RPE Radiation Physics & Engineering
A Peer-Reviewed Journal
Published by K.N. Toosi University of Technology
http://rpe.kntu.ac.ir
Research Article

Radiation Physics and Engineering 2023; 4(3):15–22

Experimental and Monte Carlo investigation of neutron detection by THGEM detector in SQS mode

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HIGHLIGHTS

- Introducing a new method for neutron detection by Thgem detector in SQS mode.
- The condition of Thgem for neutron detection was done by Monte Carlo and practical methods.
- The 1 mm Plexiglas converter layer on Thgem detector can be converted neutrons to protons.
- The suitable distance between the converter layer and the THGEM detector is 3 cm.
- The SQS mode by protons in THGEM holes happens when voltage is 980 volt.

ABSTRACT

Neutron detection techniques are widely studied in many articles. Most of this research requires a lot of electronic equipment. In this study, using the Thick Gas electron multiplier (THGEM) detector, a new method for neutron detection is proposed to reduce electronic equipment. In the neutron detection system, the converter material is used for converting neutrons to protons that are directed to the THGEM detector. By filling the detector space with noble gas and applying special voltage, THGEM enters to Self-Quenched Streamer (SQS) mode for protons detection. All these steps are examined by simulation, then the detection system is made and is examined in the laboratory. Finally, the simulation results and laboratory results are compared. The results show that the 1 mm Plexiglas layer is suitable for converting neutrons to protons. The suitable distance between the converter layer and the THGEM detector is 3 cm. Also, the SQS mode happens in the most number of THGEM holes when the THGEM voltage is 980 volt. Investigating an approach to neutron detection by placing THGEM in SQS mode can be useful because, firstly, placing the THGEM detector in SQS mode simplifies electrical circuits and secondly, with this proposed detection system; it is possible to design detectors with different dimensions for neutrons.

KEYWORDS

Neutron
Detection
THGEM
SQS mode
MCNPX
Proton
Convert Layer

HISTORY

Received: 10 September 2022
Revised: 22 January 2023
Accepted: 25 January 2023
Published: Summer 2023

1 Introduction

So far, many studies have been conducted on neutron detection using nuclear detectors. Converting neutrons to charged ions such as alpha and protons is one way to detect neutrons. Various materials such as BF-3 or layers of Boron are investigated as Neutron to ion converter (Song et al., 2020; Pietropaolo et al., 2018; Santoni et al., 2018). In most studies, the number of produced ions has been estimated using complex electrical circuits.

In nuclear science, one of the new methods for detecting ions is the use of Gas Electron Multiplier (GEM) detectors (Song et al., 2020; Pietropaolo et al., 2018; Santoni et al., 2018; Zhou et al., 2021; Ohshita et al., 2010). The GEM is a polymer layer that its both sides are covered with a thin layer of copper. The thickness of the GEM plate is about 50 microns, which includes a large number of regular holes with a diameter of 80 microns. Gem detectors have been used to detect fast neutrons and to measure the high intensity neutrons (Croci et al., 2013; Zhou et al., 2020). Thick Gas electron multiplier (THGEM) is new generation of GEM detectors with a simpler structure that was introduced in 2007 (Pietropaolo et al., 2018). The holes and thickness of THGEM detector are also big-

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https://doi.org/10.22034/rpe.2023.361464.1103
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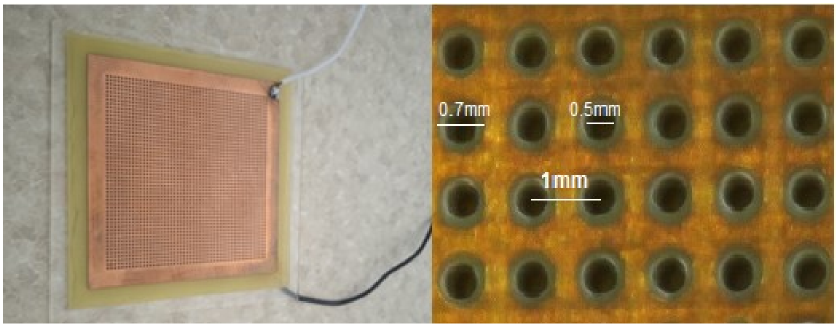

Figure 1: A picture of the THGEM on the left and a close-up of the THGEM holes on the right.

ger than GEM. Figure 1 shows an example of the THGEM detector (Khezripour et al., 2017).

