CROSS TOKAI **Experimental Report** J-PARC	承認日 Date of Approval 承認者 Approver 提出日 Date of report
実験課題番号 Project No. 2017C0004 実験課題名 Title of experiment Development of event-type neutron imaging detectors and imaging techniques for energy-resolved neutron imaging 実験責任者名 Name of principal investigator Joseph Don Parker 所属 Affiliation Neutron Science and Technology Center, CROSS	装置責任者 Name of Instrument scientist Takenao Shinohara 装置名 Name of Instrument/（BL No.） RADEN/(BL22) 利用期間 Dates of experiments 2017/4/27 (1 day) 2017/6/2 (1 day) 2017/6/19-20 (2 days) 2017/11/19 (1 day) 2018/1/10 (1 day) 2018/3/31-4/1 (2 days) Total beam time: 8 days

1．研究成果概要（試料の名称、組成、物理的・化学的性状を明記するとともに、実験方法、利用の結果得られた主なデータ、考察、結論、図表等を記述してください。

Outline of experimental results (experimental method and results should be reported including sample information such as composition, physical and/or chemical characteristics.

Introduction

RADEN/BL22 [1] represents the world's first instrument dedicated to energy-resolved neutron imaging techniques using a short-pulsed neutron beam. Energy-resolved neutron imaging techniques allow one to extract quantitative information on the macroscopic distribution of microscopic quantities of an object by analyzing the energy-dependent neutron transmission spectrum point-by-point over a sample. Performing such measurements at a high-intensity, short-pulsed neutron beam, such as at the J-PARC/MLF, requires advanced detectors with a combination of sub-μs time resolution, sub-mm to sub-100μm spatial resolution, and very high count-rate capabilities. The development of such detectors remains a challenge and is of paramount importance to reach the full potential of energy-resolved neutron imaging techniques.

At BL22, our development efforts are focused on two detectors: the micropixel chamber (μPIC)-based neutron imaging detector (μNID) [2], which provides a spatial resolution of 0.1 mm and an effective count-rate capability of 1 Mcps, and the Li-glass scintillator pixel detector (LiTA12) [3], which provides a count-rate capability of up to 60 Mcps or more but with a low spatial resolution of 3 mm. As part of our ongoing development work, we carried out the following measurements under the current project: (1) on-beam characterization of new readout elements for the μNID for improved spatial resolution (MEMS μPIC with reduced strip pitch) and increased count-rate (3-axis μPIC with additional readout plane [4]), (2) on-beam characterization of a new version of the μNID detector incorporating a boron-coated neutron converter (Boron-μNID) to achieve increased count rate, and (3) proof-of-principle demonstration of a super resolution imaging method to improve the spatial resolution of the LiTA12 detector.

1．研究成果概要（つづき） Outline of experimental results (continued).

Experimental methods

For the detector characterizations, we performed measurements to study the efficiency, gain stability, spatial resolution, and count-rate linearity. We also performed measurements of standard samples provided by BL22 for direct comparison with the other event-type detectors in use at BL22. The measurement procedures are described in Table 1, followed by a description of the samples used during the experiments in Table 2. For the spatial resolution and standard sample measurements, measurements with the sample and without the sample were taken, and the neutron transmission was then calculated as the ratio of the sample to no-sample measurements. This corrected for the intensity distribution of the beam and any detector specific image artifacts.

For the super resolution method, the experimental setup consisted of the LiTA12 detector mounted on a remote-controlled x-y stage. A series of images was then taken by stepping the detector over a two-dimensional grid perpendicular to the beam direction, with sub-pixel step sizes of 0.1 or 0.5 mm. The images were then combined off-line to form the super resolution image.

Table 1. Description of measurement methods for detector characterization.

Attribute	Detector	Description
Efficiency	Boron-μNID	Compare observed count rate with that of a ^{3}He detector of known efficiency under identical experimental conditions
Gain stability	MEMS μPIC	Monitor gain stability over time (several hours ~ 1 day) under exposure to various neutron intensities. The intensity was controlled by changing the upstream collimation of the beam.
Spatial resolution	All	Take images of Gd test pattern with Siemen's star, line-pair patterns, etc., for quantitative determination of spatial resolution.
Count-rate linearity	Boron-μNID	Measure detector response to varying neutron beam intensity. The intensity was controlled by changing the opening area of beamline slits located upstream of the detector.

Table 2. Description of samples used during the current experiments.

