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Development of two-dimensional position sensitive detector systems using multi-pixel photon counters for neutron experiments

Setsuo Satoh*, Suguru Muto

High Energy Accelerator Research Organization (KEK), Oho 1-1, Tsukuba-shi, Ibaraki 305-0803, Japan

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ABSTRACT

Neutron scattering experiments are indispensable to the structural analysis of many types of condensed matter and in the development of advanced materials. A high resolution detector system and a high counting rate detector system, both utilizing a neutron scintillator and multi-pixel photon counters (MPPCs), have been developed at the High-Energy Accelerator Research Organization (KEK). These systems will be used in the BL16 and BL06 neutron scattering instruments at the Material and Life Science Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC). The high resolution detector is an MPPC position-sensitive detector (MPS) with a $105 \times 128\ \text{mm}^2$ detection area and has positional resolution of 1 mm. The high counting rate detector is an MPPC Pixel detector (MPIX) with a $320 \times 40\ \text{mm}^2$ detection area. The maximum counting rate is 4 million counts per second (Mcps).

1. Introduction

The KENS-DAQ group at the Neutron Science Laboratory (KENS) in the High-Energy Accelerator Research Organization (KEK) was established in order to develop data acquisition (DAQ) electronics and software for experimental instruments used at the Materials and Life Science Experimental Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC). Generally, neutron experiments will use the most reliable type of neutron detector—a ^{3}He gas detector. However, as these are gas detectors, they have low positional resolutions and counting rates. For high intensity pulsed neutron beam experiments, two types of neutron detectors using multi-pixel photon counters (MPPCs) have thus been developed as two-dimensional (2-D) detectors.

- The MPPC position-sensitive detector (MPSD) consists of a stack of 1-D detectors. This system has a total detection area of $105 \times 128\ \text{mm}^2$ and obtains a resolution of approximately 1 mm by using a ^{6}Li/ZnS scintillator. This detector can be used with the NEUNET readout system [1], which is widely used at MLF/J-PARC.
- The MPPC pixel detector (MPIX) is a pixel read-out, high counting detector with a detection area of $320 \times 40\ \text{mm}^2$. The maximum counting rate of this prototype is 4 million counts per second (Mcps).

2. MPSD system

Using a large linear array of MPPCs, the MPSD can function as a 1-D detector of neutron positions [1,2] as shown in Fig. 1. In this configuration, a neutron captured in a scintillator generates thousands of photons that radiate through an optical diffusion glass onto the array of MPPCs. Those MPPCs registering photons feed their output charges into a resistance array in order to determine the captured neutrons position (along the axis of the detector) using the charge division method, described later. The magnitude of charges at each end of the resistance array will be inversely proportional to their respective distances from the neutron capture position; that is, if QA and QB are the respective charges measured at each end, then the offset distance of neutron capture, x, from end QA can be found using $x/L = QB/(QA+QB)$, where L is the total length of the array.

Since MPPCs are vulnerable to neutron radiation damage, a silicic acid glass containing boron is used as the diffusion glass. As the ^{6}Li/ZnS neutron scintillator typically used for capturing neutrons has a roughly 30% efficiency, the remaining 70% of the neutron must be blocked by the glass. Given that 2 mm of glass containing approximately 13% boron can attenuate cold neutrons by approximately 90%, the use of an 8 mm thick diffusion glass in this system is likely to be sufficient for limiting neutron damage.

* Corresponding author. Tel.: +81 2986452004517.
E-mail address: setsuo.satoh@kek.jp (S. Satoh).

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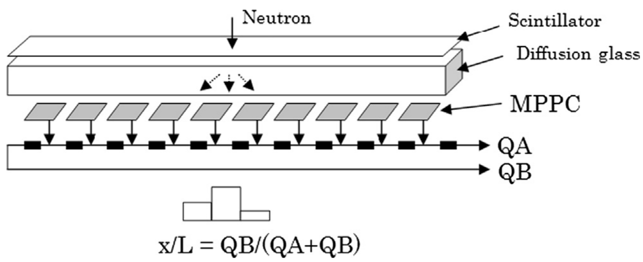

Fig. 1. Block diagram of the MPSD.

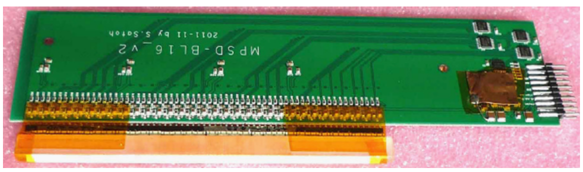

Fig. 2. MPSD using 3 mm MPPC for SOFIA.

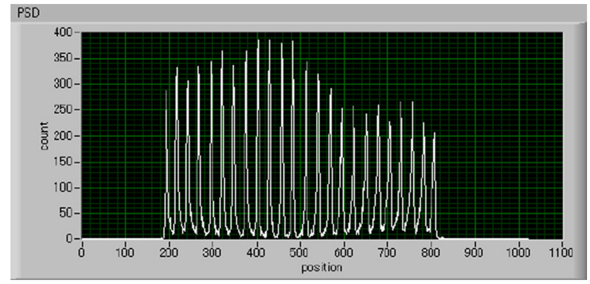

Fig. 3. MPSD data of average FWHM = 0.99 mm.

