ABSTRACT
The Energy-Resolved Neutron Imaging System RADEN, located at the J-PARC Materials and Life Science Experimental Facility (MLF), began user operation in April 2015 as the world’s first dedicated high-intensity, short-pulsed neutron imaging beam line. To carry out energy-resolved neutron imaging at RADEN, we use cutting-edge detector systems, recently developed in Japan, employing micro-pattern detectors or fast Li-glass scintillators coupled with high-speed, all-digital data acquisition systems. These counting-type detectors provide sub-μs time resolution, high neutron count rates, and event-by-event gamma rejection. The detectors available at RADEN offer a range of spatial resolutions from 0.25 to 3 mm and counting rates up to 8 Mcps. In the present paper, we show the performance of these detector systems as measured at RADEN and discuss ongoing development efforts aimed at improving spatial resolution and count rate performance.

Keywords: Pulsed neutron imaging, micro-pattern detectors, pixel scintillator detectors

1. Introduction
The Energy-Resolved Neutron Imaging System RADEN [1], located at beam line BL22 of the J-PARC Materials and Life Science Experimental Facility (MLF), began user operation in April 2015 as the world’s first dedicated high-intensity, pulsed neutron imaging beam line. RADEN was designed with adjustable beam optics and a large experimental area with two detector stations to provide an L/D up to 7500 and a beam size up to 30 × 30 cm². (L/D is the ratio of the distance of the detector from a beam collimator to the size of the collimator opening, and gives an indication of the geometric quality of the beam.) RADEN features a high design peak neutron flux of 9.8 × 10⁷ n/s/cm²/MW and a wide bandwidth of nearly 9 Å with a resolution as low as 0.20% for cold neutrons. RADEN also provides computer-controlled, motorized sample stages, optional diffraction and gamma detectors, and a neutron polarizing apparatus.

In addition to conventional radiography and tomography, RADEN takes advantage of the wide available energy range and accurate measurement of neutron energy by time-of-flight afforded by the short-pulsed beam of the MLF to perform energy-resolved neutron imaging. These techniques utilize the energy-dependent neutron transmission measured with a two-dimensional imaging detector to extract quantitative information about the macroscopic distribution of microscopic properties within bulk objects in situ, including crystallographic structure and internal strain (Bragg-edge transmission [2]), nuclide-specific density and temperature distributions (neutron resonance absorption [3]), and internal/external magnetic fields (pulsed, polarized neutron imaging [4]). This added layer of quantitative information makes energy-resolved neutron imaging techniques very attractive for new materials science and industrial applications.
the high-rate, high-background environment at a pulsed spallation source such as the J-PARC MLF requires advanced detectors with sub-μs time and sub-mm spatial resolutions, excellent background rejection, and high rate capability. At RADEN, we use cutting-edge detector systems developed in Japan, employing micro-pattern detectors [5] or fast Li-glass scintillators coupled with high-speed FPGA (Field Programmable Gate Array)-based data acquisition systems. These counting-type detectors measure each individual neutron event to achieve the necessary time resolution and allow for event-by-event background rejection. Additionally, micro-pattern detectors, by virtue of their compact, sub-mm structure, are able to operate at 10s of Mcps neutron rates and provide spatial resolutions that can approach conventional CCD camera systems, while the fast decay time of about 100 ns for the Li-glass scintillator can potentially allow very high count rates on the order of 100 Mcps. Below, the performance of the counting-type detectors available at RADEN is presented, followed by a description of ongoing development.

2. Counting-type detectors at RADEN

The counting-type detectors currently available at RADEN include two micro-pattern detectors, the μNID (μPIC-based Neutron Imaging Detector) [6] and the nGEM (boron-coated Gas Electron Multiplier) [7], and a Li-glass pixelated scintillator detector, the LiTA12 (6Li Time Analyzer, model 2012) [8]. The main features of these detectors are listed in Table 1, and each detector is described below, along with results of on-beam testing at RADEN [9,10].

Table 1. Main features of the counting-type detectors at RADEN. The values for the spatial resolution and count rate were confirmed during on-beam testing at RADEN.

| Detector  | μNID | nGEM | Li-glass |
|-----------|------|------|----------|
| Type      | Micro-pattern | Micro-pattern | Scintillator |
| Converter | 3He   | 10B  | 6Li      |
| Area      | 10 × 10 cm² | 10 × 10 cm² | 5 × 5 cm² |
| Time res. | 300 ns | 15 ns | 40 ns    |
| Spatial res. | 0.25 mm | 1 mm | 3 mm |
| Efficiency | 26%    | 10%  | 40%      |
| Count rate | 0.4 Mcps | 1 Mcps | 8 Mcps |

2.1. μPIC-based Neutron Imaging Detector (μNID)