Figure 1 shows the THGEM used in this research where Fr-4 plate with a thickness of 0.35 mm is covered by two copper layers with a thickness of 0.025 mm and the number of 2601 holes regularly in 51×51 rows, makes up the area of 5×5 cm^2 THGEM board. According to Fig. 1, the diameter of the hole created in the Fr-4 plate is 0.5 mm, and the distance between the centers of the two holes (Pitch) is 1 mm.

The basis of THGEM work in most studies is applying voltage to its copper plates and detecting charged ions in the holes, but how to detect ions in THGEM holes is different and depends on the used electrical circuits.

THGEM was used to detect various charged particles. It also showed good performance for thermal neutrons (Yang et al., 2015). Enhanced response to neutron dose with high detection efficiency is an important factor in the THGEM detector and various methods have been introduced for this purpose. In most of these techniques, electronic equipment is required to extract the simulation results (Anjomani et al., 2014). In this study, the aim is to design a neutron detection system using THGEM with simple electronic circuits. For this purpose, THGEM must be in Self-Quenched Streamer (SQS) mode.

SQS mode is a mode of gas detector that acts like other gas detectors by colliding particles or photons with gas atoms and creating ionization and electric spark. In gas detectors, if the photons have the ability to create new avalanches so that they complete the space of the detector, the gas detector is in Geiger-Müller mode. If the electrical field is controlled and the avalanche rate is kept low, the gas detector is in proportional mode (Knoll, 2010). The difference in SQS mode is that the detector space is filled with noble gas, which absorbs the extra photons and prevents the creation of additional sparks away from the main spark. Therefore, only the initial avalanche is observed as a small spark and its intensity depends on the initial charge density and voltage (Khezripour et al., 2018; Souri et al., 2017, 2018; Hashemi and Negarestani, 2019; Hashemi et al., 2019; Hashemi and Negarestani, 2018).

In the neutron detection system proposed in this study, the initial neutrons is collided with convertor material to neutron - proton convertor. Then protons have been detected by THGEM detector in SQS mode. The process of detecting the protons, like the first step of other gas detectors, is to ionize the gas elements of the detector. Accelerated movement of protons and collision with P-10 gas particles cause ionization of gas elements. Electrons produced from ionization reach the THGEM sensitive area due to the force of the electric field between the cathode and the anode. At this stage, by applying the appropriate voltage, the THGEM holes reach the SQS mode and create a spark (streamer).

Detection system geometry, converter layer material and voltage applied to THGEM are the main topics in this study. All these steps are examined by MCNP simulation code, then the detection system is made and examined in the laboratory. Finally, the simulation results and laboratory results are compared.

2 Materials and methods

2.1 Simulation method

The purpose of the simulation is to design the detection system with the best performance. For this purpose, items such as material and thickness of the converter layer, distance of the converter layer from THGEM, and the amount of voltage applied to THGEM must be calculated. For simulation of neutron detection system, a schematic of detector device is first considered as Fig. 2.

According to Fig. 2 the neutron beam collided with the elements of the Neutron-to-proton convertor layer. Protons produced from this layer enter the sensitive region of the THGEM holes with an accelerated movement and ionize the gas particles in this area. If the gas used in the detection space is a noble gas, by applying a special voltage to THGEM, the detector will go to SQS mode. In this case, a proton can produce a spark (Streamer). Streamers are recorded by the camera at regular time intervals and the detection process is completed.

In this study, the 5 Ci Am-Be neutron source of Kerman university was used. The noble gas used is P-10, which is a mixture of 90% Argon and 10% Methane (Khezripour et al., 2018; Souri et al., 2017, 2018; Hashemi and Negarestani, 2019; Hashemi et al., 2019; Hashemi and Negarestani, 2018). Also, plastic, CR-39 or Plexiglas can be used as a Neutron-to-proton converters layer (Yang et al., 2015). In the proton production process, protons are produced after the neutron elastically collides with the elements of the converter layer. In this step, the energy E

