Exploration of Photodetectors for Pulse Shape Discrimination in a Dual Particle Imager

Jihwan Boo, Seoryeong Park, Suyeon Hyeon, and Manhee Jeong*

Department of Nuclear and Energy Engineering, Jeju National University (*Email: mhjeong@jejunu.ac.kr)

Introduction

- **A Dual Particle Imager (DPI)**
  - Simultaneously detecting gamma-rays and neutrons to reconstruct radiation images for
    1) visual aids on the distribution of radioactive sources
    2) double verification of the presence of a special nuclear material (SNM)
- **Efforts on a Highly Qualified Neutron-gamma Discrimination**
  - Various pulse shape discrimination (PSD) methods having been developed
  - The effect of analog-digital converters (ADCs) with different resolutions and sampling rates having been studied
  - Few studies illustrating on how to improve a degraded PSD capability of a pixelated scintillator array
- **Study Goal**
  - We illustrate that a pixel size matching between the pixelated stilbene scintillator array and silicon photomultiplier (SiPM) array can improve the PSD performance even with the use of ADCs that has a low bit resolution (12 bit) and a low sampling rate (50 MHz) in a DPI system

Materials & Methods

1. Pixelated Scintillator Array and SiPM Arrays

- The stilbene scintillator array (Inrad Optics)
  - 12 × 12 pixels with a pixel size of 4 × 4 × 20 mm
  - A reflector (polytetrafluoroethylene, PTFE) with a thickness of 200 μm formed for a pixel pitch of 4.2 mm
- SiPM arrays (On Semiconductor)
  - C-series 12 × 12 pixelated SiPM array with a pixel size of 3 × 3 mm (ArrayC-30035-144P)
  - A self-developed J-series SiPM array, in which the number of 144 J-series SiPM pixels (MICROFJ-40035-TSV-TR1) with a pixel size of 4 × 4 mm are assembled
  - Note that On Semiconductor does not provide a 12 × 12 pixelated SiPM array with a pixel size of 4 × 4 mm

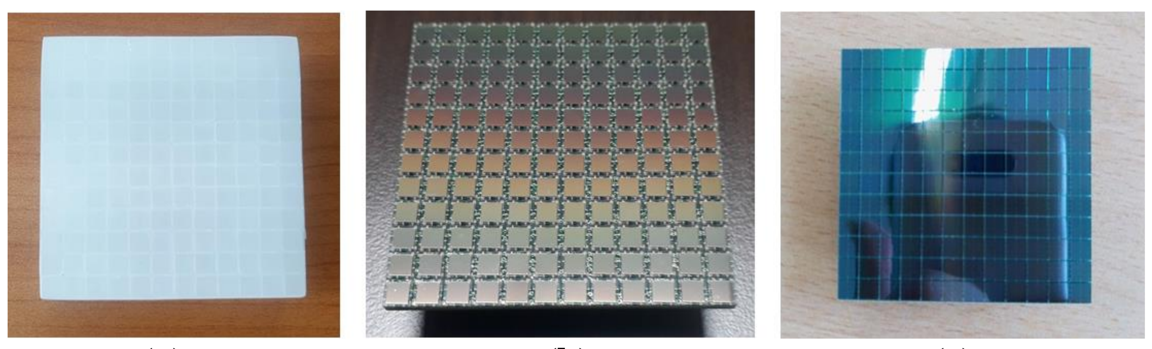

Fig. 1. Stilbene scintillator array (a), C-series SiPM array (b), and a self-developed J-series SiPM array (c)

Table I. Comparison of the most prominent properties of a C-series SiPM array and a J-series SiPM pixel.

	C-series	J-series
Pixel size [mm^2]	3 × 3	4 × 4
Micro cell size [μm]	35	35
Microcell fill factor [%]	64	75
PDE @420 nm [%]	31	38
Gain	3 × 10^6	2.9 × 10^6
Afterpulsing [%]	0.2	0.75
Crosstalk probability [%]	7	8
Dark current [nA]	154	350

2. Hardware Configurations for Signal Processing

- Front-end electronics board
  - A row/column readout with resistive dividers, in which the 144 signals from the 12 × 12 SiPM array are processed into 24 analog signals
  - 24 trans-impedance amplifiers (TIAs) that provide current-to-voltage transforms for each orthogonal X and Y direction
  - Shaping amplifiers that shape and amplify the output of each TIA
- Data acquisition board
  - The 24 analog signals connected directly to ADCs (ADC3421, Texas Instruments), with quad channel, 12-bit resolution, and a sampling rate of 25 MHz

