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Development of a two-dimensional gaseous detector for energy-selective neutron radiography

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Abstract

Energy-selective neutron radiography is a new method for studying the fine structure of heavy materials by using pulsed neutron sources. To perform such radiography, precise measurements of temporal information and two-dimensional position are essential. Therefore, we developed a gaseous neutron detector using the gas electron multiplier (GEM). In addition, to detect neutrons, a single surface of an aluminium cathode plate and both surfaces of two GEM foils were coated with boron-10. Two normal GEM foils were stacked in a chamber for gas amplification. An anode plate with two-dimensional strips (0.8-mm pitch) was mounted in order to precisely reconstruct neutron incident positions. To allow high-speed data transfer, a compact readout system with new application-specific integrated circuit (ASIC) chips and a field programmable gate array (FPGA) was developed. Finally, several beam tests were conducted with pulsed neutron sources and two interesting applications were demonstrated.

Keywords: Gas electron multiplier (GEM); high-density electronics; high-speed data transfer; neutron beam monitor; energy-selective neutron radiography.

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1. Introduction

The gas electron multiplier (GEM), which is a type of micro-pattern gas detector (MPGD), was introduced by F. Sauli in 1997 [1]. Typical GEMs consist of a 50-μm-thick polyimide printed-circuit foil that has many small holes etched on it; in addition, the foil is coated with 5-μm thick copper layers on both sides. The diameter of each hole is 70 μm and many holes are distributed at a 140-μm pitch. A high voltage of 250-450 V is applied across the GEM foil to generate a large electric field in the holes. Gas multiplication occurs in the holes in a manner similar to that in the sense wire of ordinary wire chambers. Many small holes are distributed uniformly over the foil and each acts as a gas multiplication device. Therefore, GEMs provide good counting capabilities and uniform two-dimensional responses. These features enable imaging capability under high counting rates, which is useful for various applications.

A new gas detector for neutrons that employs GEM is being developed as a detector for energy-selective radiography using thermal (cold) neutrons from pulsed sources, such as those available at the Japan Proton Accelerator Research Complex (J-PARC). The two-dimensional position must be measured for radiography (e.g., X-ray radiography). In addition, temporal information, which is essential in determining the neutron wavelength (i.e., energy), is determined using the time-of-flight (ToF) method. To detect neutrons, a single GEM foil is coated on both sides with ^{10}B. Neutrons react within the boron layer and charged particles (an alpha particle and a lithium nucleus) are emitted, which can produce ionization electrons in the gas volume between the GEM foils.

The features of this detector are described below and compared with a ^{3}He counter and a scintillation counter, which are commonly used at neutron facilities worldwide. ^{3}He gas is not necessary for neutron detection, because neutrons react within the boron layers coated over the GEM foil. Using this technique, it is easy to capture the two-dimensional neutron images. The wire position (X) and the charge division method (Y) are used to obtain the two-dimensional position from the ^{3}He counter. In such cases, the X and Y coordinates are measured using different methods and resolutions that do not give a uniform two-dimensional image. Good position accuracy (1 mm) and high time resolution (10 ns) can be obtained using this detector. For example, a fine strip pitch (1 mm) can be obtained using the GEM chamber, which is much better than that obtained with the typical diameter of a ^{3}He counter (~1 cm). In addition, ^{3}He counters have a typical time resolution of only 1 μs. Furthermore, this detector is insensitive to gamma rays, which is in contrast to scintillation counters that are normally used for neutron detection and contain heavy materials, making them relatively sensitive to gamma rays. Finally, while the GEM detector provides a high counting rate, ^{3}He counters do not work in the high-counting-rate regime of J-PARC.

This type of neutron detector was originally developed in Germany [2], but has not yet been established for actual physics experiments. Therefore, we constructed a prototype chamber and conducted several beam tests. In this paper, we describe the structure of the chamber and present the results of the beam tests.

2. Experimental

2.1. Prototype chamber

The prototype chamber (Fig. 1) was constructed to confirm the principles governing neutron detection. The chamber comprised one aluminum cathode plate, two boron-coated GEM foils, two normal GEM foils, and one readout board. The 10 cm × 10 cm GEM foils were produced by a Japanese company [3].

For high efficiency, both surfaces of the two GEM foils were coated with enriched boron ^{10}B (purity > 99%). In addition, boron was coated on one side of the aluminum cathode plate. The typical thickness of each boron layer was 1.2 µm.

The high voltage applied to the boron GEM foils was adjusted to give unit gas gain in order to attain the same average pulse height for each conversion layer. This voltage adjustment was performed as a pre-experiment with a special setting using X-rays from a ^{55}Fe radioactive source. The two normal GEM foils provided a gas gain of ~400 on detecting a signal. A negative high voltage was supplied to the cathode and appropriate voltages were distributed to each GEM foil using a resistive chain. The readout board had two-dimensional strips with a 0.8-mm pitch that measured the X and Y coordinates simultaneously. The entire 100-cm^2 sensitive region was covered by 120 (X and Y each) strips. The chamber was filled with Ar-CO_2 (70/30) during the tests.