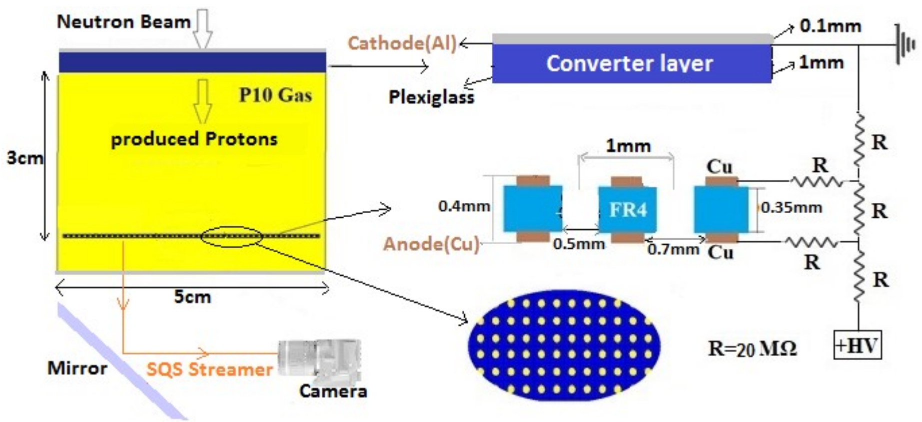

Figure 2: Schematic of the neutron detection system by THGEM in SQS mode.

transfer to the target with mass number A that calculate with Eq. (1) (Knoll, 2010):

$$E = [\frac{4A}{(1+A)^2}]\,[\cos^2\theta]\,E_n \tag{1}$$

where E_n is neutron energy and θ describes the scattering angle of neutrons after hit with target. According to Eq. (1), the proton receives the most energy, which is produced by the direct neutron colliding with the target ($\theta = 0$).

The protons that produced by the converter, collide with the P-10 gas elements and their energy decreases from E_1 to E_2 . At this stage, by using simulation, the THGEM distance from the converter layer can be calculated so that the maximum proton energy, deposited at the THGEM location.

For proton detection in SQS mode, the Raether condition must be established. Khezripour et al, by studying the Raether conditions in the THGEM detector, found the relationship between the applied voltage (V (in volt)) to the THGEM and the deposited energy (ΔE (in MeV)) at its location that is expressed by Eq. (2) (Khezripour et al., 2018):

$$V = \frac{0.2 - \log \Delta E}{0.999} \tag{2}$$

By placing the simulation result in Eq. (2), the appropriate voltage for establishing SQS mode is obtained. In this study, MCNPX code is used for deposited energy calculation. The MCNPX is a multi-purpose code based on Monte Carlo methods that can be traced up to 32 nuclear and atomic particles (Werner et al., 2017). The input file of the code includes three basic parts: the cell, the surface, and the data cards. The cells are closed spaces that are made from the intersection of surfaces defined in the surface card. The data card contains information that is used to solve problems and dosimetry calculations. The data card information also specifies the type of radiation sources and the composition of elements used in each cell.

The detection system proposed in Fig. 2 consists of 6 cells: Cell 1 is defined for the neutron-to-proton converter layer with an area of 5×5 cm^2 that thickness can be changed. Cell 2 is a rectangular containing P-10 gas, with an area of 5×5 cm^2 that height is variable, which includes the space between the converting layer and THGEM layer. Cell 3 is a THGEM layer with an area of 5×5 cm^2 and a thickness of 0.40 mm (Fig. 1). Due to the repetition of THGEM holes in its geometry, Fill and Lat commands in MCNPX code were used for THGEM holes building. To apply the Fill command, the concept of universe (u) was used. The universe is like a cell, with the difference that one of its dimensions can be infinite. A small part of THGEM including the hole that is repeated in THGEM was considered to be the universe. Cell 4 is a hollow Plexiglas rectangular layer with a thickness of 1 cm as body of detector. Cell 5 is a sphere of air around of the other cells that the Am-Be neutron source is inside it. Finally, the outer space of cell 5, which includes a vacuum is as cell 6.

The most important part of the data card is defining of the source, material with percentage of elements, how to extract dosimetry data in the active zone of the detector, the calculation of proton generation yield from the converter layers and the energy of produced protons. The mesh tally types 1 and 3 with Pedep and Total commands, were used to extract dosimetry data. The results of this research are presented in the results section.

2.2 *Measurement apparatus*

In the experimental method, the proposed detection system is designed and constructed according of the Fig. 3. The detection system consists of five parts: a) Neutron detector which is the main part of the detection system, b) P-10 gas source, c) Voltage source, d) Control board., and e) Camera.