Name	Composition	Form	Cell	Description
Gd test pattern	Gd, Si	Solid	None	3μm-thick layer of Gd on glass substrate
Fe step wedge	Fe	Solid	None	1 cm x 5 cm x 2 cm, wedge-shaped
Cu step wedge	Cu	Solid	None	1 cm x 5 cm x 2 cm, wedge-shaped
C step wedge	C	Solid	None	1 cm x 5 cm x 2 cm, wedge-shaped
Fe pellets	Fe	Solid	Aluminum	φ1~3 mm pellets in rectangular aluminum cell

All samples were provided by the BL22 Instrument Group.

必要に応じて、A4 サイズの用紙に続きを記入して下さい。
Please use A4-size papers for further reporting, if necessary.

1．研究成果概要（つづき） Outline of experimental results (continued).

Results

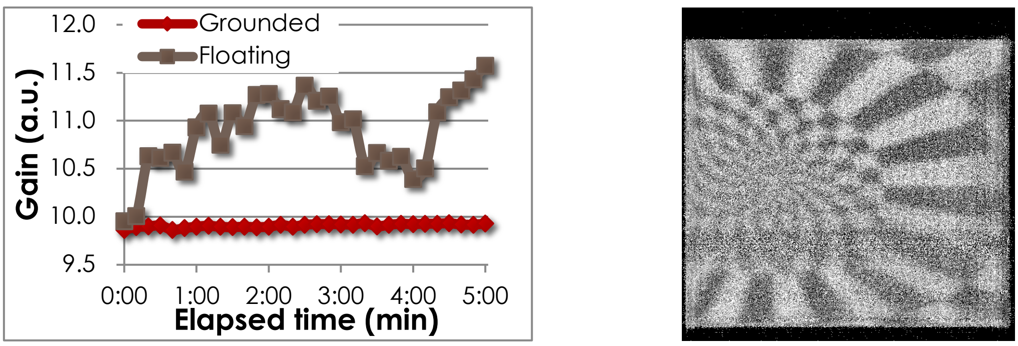
The measurements described above were carried out over 8 days (4 days in 2017A, 4 days in 2017B). A summary of the beam times and measurements performed are listed in Table 3.

Table 3. Summary of measurements carried out under current project.

	Dates	Detector	Measurements	Samples
1	2017/4/27	MEMS μPIC	Gain stability versus incident intensity	None
2	2017/6/2	Boron-μNID	Count-rate linearity (beam power: 150 kW), spatial resolution, standard samples	Gd test pattern Fe, Cu, C step wedges
		MEMS μPIC	Gain stability, spatial resolution with small-area MEMS μPIC	
3	2017/6/19-20	LiTA12	Super resolution (detector stepping)	Gd test pattern
4	2017/11/19	LiTA12	Super resolution (detector stepping)	Gd test pattern
5	2018/1/10	3-axis μPIC	Operation test	Gd test pattern Fe, Cu, C step wedges Fe pellets
		Boron-μNID	Count-rate linearity (beam power: 400 kW), spatial resolution, standard samples	
6	2018/3/31-4/1	Boron-μNID	Count-rate linearity (beam power: 400 kW), spatial resolution, efficiency	Gd test pattern
		MEMS μPIC	Gain stability, spatial resolution with large-area MEMS μPIC	

MEMS μPIC – The nearly two-times reduction in pitch of the MEMS μPIC (from 400 μm to 215 μm) is expected to provide a similar improvement in the spatial resolution. A study of the gain stability versus exposure time and intensity was carried out to characterize a large gain instability observed in preliminary testing in JPY2016. We eventually found that grounding the silicon substrate of the MEMS μPIC appeared to stabilize the gain as demonstrated in Fig. 1. The small size of the first MEMS μPIC (1.4 cm × 1.4 cm), however, made it difficult to determine the spatial resolution. A larger area MEMS μPIC (5.5 cm × 5.5 cm, delivered mid-March 2018) was also tested, and the data analysis to determine the spatial resolution is underway.

Figure 1. (Left) Plot of MEMS μPIC gain over time under neutron exposure with and without substrate grounding. (Right) Image of a gadolinium test chart (Siemen's star) taken with the MEMS μPIC with a field of view of 1.4 cm × 1.4 cm. Image distortion is due to the small size and damaged readout strips.

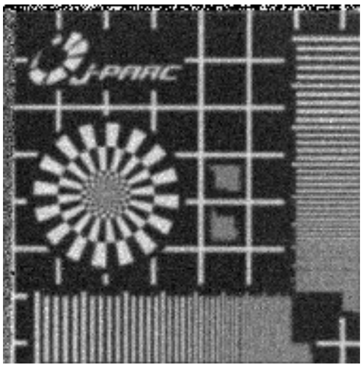


１．研究成果概要（つづき） Outline of experimental results (continued).