The μNID uses a time projection chamber with an active volume of 10 × 10 × 2.5 cm³ and a readout plane consisting of a micro-pixel chamber (μPIC) micro-pattern detector with a 0.4mm-pitch, two-dimensional strip readout [11] and a modular, FPGA-based data acquisition system [12]. To facilitate neutron detection, a CF₄-iC₄H₁₀-3He gas mixture (mixing ratio 45:5:50) at 2 atm total pressure is used, giving a detection efficiency of 26% for thermal neutrons. Following a neutron-3He interaction, the three-dimensional track and energy deposition (estimated via time-over-threshold) of the resultant proton-triton pair are recorded in the FPGA-based data encoder modules and sent to PC via Gigabit Ethernet. This detailed tracking information allows the μNID to achieve a fine spatial resolution of 0.25 mm (FWHM) and an excellent gamma sensitivity of less than 10⁻¹². The μNID also features a time resolution of 0.3 μs and neutron count rates up to 0.4 Mcps.

Fig. 1 shows the image of a Gd test chart taken at RADEN with an L/D of 5000 and an exposure time of 1.5 hours, with the test chart placed directly on the entrance window of the μNID [10]. The peak neutron count rate was 133 kcps over the entire detection area. The image has been normalized by the image without sample to remove any effects of the neutron intensity distribution and detector artifacts. The μNID shows good resolving power with a 16% contrast at 2.5 line-pairs/mm (or a line width of 0.2 mm). Rate testing of the μNID will be discussed in Section 3.1.

Fig. 1. μNID test image taken at RADEN. (Top) Neutron transmission image of a Gd test pattern (bin size: 40 × 40 μm²). (Bottom) 1-D projection of line pairs in the region indicated by the dashed rectangle.

2.2. Boron-coated Gas Electron Multiplier (nGEM)

The nGEM detector uses a time projection chamber incorporating a drift cathode and GEM, each coated with a thin layer (~1 μm) of 10B, to achieve a detection efficiency of 10% for thermal neutrons. These are followed by a pair of normal GEMs used to amplify the charge deposited in the Ar-CO₂ (70:30, 1 atm) gas
of the detector by the alpha particle or $^7$Li nucleus released in the neutron-$^{10}$B interaction, which is then read out via a 0.8mm-pitch, two-dimensional strip plane. These signals are processed by an FPGA-based data acquisition board, and the resulting digitized neutron event data is recorded to PC via Gigabit Ethernet. By measuring the center of the charge cloud, the nGEM achieves a spatial resolution of about 1 mm (FWHM), and it features a detection area of $10 \times 10$ cm$^2$, an excellent time resolution of 15 ns, a gamma sensitivity of $10^{-3}$, and Mcps rate capability.

Fig. 2 shows the results of imaging and rate tests of the nGEM performed at RADEN. The expected spatial resolution was confirmed using the same Gd test chart as above (L/D: 2000, 0.5 hours), as shown in Fig. 2(a). Additionally, the rate linearity was examined by scanning the incident neutron intensity using a set of B$_4$C slits [9]. Although a maximum peak rate of 4.6 Mcps was observed, the resulting curves for neutron count rate versus slit area, shown in Fig. 2(b), clearly deviate from a straight line, indicating non-linear rate performance. The observed count loss in the nGEM was about 1% at 90 kcps peak rate, increasing to 10% at 1 Mcps (consistent with a dead time of 114 ns).

2.3. $^6$Li Time Analyzer, Model 2012 (LiTA12)

The LiTA12 Li-glass pixelated scintillator detector consists of a 16 $\times$ 16 array of $^6$Li-impregnated, Cerium activated glass scintillator pixels (scintillator type GS20) of size $2.1 \times 2.1 \times 1$ mm$^3$. The Li-glass pixels are matched to a Hamamatsu H9500 multi-anode photomultiplier (MA-PMT) with an anode pitch of 3 mm and covering an area of $5 \times 5$ cm$^2$. The signals from each anode of the MA-PMT pass through an amplifier module and are then digitized and histogrammed in custom FPGA modules. The LiTA12 achieves a detection efficiency of about 40% and is capable of high counting rates up to 8 Mcps, but with spatial resolution limited by the 3-mm pixel pitch.

An image of a Cd mask in the shape of the letter ‘t’ taken at RADEN is shown in Fig. 3(a). The observed image quality is consistent with that expected for the LiTA12. Also, the rate performance of the LiTA12 was studied by changing the size of an upstream rotary collimator (from $\varnothing 2$mm to $\varnothing 15$mm) to vary the incident neutron flux. As seen in Fig. 3(b), a maximum count rate of 8 Mcps was observed at the cold neutron peak with the largest collimator opening. Study of the rate linearity is ongoing.

3. Ongoing detector development at RADEN

To better meet the needs of neutron imaging at the high-intensity, pulsed neutron source of the MLF, ongoing development of the counting-type detectors is focused on improvement of the spatial resolution and count rate performance. Specifically, we are actively pursuing the development of the $\mu$NID and Li-glass detectors within the RADEN group.

