Performance evaluation of high-pressure MWPC with individual line readout under Cf-252 neutron irradiation

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Abstract. A multiwire proportional chamber (MWPC) neutron detector system was developed for the Materials and Life Science Experimental Facility at the Japan Proton Accelerator Research Complex. Its basic performance was evaluated by an irradiation experiment using a Cf-252 neutron source. A short response time and high spatial resolution can be obtained using an individual line readout method. The detector system exhibited a one-dimensional uniformity of response of 4.8% and 3.8% in the x- and y-directions, respectively. The uniformity of all pixels in the two-dimensional image was 7.9%. The average intrinsic spatial resolution was 1.55 mm full width at half maximum in the sensitive region calculated by taking into account the track lengths of secondary particles. The signal intensity of the system remained constant during the operation for 500 min under Cf-252 neutron irradiation.

1. Introduction

The high-intensity pulsed neutron facility at the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC) has 23 beam lines (BLs), and time-of-flight (TOF) measurements are performed using 25-Hz pulsed neutrons [1]. Some neutron scattering experiments performed at the J-PARC/MLF require advanced two-dimensional neutron detectors with short response time, good spatial resolution, and high detection efficiency. For this purpose, we are currently developing a two-dimensional position-sensitive neutron detection system consisting of a two-dimensional detector element and capable of individual signal line readout [2–4]. In a two-dimensional gas-based neutron detector, the thickness of the conversion gap should be made as small as possible to prevent the occurrence of the parallax effect of incident neutrons. Therefore, it is necessary to increase the gas pressure to achieve detection efficiency greater than 70%. Superior spatial resolution can be obtained by using a buffer gas with a high stopping power such as CF$_4$ used in this study, and by increasing the gas pressure.

Multiwire type two-dimensional neutron detectors with helium-3 ($^3$He) gas are widely used in neutron scattering experimental facilities. These detectors are known to have high detection efficiencies, low gamma-ray sensitivity, and excellent long-term stability [5–8]. These gas-based neutron detectors measure the ionized charges generated by secondary particles in nuclear reaction $^3$He(n,p)t. At the J-PARC/MLF, we develop an advanced multiwire type two-dimensional neutron detector system without sacrificing the excellent performances of the conventional detector. A short response-time and

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better spatial resolution can be achieved by our system using an individual line readout method. Optical devices have also been developed and incorporated in the system for long-distance signal transmission and for isolating the detector head in the sample irradiation area from the signal processing circuits in the data acquisition room. In this paper, we present our multiwire-type detector system developed for the J-PARC/MLF, and discuss its performance based on neutron irradiation experiments using a Cf-252 neutron source.

2. Experimental

The multiwire element used in our detector system comprises 128 anode wires, 128 cathode wires along y-axis, and 128 cathode strips along x-axis. The pitch between anode/cathode wires is 1.0 mm, and the distance from the anode wires to the cathode wires and strips are 1.0 and 1.5 mm, respectively. The multiwire element was placed inside a pressure vessel. To prevent outgassing from the detector element, the pressure vessel was vacuumed to below $10^{-5}$ Pa for at least 60 h prior to the gaseous mixture filling. Hereafter, we refer this detector head as a multiwire proportional chamber (MWPC).

The system consists of a 256-channel detector element (x: 128 lines, y: 128 lines), a pressure vessel, amplifier-shaper-discriminator (ASD) boards, optical signal transmission devices, position encoders with field-programmable gate arrays (FPGAs), and a data acquisition device. A schematic view of the system and a photograph of the detector head are shown in Figure 1. The multiwire element was installed in the pressure vessel with a conversion gap of 20 mm. The pressure vessel could withstand pressures of up to 0.8 MPa and with a helium leakage of less than $10^{-8}$ Pa$\cdot$m$^3$/s. Experiments were performed using a gaseous mixture of $^3$He and CF$_4$ which functioned as a neutron converter and a stopping gas, respectively. The performance of the detector was strongly dependent on the gas conditions in the pressure vessel. In this experiment, the pressure vessel was filled with He/(20%)CF$_4$ at 0.6 MPa. Under this gas condition, the thermal neutron detection efficiency was 74% determined from the nuclear reaction cross section of $^3$He gas and the size of the conversion gap. Taking into account the gas pressure, the track lengths of secondary particles, protons ($L_p$) and tritons ($L_t$), calculated by the TRIM code [9] were 2.68 and 0.94 mm, respectively. Therefore, it can be estimated that the MWPC has a few output signal lines since the pitch of both axes is smaller than the track length.

Figure 1. A photograph of the detector head (left) and a schematic view of the detector system (right). The detector head which includes the detector element and amplifier-shaper-discriminator boards are isolated from the position encoder and data acquisition device, and connected together using optical fibers.

In the MWPC, a charge signal is generated as a result of the gaseous amplification around each anode wire induced by the strong electric field between the electrodes. Cathode wires and strips are arranged...
orthogonally. The signal from each cathode is individually amplified, shaped, and discriminated by amplifier-shaper-discriminator application-specific integrated circuits (ASD-ASICs), which nominal settings are an amplification factor of 3.1 V/pC and a decay time of 90 ns. Digital signals from the ASD-ASIC are transmitted to the position encoders through optical fibers as optical signals converted by a specially fabricated electrical/optical (E/O)-O/E converter. The optical fiber is insensitive to electromagnetic fields and electrical noises. Further, optical fibers can significantly extend signal transmission distance due to the low transmission loss compared to that of conventional electrical cables.

Neutron irradiation on the MWPC was performed by embedding a Cf-252 neutron with an intensity of 100 MBq in a graphite cube with sides measuring 80 cm. The MWPC was placed at a distance of 30 cm from the surface of the graphite cube. Upon measurement with an absolutely calibrated BF$_3$ counter, the neutron fluxes at the surface of the cube and detector position were found to be $1.2 \times 10^7$ and $5.6 \times 10^6$ n/m$^2$s, respectively.