A new application-specific integrated circuit (ASIC) chip was developed for the front-end electronics of MPGDs. It contained a preamplifier, shaper, and discriminator. A single chip contained 32 channels and 8 chips were mounted on a single printed circuit board. One field programmable gate array (FPGA) was also mounted to serve as a readout system, and it controlled the digital signals and correlated the active X and Y strips. In addition, it directly sent data to a PC through a single Ethernet cable using the TCP/IP protocol [4], as shown in Fig. 2. This system achieved an 11.8-MHz event transfer rate, which is consistent with an Ethernet data transfer speed (1 Gbps).

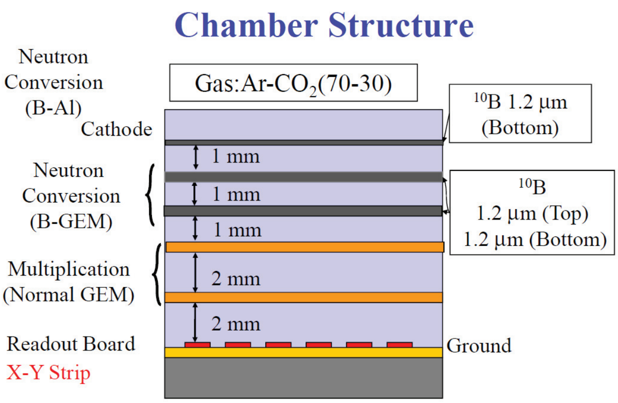

Fig. 1. Schematic of the prototype chamber.

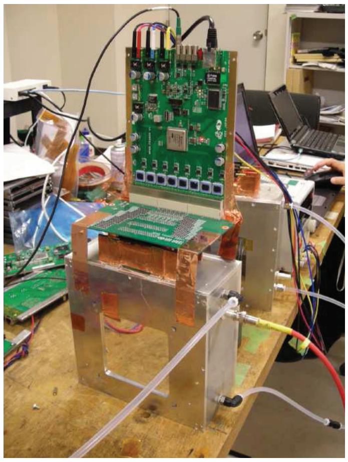

Fig. 2. Photo of the prototype chamber with a readout board.

2.2. Test with pulsed neutron sources

One good application of this detector is a neutron beam monitor. To measure an absolute scattering cross-section, the two-dimensional beam position and neutron wavelength should be monitored. In this case, high detection efficiency is not required; therefore, only a single boron-coated cathode was installed in the chamber with no boron-coated GEM foils. The detector was set up at beam line (BL) 21 at the Materials and Life Science Facility (MLF) of J-PARC. A two-dimensional beam profile was observed and the collimator shape could be seen clearly, as shown in Fig. 3(a). The energy spectrum of the neutron beam was also calculated based on a measurement of the time-of-flight of neutrons, as shown in Fig. 3(b). More detailed information is available elsewhere [5].

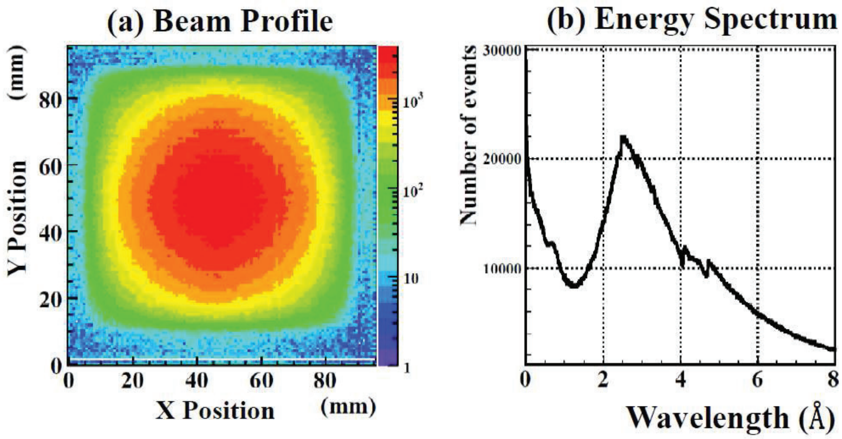

Fig. 3. (a) Neutron beam profile obtained by the developed detector using GEMs and (b) neutron energy spectrum measured in the time-of-flight method at BL21 of the J-PARC MLF.

The detector can be applied to energy-selective neutron radiography. Two applications of this were demonstrated. The first one was normal radiography (e.g., X-ray radiography). Absorption images were obtained for neutrons within a selective energy range. The neutron absorption cross-section became large around energies characteristic of atoms. If neutrons in the narrow energy range of the target atom were selected, a clear image with strong contrast could be obtained. To illustrate this, one Japanese oval gold coin and four euro coins were set in a neutron beam line at the MLF, as shown in Fig. 4(a). Figure 4(b) shows the two-dimensional radiography image of these coins for neutrons with the characteristic energy of gold. The image shows the Japanese gold coin, and that the coin contains gold uniformly. In contrast, the euro coins do not contain gold. The selected neutron energies, and therefore velocities, are relatively high; the corresponding wavelengths are less than 0.5 Å. Therefore, precise timing resolution is required for the detector. The developed neutron detector using GEMs meets such a requirement with a resolution of ~10 ns.

