Exploring the Potential Configurations of Fast Neutron Imaging System Based on the Compact Neutron Source

Hanna Lee[a,b] , Pilsoo Lee[a,b*], Soobin Lim[c], Bongki Jung[c], Dong Won Lee[b]
[a]*University of Science & Technology, Gajeong-ro 217, Yuseong-gu, Daejeon, 34113*
[b] *Nuclear Physics Application Research Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, 34057*
[c]*Q-Beam Solution Inc.,160, Daehwa-ro, Daedeok-gu, Daejeon, 34368*
[*]*Corresponding Author: pilsoolee@kaeri.re.kr*

***Keywords : Accelerator-Based Neutron Sources, Neutron Imaging, Neutron Imaging for Non-Destructive Testing**

1. Introduction

Research and applications exploiting the unique properties of neutrons—such as neutron imaging, neutron activation analysis, and radiation shielding evaluation—have been increasingly applied across various scientific and technological fields, including the nuclear industry. Neutron sources used for such purposes are primarily based on nuclear reactors and accelerators; however, their utilization is often constrained by strict safety regulations and limitations in operational availability. Meanwhile, demand in both industrial and research sectors continues to grow, particularly for field-deployable neutron imaging systems used in non-destructive testing applications. Consequently, the development of accelerator-based neutron sources capable of providing on-site neutron imaging has become increasingly necessary [1].

Neutron imaging for non-destructive testing (NDT) is applied to a wide range of objects; however, when inspecting large-volume samples, conventional thermal neutron imaging suffers from limitations due to insufficient penetration depth, resulting in restrictions on sample size. This limitation becomes more pronounced for components such as divertor devices, which are large in volume and primarily composed of tungsten (W, Z = 74), a high atomic-number material that strongly attenuates thermal neutrons. To overcome these limitations, the application of fast neutron imaging for non-destructive evaluation is proposed. The primary objective of the present system design is therefore to identify structural defects in domestically manufactured fusion divertor components through fast neutron imaging–based NDT. The required spatial resolution for defect detection was set to achieve performance comparable to existing imaging systems, even for thick samples. The nominal spatial resolution of the system is 200 µm. however, Paul Scherrer Institute (PSI) line pattern analysis demonstrated that clear feature discrimination was practically achievable up to 300 µm [2].

2. Conceptual design of the imaging system

2.1 Overall System Concept

A conventional neutron imaging system typically consists of a scintillator screen, mirrors, optical lenses, image sensors, and a shielding enclosure. The fast neutron imaging system proposed in this study is based on this conventional arrangement, with primary emphasis placed on the development and optimization of the detector and optical subsystems. The conceptual baseline design for the proposed system is shown in Fig. 1.

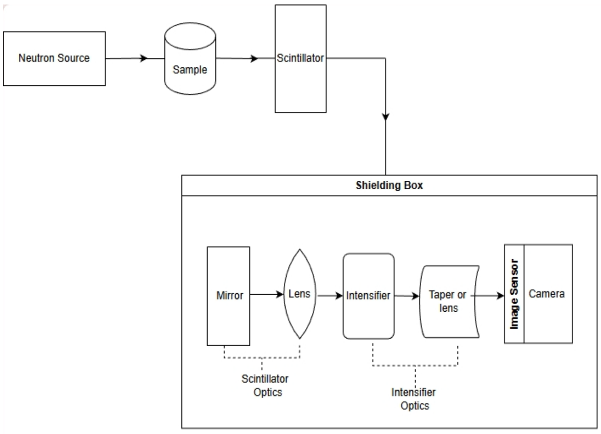

Fig. 1. Conceptual baseline design for the proposed system.

2.2 Scintillator Screen

In a neutron imaging system, the scintillator serves as the medium that converts incident neutrons into visible light. For thermal neutrons, a 400 µm thick ^{6}LiF/ZnS-based plastic scintillator with an efficiency of approximately 80% can be used. While the position of light emission can be localized due to the short range of alpha particles within the scintillator, scintillation light originating from varying depths scatters, leading to significant image blurring. Furthermore, ^{6}LiF/ZnS is inherently inefficient for fast neutron detection, necessitating the incorporation of appropriate neutron converters. A scintillator screen with a thickness of approximately 25.4 mm and an area of 200 × 200 mm² [3], based on a BCF-12 plastic scintillator employing a fiber structure or scintillator composed of NNPC182-01 with densities of approximately 1.16 g/cm³ was considered. The emission peak of the scintillator composed of plastic based on optical materials is approximately 415 nm, while that of the BCF-12 scintillator is around 435 nm. The scintillator structure is designed to be optically coupled with the image sensor through the optical system.