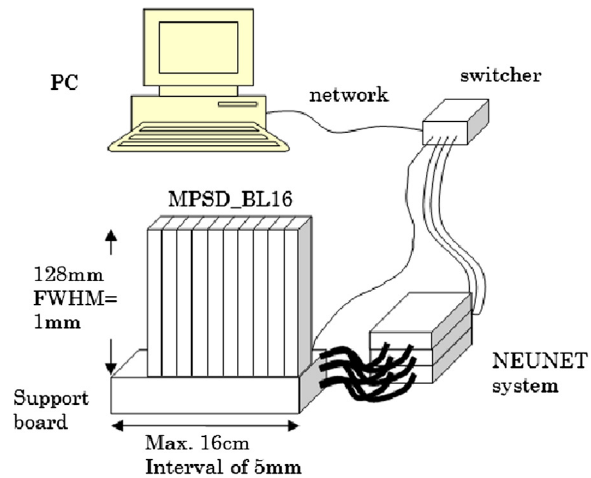

Fig. 4. Block diagram of the MPSD system.

The use of MPPCs can be problematic in that they tend to experience large values of dark count noise—an effect that can be additive, as the resistance array of the MPSD board integrates the noise of all the connected MPPCs. As a countermeasure, each MPPC is fitted with a noise canceling circuit having a discrimination level higher than the dark noise level. Although this measure generates some distortion, it lowers system noise considerably.

Another difficulty in using MPPCs is that their working voltages differ (exceeding 1 V in some cases) leading to a variance in amplitudes. For instance, a differential in working voltage of 0.2 V can double the amplitude differential. To compensate for this, each MPPC is fitted with an adjusting-circuit employing a digital-to-analog converter (DAC) that adjusts the working voltage and stores the voltage values in an electrically erasable programmable read-only memory (EEPROM) for automatic recall at power-on. The output of the DAC is adjusted by an adjusting-circuit consisting of a light-emitting diode (LED) mounted on a pulse motor-driven slider. As the LED, which corresponds with the level of neutron generation, is moved by the slider into position in the front of each MPPC, it can adjust that amplitude to the same value. Each DAC is able to adjust the voltage from 0 to 5 V.

Finally, an MPPC's supply voltage needs to adjust to temperature changes at relatively large temperature coefficient of 56 mV/°C in order to keep the amplitude constant. To accomplish this, this system is equipped with another voltage-adjusting circuit, which also uses a DAC. Although the MPPCs can function properly with periodical adjustments of this circuit, it is nevertheless vital to keep the atmospheric temperature of an experiment with MPPCs constant.

Fig. 2 shows an MPSD board that was designed for the SOFIA (BL16) neutron reflection meter at MLF/J-PARC in order to increase SOFIA's-vertical resolution.

The MPPCs, which are manufactured by Hamamatsu Photonics Co., each have a detection area of 3×3 mm^2, and because it has a recovery time of less than 20 ns, it can detect neutrons at a high count rate of around 500 ns. The MPSD board, using 32 MPPCs at intervals of 4 mm has obtained 0.99 mm average resolution in a measurement taken at the Kyoto University Reactor (KUR), shown in Fig. 3 (here, the horizontal axis gives the neutron irradiation position and the vertical axis maps the neutron count).

The SOFIA system assembly incorporates 21 MPSD boards stacked at intervals of 5 mm with a total detection area of 105 mm (horizontal) $\times$ 128 mm (vertical). The system requires a high positional resolution in the vertical direction and a high overall count rate.

A block diagram of the assembly is shown in Fig. 4. The overall system consists of the 21 stacked detectors, a support board, and the 3 NEUNET modules. The support board, which supplies the adjusted voltages, is controlled by a PC through a network. Fig. 5 shows areal image of the system set-up, along with a 2-D image result. The boards are stacked along the horizontal axis in this 2-D image, while the varying shading along the vertical axis, based on the neutron count, shows the positional resolution of the MPSD boards; here, the word "KENS" is formed by the pattern of cadmium masks. At SOFIA, this system obtained a maximum counting rate of 250 kilo counts per second (kcps) from a 50 mm wide horizontal neutron beam.

3. Remodeling the MPSD system

In order to obtain clearer images, the sections of diffusion glass covering each 1-D MPSD are replaced with a single glass plate, resulting in the 2-D MPSD system shown in the block diagram in Fig. 6. Using crosstalk between the 1-D MPSDs, this system is able to calculate the position of a captured neutron.

The image generated with this 2-D MPSD can be rendered at a horizontal resolution of either 2.5 or 1.25 mm, representing twice or four times, respectively, the 5 mm resolution of the original SOFIA assembly. Under any of the above conditions, the vertical resolution is about 1 mm. Fig. 7 shows 2-D images at these two improved resolutions. As the pixel pattern at 2.5 mm resolution is symmetrical with respect to the MPPC structure, it does not generate distortion. On the other hand, even though the resolution at 1.25 mm is higher than the image pixels that will be split at an edge or at the center of an MPPC, creating vertical stripes along the array of 1-D MPSDs and necessitating additional compensating.