The second demonstrated application of this detector was visualizing the microstructure of materials. In this case, neutrons with lower energies (in the so-called Bragg edge region) were selected. The neutron scattering cross-section changed steeply near a wavelength of 4.5 Å, as shown in Fig. 3(b), and the microstructure affected its energy-dependent shape. Therefore, crystallite size, which is a microstructural parameter, could be calculated two-dimensionally from the measurement of the neutron energy for each position on a bin-by-bin basis. Finally, a two-dimensional image (Fig. 5(b)) was obtained. In this case, five iron plates were set in front of the detector. Each plate had different bending conditions, as shown in Fig. 5(a). The bent regions clearly showed smaller crystallite sizes. In particular, the re-flattened iron plate had a smaller crystallite size although its shape was the same as the reference plate prior to bending. The method and different samples are described in more detail in Ref. [6].

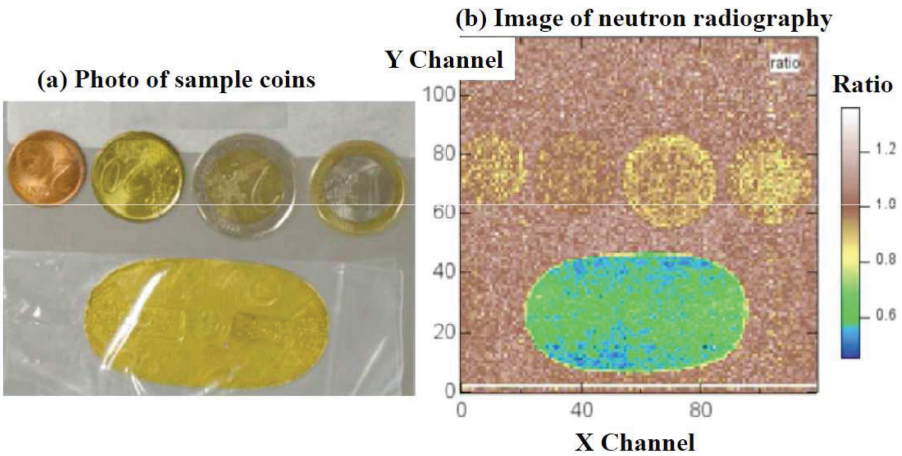

Fig. 4. (a) Photograph of four euro coins and one Japanese oval coin and (b) experimental two-dimensional radiography image for neutrons with the characteristic energy of gold. The image shows the Japanese gold coin contains gold uniformly.

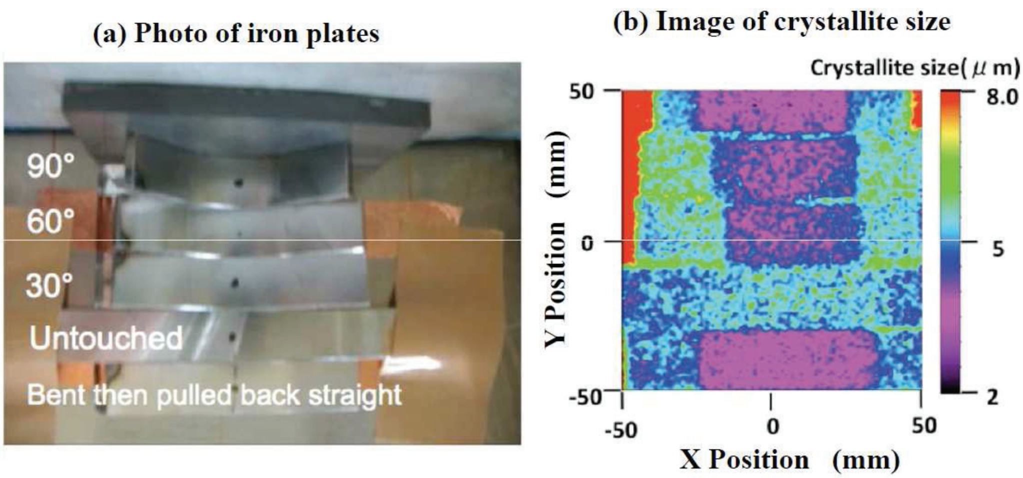

Fig. 5. (a) Photograph of five iron plates in various bending conditions and (b) Image of calculated crystallite size on bin-by-bin basis from fitting the energy-selective absorption cross-section near the Bragg edge. The image shows the crystallite size becomes smaller in the bent regions.

3. Summary

The neutron detector developed by us can precisely measure temporal information and the two-dimensional position. Therefore, it facilitates a new method of energy-selective neutron radiography when used with pulsed neutron sources.

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