The neutron detector is a chamber of glass with dimensions of $11 \times 15 \times 17$ cm^3, so that a cylindrical hole with a diameter of 4 cm is installed on the upper side to place the neutron source. The converter layer and the THGEM layer have equal dimensions (8×8 cm^2), which are placed in the inner grooves of the chamber. To make the chamber airtight, a gasket is placed on its lid and closed with eight screws. A mirror is installed under the lower face of the chamber to view the THGEM holes (Fig. 4). The camera is also placed in front of the mirror to take pictures (Fig. 3).

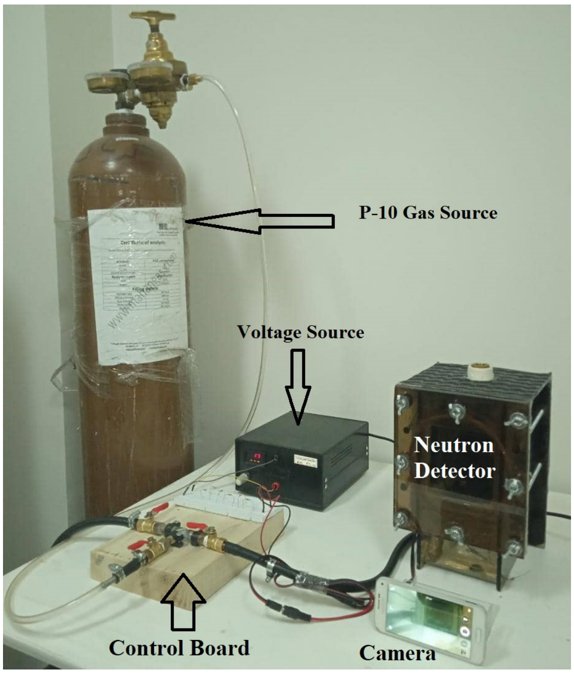

Figure 3: The detection system setup.

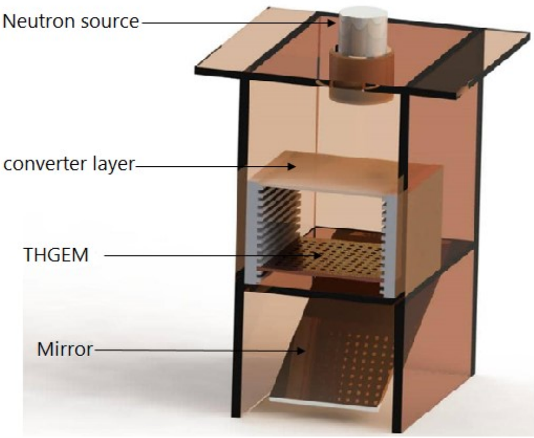

Figure 4: Schematic of the neutron detector and its contents.

The voltage source enters the control board circuit and is then directed to the chamber. Also, P-10 gas is directed into the chamber after controlling the pressure by the valves of the control board.

3 Results

3.1 Simulation results

In this section, the simulation results of MCNPX code are presented. To start the calculations, the spectrum of the neutron source is needed. In this study, Kerman Am-Be neutron source with 5 Ci activity was used (Fig. 5).

Plastic, CR-39 or Plexiglas can be used as a Neutron-to-proton converters layer. By placing these materials with a thickness of 1 mm as cell 1 and placing the Am-Be neutron source in cell 5, the energy spectrum of protons produced by applying the Am-Be neutron source can be obtained as Fig. 6.

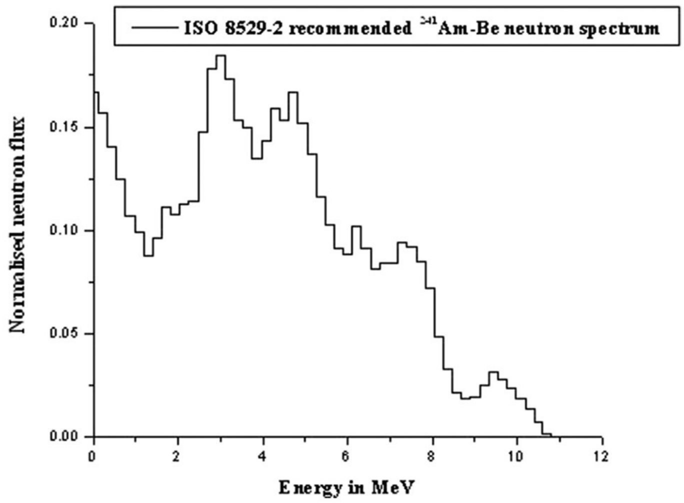

Figure 5: Energy spectrum of Am-Be neutron source (Pujala et al., 2011).