3. Neutron/gamma Separation Using PSD

- The charge comparison method
  - The ratio of tail-integral to the peak amplitude, providing a PSD value that is a separates neutron and photon pulses

$$PSD = \frac{Q_{tail}}{Q_{peak}} = \frac{\int_{tail_{start}}^{tail_{end}} Q dt}{Q_{peak}}$$

  - A figure of merit (FOM) quantifying the quality of PSD
  - The FOM of 1.27 or higher, which is considered a criterion for good PSD performance

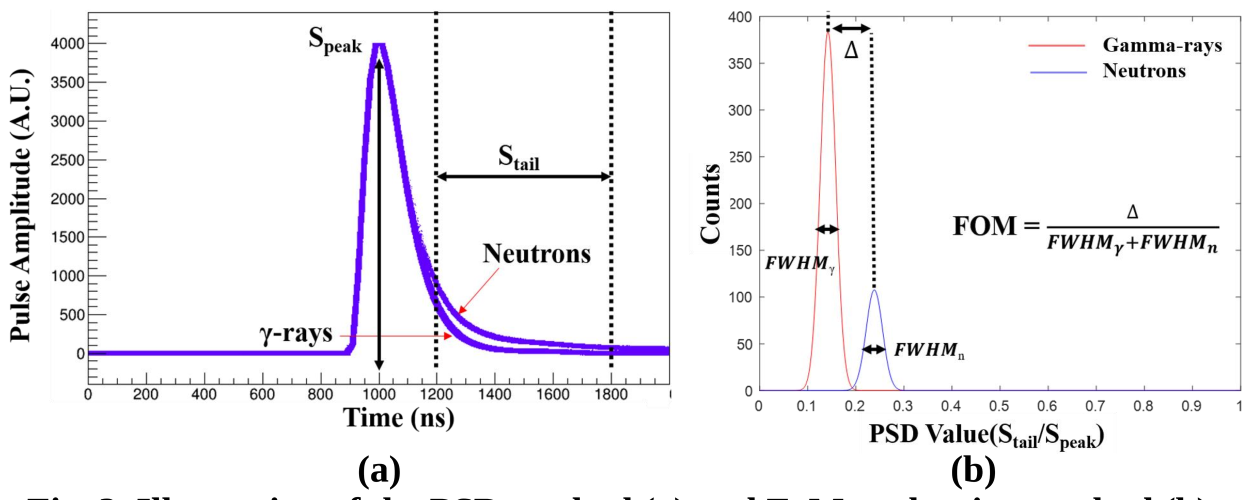

Fig. 2. Illustration of the PSD method (a) and FoM evaluation method (b).

Results & Discussion

1. Energy Calibration Using Two Different SiPM Arrays

- Energy spectra acquired by measuring ^{57}Co, ^{137}Cs, and, ^{22}Na sources (with 0.312 MBq of radiation) located 10 cm away
- A channel number corresponding to the Compton edge, which is to be a positional determination equivalent to 80%
- The extent of amplification of shaping amplifier, which is adjusted for the output signals of the two SiPM arrays to have a comparable pulse height for a gamma-ray with a specific energy

