEPC detector, it will end up diluting the advantages of TEPC.

Another way of enhancing the neutron detection efficiency is to increase the surface area of the gaseous sensitive volume, which is based on the fact that the neutron interaction with the detector wall contributes predominantly to fast neutron detection in TEPCs in a wide energy region. For a fixed detector volume, the effective surface area of detector can be increased by subdividing the sensitive volume into many smaller volumes, i.e. “multi-elements”. This idea was first proposed by Rossi [22] for monitoring low dose-rate mixed field exposures and later, a multi-element proportional counter was reported by Kliauga et al. [23]. This counter consists of 296 cylindrical sub-elements arranged in a hexagonal array in the alternative layers of TE plastic discs. In spite of the enhanced neutron detection efficiency, there are notable limitations with this design in terms of the detector fabrication aspect. The counter incorporates 37 stainless steel wires of 0.0635 mm diameter as anodes. To hold all the components in place additional structural components such as the anode wire support system are required [24]. Moreover, the electric field at the ends of each cylindrical cavity tends to be non-uniform [22], which requires field shaping septa [23], field tubes [25] or guard rings to eliminate the edge effects and keep the multiplication process spatially uniform. These efforts were demonstrated to be effective but resulted in a complicated fabrication process. The assembly process becomes even more tedious whenever more reduction in the size of the counter is required [25].

To overcome the difficulties encountered with the traditional proportional counter technique, a modern type of gas-filled detector without any wire electrode is required. In the past two decades, a variety of gaseous micro-pattern detectors have been introduced. Among them, the most innovative are the MicroMegas, microstrip detectors and Gas Electron Multiplier (GEM) [26–28]. Both microstrip and GEM detectors are wireless structures in which an avalanche electric field is produced through using either a hole-type structure or alternating electrodes of fine strips.

To investigate the feasibility of modern proportional counters for microdosimetry, Farahmand et al. employed a standard GEM detector [29], while Dubeau and Waker tried a microstrip detector [27] and a GEM detector [30], respectively. To the same end, our group developed a prototype microdosimetric detector based on the THick Gas Electron Multiplier (THGEM) [31–33] concept. When compared with the standard GEMs, THGEMs are approximately 10 times larger in diameter and insulator thickness and offer similar multiplication performance with an inexpensive and more convenient fabrication process. However, to date, there have been no activities dedicated for monitoring weak neutron fields using these new detectors. Although Wang et al. developed a GEM-based TEPC for neutron protection dosimetry [34], it is hardly feasible for weak field dosimetry since the sensitive volume consists of a single element and is relatively small.

Founded on our prototype microdosimetric THGEM detector, the main goal of this study is to investigate the responses of the multi-element detector designs. A critical issue encountered in designing a multi-element detector is how to compromise the two conflicting requirements: enhancing detection efficiency versus simplifying detector structure for easy fabrication. To answer this question, Monte Carlo simulations were systematically carried out using the Geant4 code [35]. For various multi-element designs, the microdosimetric responses were simulated using mono-energetic neutron beams and efficiencies in terms of absorbed dose and dose equivalent were compared.

2. Conceptual design

To investigate the performance of different THGEM multi-element detectors with regard to dosimetric response and efficiency, five different designs were studied through Monte Carlo simulations. Table 1 summarizes the detailed specifications of the five detector designs. For each design, the outer dimension was fixed to a cylindrical volume with 5.5 cm diameter and the number of the gas cavities was gradually increased by subdividing the entire gas volume into sub-elements. This allows for a full investigation of the dependence of the detection efficiency on the multi-element density through simulations.

The simplest design, THGEM1 × 1, has a single gas cavity element with a diameter and length of 5.3 cm (132 cm^2) while the most complicated design, THGEM61 × 9, consists of 549 cavity

Table 1
Specification of the THGEM multi-element detector designs.

	THGEM1 × 1	THGEM7 × 3	THGEM19 × 5	THGEM37 × 7	THGEM61 × 9
SV[a] Diameter and height (cm)	5.30	1.70	0.98	0.67	0.50
Total number of sub-elements	1	21	95	259	549
Total SV surface area (cm^2)	132.30	285.85	429.73	549.95	646.45
Mass of gas (mg)	4.41	9.53	14.32	18.33	21.55
Gas density (mg/cm^3)	0.04	0.12	0.20	0.30	0.40
Gas pressure (Torr)	15.74	49.08	85.14	124.27	166.87

[a] SV stands for sensitive volume.