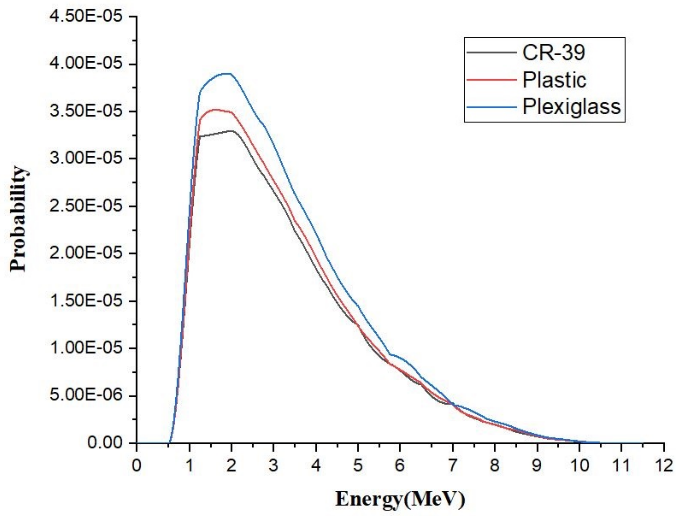

Figure 6: The energy spectrum of protons produced by applying the Am-Be neutron source to 1 mm thick converter layers in different materials.

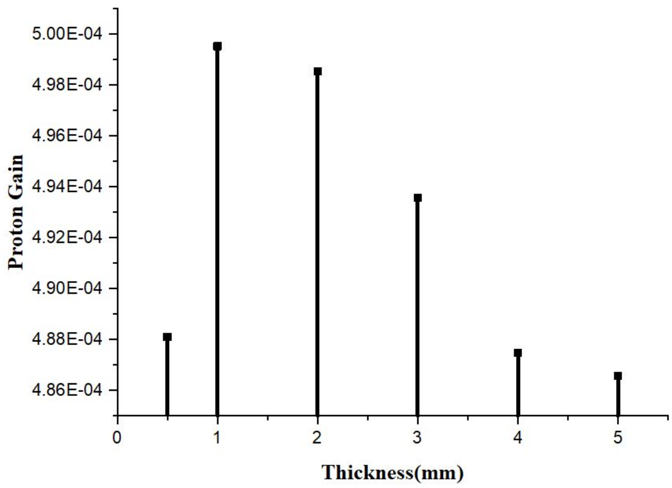

Figure 7: The proton gain versus the thicknessof Plexiglas.

According of the result the Plexiglas layer with a thickness of 1 mm can be a good choice as a converter layer (Fig. 7).

In Fig. 7 proton gain is the number of proton produced per neutron. The results of Fig. 7 were obtained by considering different thickness in cell 1. The earth connection can be applied by placing an aluminum thin sheet on the Plexiglas layer.

By performance the simulation calculations, Proton energy deposited in P-10 gas was obtained as a function of the distance to the converter layer. For this purpose, the height in cell 2 was considered variable and the mesh tally type 1 with Pedep command was used. The results for the extreme points are shown in Fig. 8.

According to Fig. 8, the most energy was deposited at a distance of 2.6 cm and 3.6 cm from the converter layer. Therefore, the best place for THGEM is 3 cm below the converter layer. The simulation results show deposited energy of protons in this distance (Fig. 9).

By placing the simulation result in THGEM holes in Eq. (2), the appropriate voltage for establishing SQS mode is obtained for different areas of THGEM coordinates (Fig. 10).