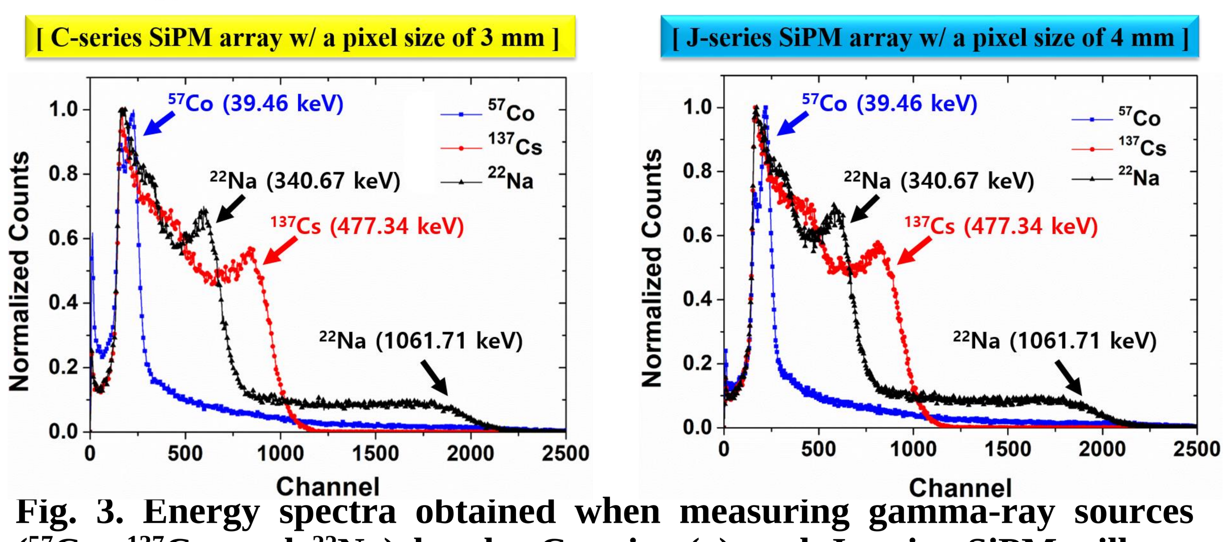

Fig. 3. Energy spectra obtained when measuring gamma-ray sources (^{57}Co, ^{137}Cs, and ^{22}Na) by the C-series (a) and J-series SiPM-stilbene array sensor module (b), respectively, when the SiPM arrays are operated at a bias voltage of 28 V and a temperature of 25℃.

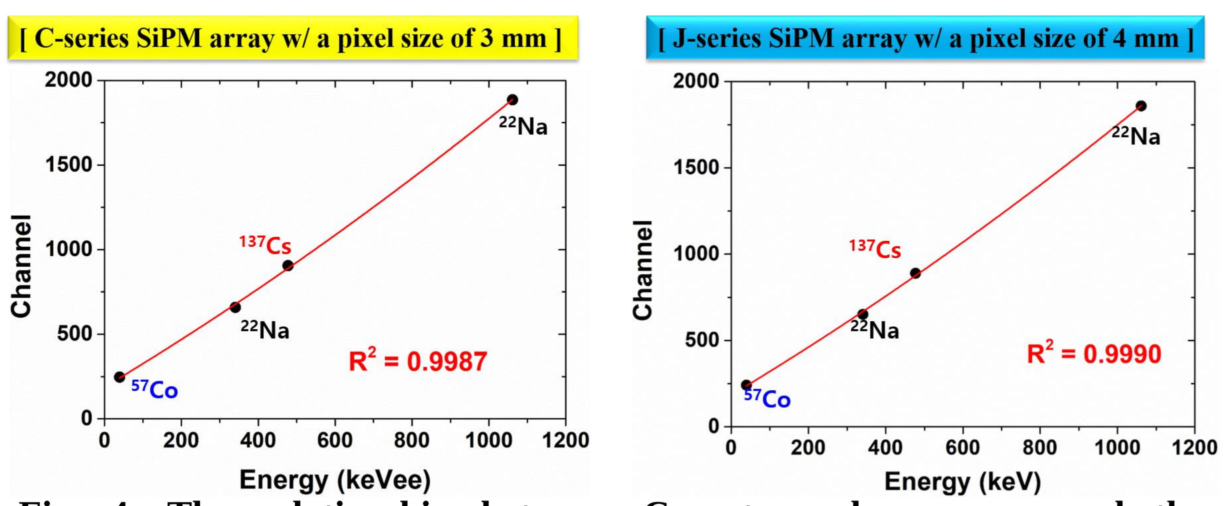

Fig. 4. The relationship between Compton edge energy and the corresponding channel number obtained from the C-series (a) and J-series SiPM-stilbene array sensor module (b), respectively

2. *Overall-detector* PSD Performance

- The PSD metric plot acquired by measuring a 2.8× 10^5 n/s ^{252}Cf source at the distance of 30 cm from the detector module
- The FOM values given for each energy region (0-50 keVee, 50-100 keVee, ···· 1500-1550 keVee) of the PSD distribution
- In the energy range of 100-150 keVee, the J-series SiPM-stilbene array module having a FOM value of 1.28 equivalent to the FOM criterion of 1.27, which is superior to the C-series SiPM-stilbene array module