3.1. $\mu$NID development

The development of the $\mu$NID includes upgrades to
all aspects of the detector system, including modifications to the data acquisition hardware, optimization of the gas mixture, and the development of new μPIC readout planes [10]. We are also updating the offline data analysis software with new algorithms and a new interface to improve reliability, speed, and ease-of-use, and make the software more accessible to general users at RADEN.

We have recently completed testing of an upgraded data encoder module and optimized gas mixture that saw an improvement in the rate capacity of the μNID from 0.6 Mcps up to 8 Mcps [10]. This was accomplished by upgrading the data transfer of the data encoder module from 100BASE-T to Gigabit Ethernet, and by changing from an Ar-based gas mixture [13] to the current CF$_4$-based gas mixture for a 2 times higher stopping power and 2.5 times faster drift velocity. The CF$_4$-based gas mixture also has a smaller electron diffusion coefficient for a slightly improved spatial resolution and a larger $^3$He fraction for increased neutron detection efficiency. Fig. 4 shows the results of rate tests carried out at RADEN using the same conditions as for the nGEM tests of Fig. 2(b). Owing to the increased transfer rate and reduced event size, the rate capacity of the μNID reached a maximum of just over 8 Mcps. Furthermore, a second revision of the data encoder module including on-board memory should allow us to extend the peak rate to over 15 Mcps through buffering of high-rate data. This new module will be tested soon.

![Graph](image)

Fig. 4. Measured peak neutron count rate versus slit area. (Top) Rate curves for data encoders with 100BASE-T (diamonds) and Gigabit Ethernet (squares). The detector was filled with the original Ar-C$_2$H$_6$-$^3$He gas mixture. (Bottom) Rate curves with the old Ar-based (squares) and current CF$_4$-based (triangles) gas mixtures, both with Gigabit Ethernet data transfer.

While carrying out the above rate testing, it was discovered that our data analysis algorithms were not adequate for such high-rate data. In fact, the event clustering algorithm began to fail for neutron count rates above 400 kcps, limiting the effective rate of the μNID system. We are now developing new event clustering, using a density-based clustering algorithm based on DBSCAN [14], aimed at high-rate operation.

Finally, to provide a significant improvement in the spatial resolution, we have developed a new μPIC detection element with a reduced strip pitch of 215 μm [10]. Such a small pitch was achieved by switching the manufacturing process from conventional printed circuit board techniques to a MEMS (Micro Electro Mechanical Systems)-based process. In preliminary testing, the small-pitch μPIC produced adequate gain for neutron detection, but showed poor gain stability under neutron irradiation, most likely originating from the use of a silicon substrate (in place of the polyimide substrate of the original 400μm-pitch μPIC). This gain instability is currently under study.

3.2. LiTA12 development

Development of the Li-glass detector includes an upgrade to new amplifiers designed by S. Satoh at KEK for an order-of-magnitude increase in count rate, and improved spatial resolution using so-called super resolution methods. Preliminary testing of the new amplifiers at RADEN has already shown an increased maximum rate of over 50 Mcps [8]; however, rate linearity remains to be investigated. The super resolution methods to be studied fall under two types: 1) charge centroiding with a flat-panel scintillator in place of the current pixelated scintillator, and 2) multi-image reconstruction techniques whereby multiple images taken at sub-pixel shifts of the detector or sample are combined to produce a higher resolution image [13]. Preliminary tests of the flat-panel scintillator with charge centroiding at RADEN showed an improved spatial resolution down to about 0.5 mm, although the data acquisition mode limits the maximum rate to about 1 Mcps. Additionally, an initial test of the multi-image method was recently performed, with data analysis underway. Testing of these methods will continue at RADEN.

4. Conclusion

At the RADEN instrument of the J-PARC MLF, we employ advanced counting-type neutron imaging detectors developed in Japan, including the μNID and nGEM micro-pattern detectors and the LiTA12 Li-glass pixelated scintillator detector, to carry out energy-resolved neutron imaging. During on-beam testing at RADEN, we confirmed the expected spatial resolution of each detector and studied their neutron count rate performance. Furthermore, in order to fully
utilize the high-intensity neutron beam at the MLF, we are pursuing the development of the μNID and Li-glass detectors to provide improved spatial resolutions and higher count rates. Through our testing, the counting-type detectors at RADEN have been shown to be well suited to pulsed neutron imaging and, with the ongoing development described here, can become very powerful tools for energy-resolved neutron imaging at high-intensity, pulsed neutron sources both in Japan and throughout the world.

Acknowledgement

The development of the μNID was partially supported by the Momose Quantum Beam Phase Imaging Project, ERATO, JST. The on-beam tests of all three detectors were carried out under the BL22 Instrument Group Use (MLF proposal nos. 2015I0022 and 2016I0022).

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