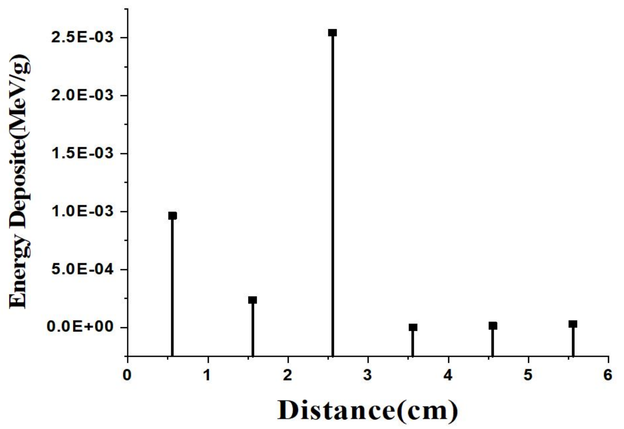

Figure 8: The extreme points of proton energy deposited in P-10 gas as a function of the distance to the converter layer.

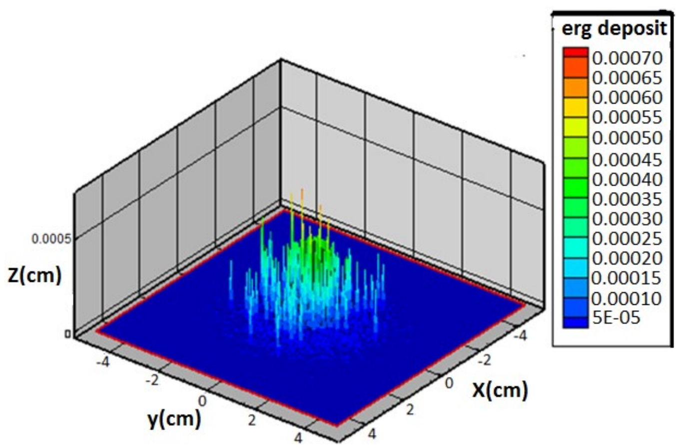

Figure 9: Deposited energy of proton at THGEM location.

In Fig. 10, the holes reached the SQS mode are shown as a function of voltage, in the area of a quarter of the THGEM plate. According the numbering data of Fig. 10, the range of appropriate voltage for reaching to SQS mode in THGEM holes is given in Table 1.

According to Fig. 10 color map or Table 1 data, the SQS mode occurs in the maximum number of THGEM holes when the color reach to yellow or applied voltage is in the range of 900 to 1000 volt. If the applied voltage was 980 volt, the SQS phenomenon occurs in near of the 34% THGEM holes.

3.2 Experimental results

First, the feasibility of the detection system designed in Fig. 3 should be checked. For this purpose, Khezripour's alpha detection system was used for testing (Souri et al., 2017). An alpha source with an activity of 150 kBq, almost equal to the Khezripour experiment, was selected and placed close to the THGEM plane. With closing the lid of the chamber, open the P-10 gas valve turned on the voltage source. By adjusting the voltage and gas pressure, the SQS mode process was observed in the THGEM holes. At this stage, SQS mode streamers are recorded by taking pictures at appropriate times (Fig. 8).

According to this test, only the holes that were directly under the alpha source were placed in SQS mode, indicating that the detection system was working properly. Also, the frequency of SQS mode in holes is 34 SQS.s^{-1}, which is close to the frequency of 35.3 SQS.s^{-1} for Khezripour's experiment. Therefore, by performing this test, the feasibility of this detection system for charged particles was confirmed.

At the next stage, the main goal of this study, which is the detection of neutrons, is investigated. According to Fig. 4, the neutron source was placed above the converter layer of THGEM detector. In this detection system, in addition to the voltage value and P-10 gas pressure, the distance between the converter layer and THGEM is also important, which was investigated with several test steps. The best results are obtained when most of the THGEM holes are in SQS mode. In this experiment, by choosing the Plexiglas as the converter layer in 2.7 cm distance, it was determined that the best result is obtained at a pressure of 1.08 bar of P-10 gas and a voltage of 1020 volt apply to THGEM. By taking pictures at different times, an image of all the bright holes was obtained that result was shown in Fig. 8.

Mathmatica software was used to process the image and check the percentage of bright holes. Mathematica version 13.1 was used for this purpose. According to these calculations, it was found that about 35% of the THGEM holes were placed in SQS mode.

Gamma rays are always emitted in Am-Be neutron sources which reinforce the importance of neutron-gamma discrimination (NGD) techniques [0.21.22]. The NGD has important applications in neutron detection systems.