3. Results and discussion

Figure 2 shows the flat-field image measured by the detector to confirm the spatial homogeneity of the detector element. Figure 3 shows the one-dimensional projections to the x and y axes, and the histogram of the pixel contents of the flat-field image. The counts of one-dimensional projections exhibit excellent uniformity, as shown in Figure 3(a). The relative standard deviations were 3.4% and 4.3% for x- and y-projections, respectively. The histogram of all pixel contents was evaluated by a
Gaussian fit and showed good homogeneity. The average pixel count was 972 with a standard deviation of $\sigma = 76.9$, which corresponded to an average gain spread of 7.9%.

In our MWPC, incident position of a neutron, $N(x, y)$, is defined as

$$N(x, y) = \left(\frac{x_h + x_l}{2}, \frac{y_h + y_l}{2}\right)$$

(1)

where $x$ and $y$ are the channel numbers and the subscript $l$ and $h$ represent the start and end channels of signals. The errors are arisen from the differences of the track length between protons ($L_p$) and tritons ($L_t$) because the center of the track is defined as the position of the incident neutron in our position detection. Figure 4 shows a schematic view of our position detection method and the intrinsic error arisen from the difference of track lengths.

![Figure 4](image1.png)

**Figure 4.** Schematic view showing the method and its intrinsic error for position detection of incident neutron.

Figure 5. Errors in position detection of our detector.

In our detector system, all neutron event data, including $x_l, x_h, y_l,$ and $y_h$, are recorded in the data acquisition electronics. By using these event data, the total track length $L(x, y)$, defined as the sum of the lengths of proton and triton, for each neutron event can be calculated as follows:

$$L(x, y) = \sqrt{\left(x_h - x_l\right)^2 + \left(y_h - y_l\right)^2}$$

(2)

The intrinsic error $P_{err}$ of the position detection can be obtained from

$$P_{err}(x, y) = \frac{L_p}{L_p + L_t} L(x, y) - \frac{1}{2} L(x, y)$$

(3)

The errors are calculated from all recorded event data, and plotted in one-directions in Figure 5. In the figure, the horizontal and vertical axes represent the error and the number of events, respectively. The intrinsic spatial error of the detector is evaluated by fitting the data with a Gaussian function, and the full width at half maximum (FWHM) of the spatial error is 1.55 mm.

The incident neutrons are usually scattered by the MWPC itself because it has an aluminum (Al) window and the fill gas molecules act as scatterers. To estimate the effects of these scatterers, we calculated the amount of neutrons scattered by the MWPC. The calculation was performed by a Monte
Carlo simulation using PHITS (multi-purpose particle and heavy ion transport code system) [10]. This Monte Carlo code can simulate the transport and interaction process of neutrons, photons, electrons, and charged particles in an arbitrary three-dimension geometry system. In the simulation, a pencil beam of thermal neutron was irradiated perpendicularly to the detector, and the actual geometry of the MWPC such as the 7 mm window, the 20 mm conversion gap filled with gaseous mixture, and the 1 mm pitch detector element were taken as the parameters. The simulated result of neutrons scattered by the Al window and the fill gas is shown in Figure 6. The figure is the one-dimensional projection of the distribution of scattered neutrons. A simulation without the Al window (by setting the window thickness as 0 mm) is also plotted for comparison. It shows that the neutrons are scattered by the Al window and the fill gas. They were detected by the adjacent pixels relative to the incident position and the counting ratio of the pixel to the incident position was $10^{-4}$. The ratio was also one order of magnitude smaller than that when the neutrons were scattered by the fill gas only. It is concluded that the effects of scattered neutrons to the intrinsic spatial error are negligible. We continuously operated our MWPC for 500 min and the elapsed time dependence of measured counts is shown in Figure 7. It is observed that the signals remain constant during the operation.

**Figure 6.** Distribution of scattered neutrons calculated by PHITS.

**Figure 7.** Normalized counts as a function of elapsed time.

**Figure 8.** Measured image of gamma ray irradiation. The white dots indicate a detected signal.
The gamma-ray sensitivity of the detector was measured using a $^{60}\text{Co}$ gamma-ray source. The intensity of gamma-ray source was $8.9 \times 10^5$ Bq, and was placed on the surface of the detector window. A two-dimensional image generated by the $^{60}\text{Co}$ is shown in Figure 8 with an irradiation time of 2400 s. It is confirmed that the developed detector has low gamma-ray sensitivity of $8.2 \times 10^{-9}$.

### 4. Conclusions

A multiwire proportional chamber (MWPC) neutron detection system was developed. The detector had a neutron sensitive area of $128 \times 128$ mm$^2$ with a wire pitch of 1 mm. The system consisted of a 256 channel detector element (x: 128 lines, y: 128 lines) equipped with a pressure vessel, amplifier-shaper-discriminator boards, optical signal transmission devices, position encoders, and a data acquisition device. The estimated detection efficiency for thermal neutron was 74% determined from the gas condition and conversion gap. It exhibited an excellent uniformity of 7.9% with all pixels in the two-dimensional image measured using a Cf-252 neutron source. The average intrinsic spatial resolution was 1.55 mm FWHM in the sensitive region calculated by taking into account the track lengths of secondary particles with He/(20%)CF$_4$ at a pressure of 0.6 MPa. A gamma-ray sensitivity of $8.2 \times 10^{-9}$ was obtained using a $^{60}\text{Co}$ gamma-ray source. After pulsed neutron irradiation experiments, this multiwire-type two-dimensional neutron detector system, which employs the individual line readout method, will be installed at J-PARC/MLF.

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