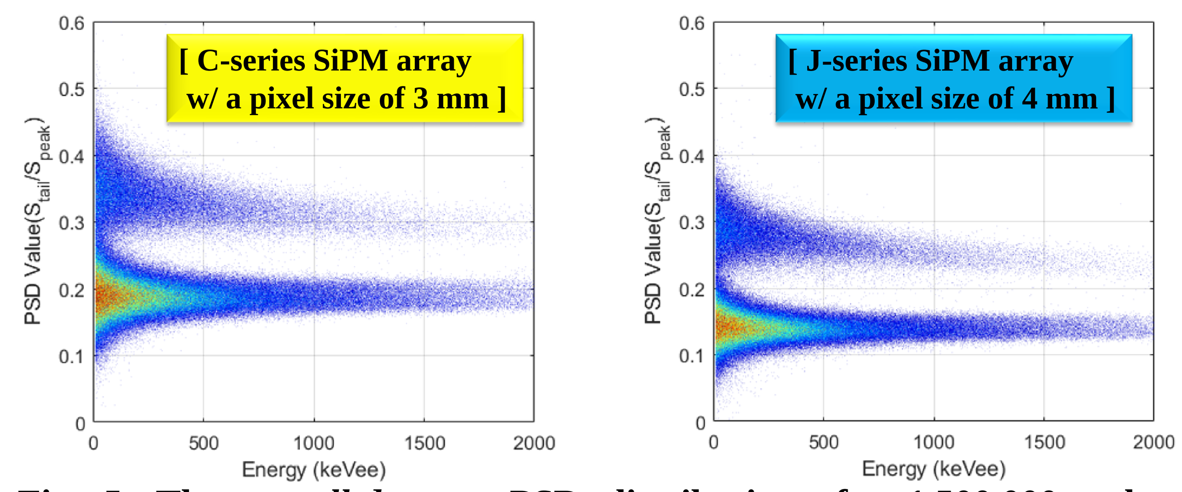

Fig. 5. The *overall-detector* PSD distributions for 1,500,000 pulses produced by the C-series and J-series SiPM-stilbene module when measuring a 2.8×10^5 n/s ^{252}Cf source at a distance of 30 cm

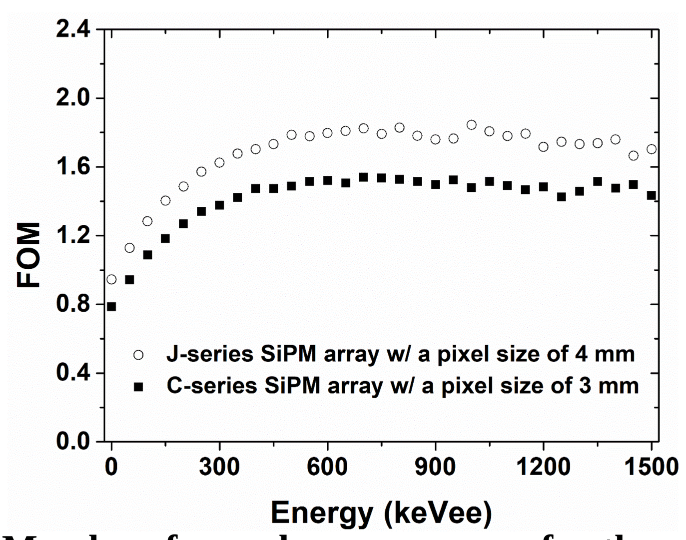

Fig. 6. FOM values for each energy range for the *overall-detector* PSD distributions obtained from each of the C-series and J-series SiPM-Stilbene array sensor modules given in the Fig. 5.

3. PSD Performance that One of the Pixels has

- One of the pixels showing a clearer distinction between the neutron and gamma-ray events, once PSD sorting is applied to each pixel
- The C-series SiPM-stilbene array sensor module that has a FOM value of 1.20 in the energy range of 100 keVee
- The J-series SiPM-stilbene array module that has a FOM value of 1.26 in the energy range of 50-60 keVee