Table 1: The range of appropriate voltage for reaching to SQS mode in Thgem holes.

Voltage (V) for reaching to SQS mode	Number of holes in SQS mode	Percent of holes in SQS mode
700 - 800	105	4%
800 - 900	840	32%
900 - 1000	903	34%
1000 - 1100	210	8%
1100 - 1200	31	1%

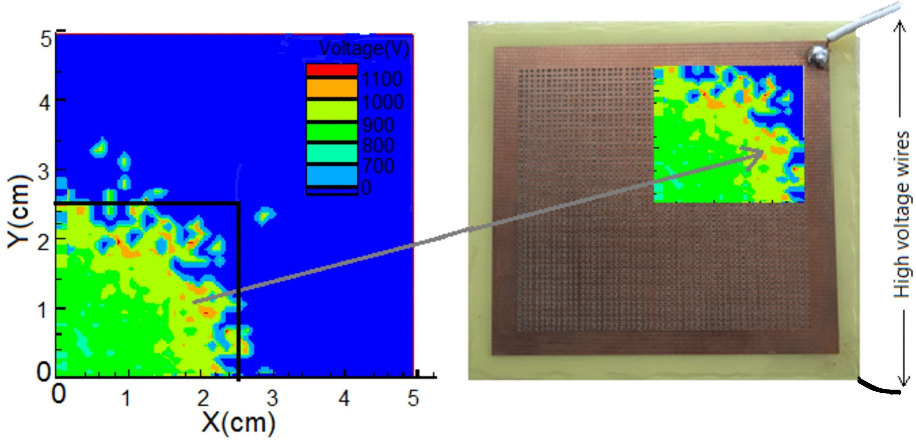

Figure 10: The relationship between the number of holes reached in the SQS mode and the applied voltage in the THGEM detector.

Figure 11: A picture of THGEM holes in SQS mode for testing the Alpha detection.

Figure 12: A picture of holes in SQS mode from the THGEM detector for neutron detection using plexiglass converter layer.

In this research, the neutron-gamma discrimination was done without converter layer (neutron-gamma field case). In this case, the SQS streamer do not observe in THGEM detector. But by placing of the neutron to proton converting layer (neutron-gamma and proton field case), the SQS streamers observed in THGEM detector. Therefore, the SQS streamers was produced by protons in THGEM detector. But more investigations are needed to study the possibility of gamma-neutron discrimination in real condition by THGEM neutron detectors.

4 Discussion

At this stage, the simulation and experimental results for neutron detection by THGEM detector in SQS mode by a Plexiglas layer as neutron to proton converter were compared that result is shown in Table 2.

According to Table 2, there is a negligible difference between the simulation results and the experimental results. Therefore, the proposed system for neutron detection (Fig. 4) could be effective.

Table 2: Comparison of simulation and experimental results for neutron detection by THGEM detector in SQS mode.

Quantities (to establish SQS mode in detection system)	Simulation results	Laboratory results	Difference
P-10 gas pressure	$\approx$ 1.06 bar	$\approx$ 1.08 bar	2%
THGEM voltage	980 volt	1020 volt	4%
Distance converter and THGEM	3 cm	2.7 cm	11%
Percentage of holes in SQS mode	34%	35%	1%

5 Conclusions

Neutron's neutrality makes it difficult to detect, and neutrons require more complex detection systems than charged particles. In this paper, it has been tried to investigate a new approach for neutron detection by using the neutron-ion converter layer and using the THGEM detector in SQS mode. One of the advantages of this method compared to other methods is the simplicity of the neutron detection structure so that it can be used for making small neutron detectors. Also, according to the THGEM structure, this detection approach can be used when neutron detection is needed in wider areas. In short, some of the reasons that justify the detection system proposed in this study are: a) The simple structure of the detection system, b) Reasonable price of THGEM and other components used in this detection system, c) The ability to use in different dimensions, and d) Ability to detect neutron particles, alpha particles and many heavy ions.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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To cite this article:

Najarzadeh, M. H., Rezaie, M. R., Negarestani, A., Akhound, A. (2023). Experimental and Monte Carlo investigation of neutron detection by THGEM detector in SQS mode. *Radiation Physics and Engineering*, 4(3), 15-22.

DOI: 10.22034/rpe.2023.361464.1103

To link to this article: https://doi.org/10.22034/rpe.2023.361464.1103