2.3 Optical System

The optical system in the proposed configuration is responsible for efficiently transferring scintillation light generated in the scintillator screen by neutron interactions to the image sensor. Since the planned image sensor has a circular active area with a diameter of approximately 21 mm, effective area size of 18.841 mm (H) × 10.598 mm (V), an image demagnification factor of about 11 is required to match the scintillator screen dimensions. In fast neutron imaging, the number of photons generated per detected neutron is limited. Therefore, the optical design prioritizes maximizing light collection efficiency. The optical components are conceptually divided into two subsystems, as illustrated in Fig. 1: the scintillator optical system and the image intensifier optical system. The scintillator optical subsystem is designed to collect as much scintillation light as possible from the screen and deliver it efficiently to the image intensifier. Therefore, to maximize light collection efficiency, a lens with the largest feasible aperture, exhibiting performance comparable to a focal length of 120 mm and an F-number of 0.95 are being considered. For the image intensifier optical subsystem, several coupling approaches are under consideration, including direct 1:1 image transfer using a fiber optic plate (FOP) output window, commercial relay lens solutions, and fiber-optic taper–based image transmission structures.

2.4 Image Sensors

For the imaging sensor, two configurations are considered: an integrating-mode Complementary Metal-Oxide Semiconductor (CMOS) characterized by high quantum efficiency and low readout noise, and an event-mode imaging detector. The quantum efficiency of the image sensor is a critical factor influencing imaging performance and achievable spatial resolution. The sensor exhibits high quantum efficiency in the wavelength range from approximately 400 nm to 550 nm, which matches well with the emission spectrum of the selected scintillator. In addition, the event-mode imaging detector demonstrates high sensitivity primarily within the 400 nm to 470 nm wavelength range. To quantitatively compare the optical coupling performance between each image sensor and the scintillator, a weighted detection efficiency was calculated by considering both the scintillator emission spectrum and the wavelength-dependent sensor quantum efficiency. The calculated results for the BCF-12 scintillator combined with each readout configuration are shown in Fig. 2. The CMOS configuration yields a weighted detection efficiency of approximately 82.6%, whereas the event-mode imaging detector shows an efficiency of about 30%.

(a)

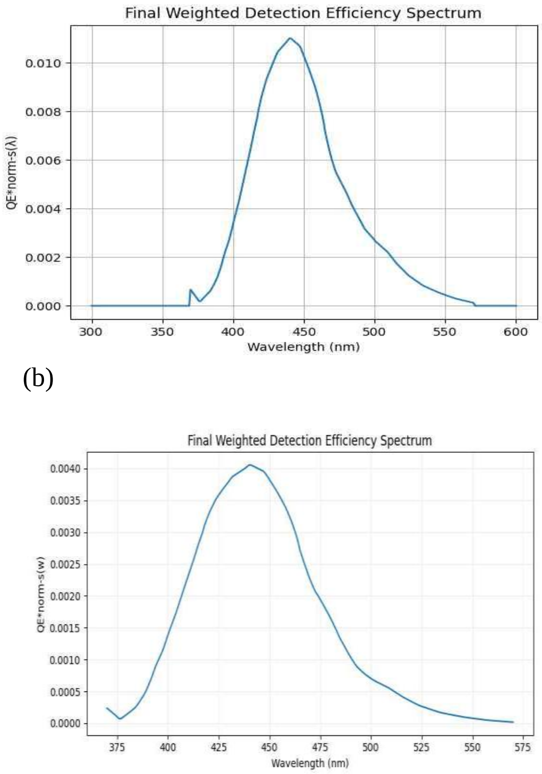

Fig. 2. (a) Weighted detection efficiency of the CMOS (b) Weighted detection efficiency of the event-mode imaging detector.

3. Conclusion and Outlook

This study presented the design concept, key components, and expected performance of an accelerator-based fast neutron imaging system. The proposed configuration focuses on optimizing the detector and optical subsystems to enable non-destructive evaluation of large and dense components of sample using fast neutrons. Future work will involve experimental validation through the implementation of the proposed scintillator screen and optical system. In addition, further investigations will be conducted to finalize system components that remain under consideration. Ultimately, once the full system configuration is established, prototype imaging experiments and performance verification will be carried out to demonstrate the proposed fast neutron imaging system.

ACKNOWLEDGEMENTS

This research was supported by the National Research Council of Science & Technology(NST) grant by the Korea government (MSIT) (No. GTL25031-410).

REFERENCES

[1] C.-H. Lee eat al., "Status of development and planning activities on CANS in Korea" Journal of Neutron Research, vol. 23, pp. 127 – 141, 2021.
[2] K. Lee et al., "Development and application of a 30 MeV cyclotron-based neutron source for neutron imaging and verification of D1S activation analysis system" Can. J. Phys, vol. 103, pp. 1213-1224, 2025.
[3] A. Wolfertz eat al., "Energy-resolved fast-neutron radiography using an event-mode neutron imaging detector" Scientific Reports, vol. 14, Art. no. 30487, 2024.