3-axis μPIC – The 3-axis μPIC includes an additional readout strip-plane oriented at a 45° angle to the usual orthogonal x and y readout planes. The additional information from the 3^{rd} strip plane is expected to improve event separation at high rates, thus improving the count-rate performance of the detector. We confirmed signals from the third-axis strip layer. The pulse heights, however, were too small to provide useful data. The design of the 3-axis readout is now being reconsidered.

Boron-μNID – Using a boron converter reduces the number of hit strips per neutron event (and thereby, increases the maximum count rate) due to the shorter track lengths of the α and Li nucleus in the gas, as compared to the proton and triton of the ^3He case. We carried out a gas study, measuring the spatial resolution/event size versus gas pressure (Fig. 2). The filling gas was CF_4-isobutane (90:10) at pressures from 1.2 to 1.6 atm. We confirmed both the expected roughly 3-times reduction in event size as compared to ^3He and, after the increase in beam power of the MLF to 400 kW, a maximum hardware count-rate increase to 21 Mcps.

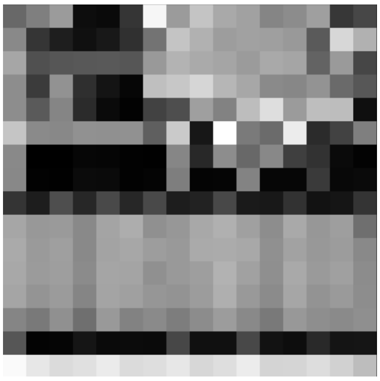
Figure 2. (Left) Image of the Gd test pattern taken with the Boron-μNID with a field of view of 7.7 cm × 7.7 cm. The gas pressure was 1.6 atm, and the observed spatial resolution is 0.45 mm. (Right) Table summarizing gas study. Increased gas pressure reduced the event size and improved the spatial resolution.

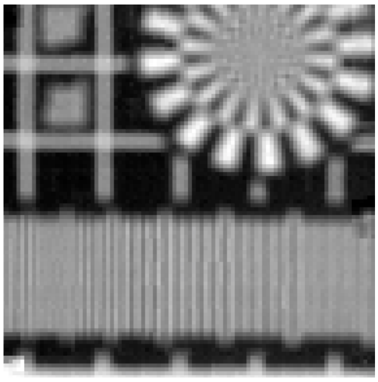


Pressure (atm)	1.2	1.4	1.6
Average hits/ event	5.86	5.42	4.82
MTF @0.6mm	27%	36%	41%
Spatial resolution @10% MTF (mm)	0.50	0.48	0.45

Super resolution with LiTA12 – In this super resolution method, it was expected that features smaller than the pixel size of the detector can be extracted by combining multiple images taken at transverse sub-pixel shifts of the detector relative to the sample. Using a simple image reconstruction method, the extraction of sub-pixel features was confirmed (Fig. 3), and we are now considering a more sophisticated image compositing algorithm.

Figure 3. (Left) A single image of the Gd test pattern taken with the LiTA12 detector with 3 mm pixel size. (Right) A composite image made from a 6×6 scan (step size 0.5 mm) showing features smaller than the pixel size of the detector. The field of view is 5 cm×5 cm for both images.





１．研究成果概要（つづき） Outline of experimental results (continued).

Conclusion

In the current project, we were able to carry out our detector testing as planned, and the information obtained was invaluable for our continuing development efforts. The operation of the new small-pitch MEMS μPIC was confirmed, and the large gain instability initially observed appears to have been resolved by grounding the silicon substrate of the detection element. The determination of the spatial resolution is ongoing. The expected operating characteristics of the Boron-μNID were also confirmed, and its optimization will continue for use as a high count-rate detector at BL22. On the other hand, the 3-axis μPIC did not operate as expected, and it is now being redesigned. Finally, the results for the super resolution method utilizing multiple image composition showed promise as a means to improve the spatial resolution of the LiTA12 detector. We are continuing our detector development in JPY2018 under the CROSS Development Project No. 2018C0002.

References

[1] T. Shinohara *et al.*, J. Phys.: Conf. Series **746**, 012007 (2016).

[2] J.D. Parker *et al.*, Nucl. Instr. and Meth. A **726**, 155 (2013).

[3] S. Satoh, JPS Conf. Proc. **8**, 051001 (2015).

[4] Japan Patent Application No. 2015-217614.