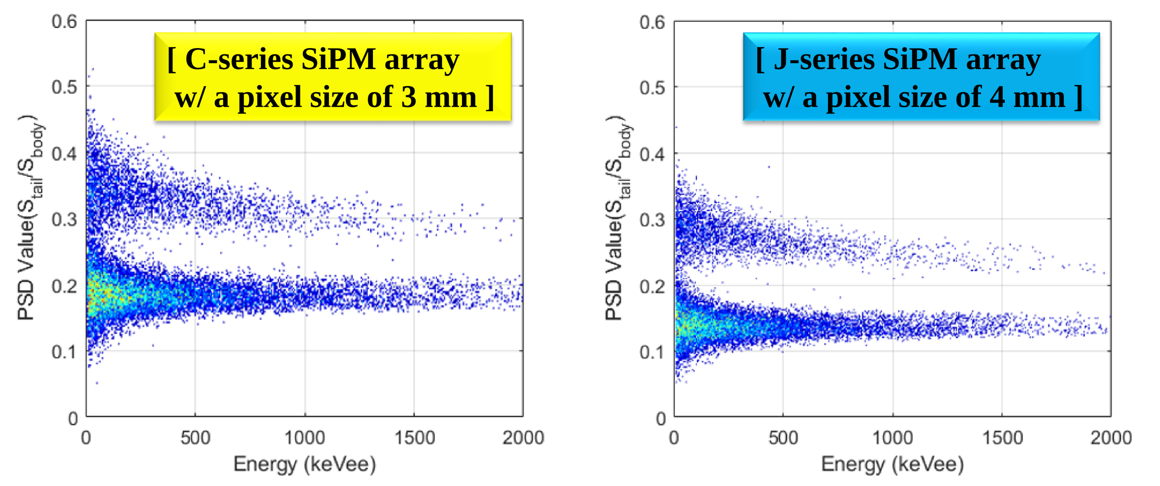

Fig. 7. PSD distributions that one of the pixels has in the C-series and J-series SiPM-stilbene sensor module, respectively.

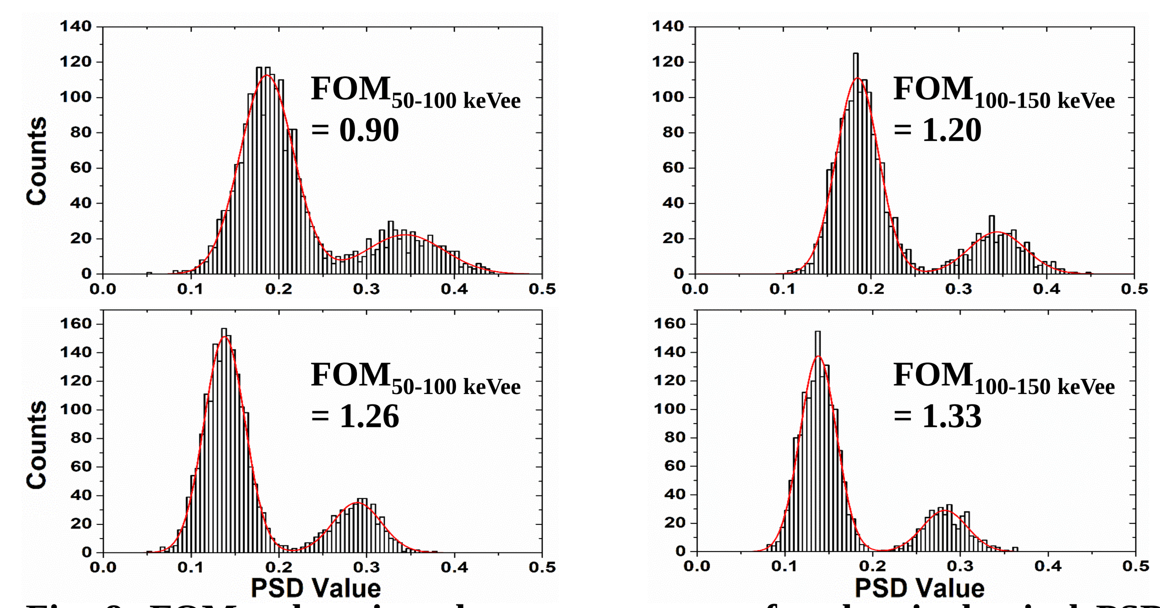

Fig. 8. FOM values in a low energy range for the single-pixel PSD distribution obtained from each C-series (top row) and J-series SiPM-Stilbene array sensor module (bottom row) shown in Fig. 7.

Conclusion

We demonstrate the pixel size matching between the pixelated stilbene scintillator array and SiPM array can improve the PSD performance even with the use of ADCs with a low resolution and a slow sampling rate. The enhanced PSD performance will allow for rapid image acquisition by maximizing the use of well separated neutron events from gamma-ray ones.

Acknowledgement

This work was partly supported by Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2103085 and No. 1903011-0119-CG100).

Dept. of Nuclear and Energy Engineering
JEJU NATIONAL UNIVERSITY

Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October 21-22th, 2021