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Original article

Development of neutron time-of-flight measurement system for 1.7-MV tandem proton accelerator with lithium target

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A B S T R A C T

In this study, we developed a neutron time-of-flight (nTOF) measurement system for a 1.7-MV tandem proton accelerator with a target covered with 300-nm-thick lithium (Li) layer. With implementation of beam chopping module after its ion source, the accelerator is configured to operate in pulsed-beam mode with a pulse width <50 ns at 20-kHz repetition rate. This enables the gamma flash-type nTOF measurement system to identify the neutron generated with 3-MeV proton beam energy. The nTOF system consists of a 3″ cylindrical NaI(Tl) and four stilbene scintillation detectors. The NaI(Tl) scintillator is placed 50 cm from the Li target to measure the time of beam irradiation on the target, and the stilbene detectors are placed 2 and 2.4 m away to measure nTOF at each location. The nTOF system successfully measured the generated neutron energy at irradiated proton energies of 2.6 and 3.0 MeV with an average energy resolution of 15%.

1. Introduction

For decades, accelerator-driven neutron sources have been studied and incorporated into various facilities in several countries. The properties of such neutron sources have been thoroughly investigated; however, in various research fields, fast neutrons are still in high demand. Besides ultrafast neutrons above 20 MeV, which are extremely expensive to operate, few-MeV fast neutron sources with a tandem-type accelerator can be easily accessible alternatives for some applications, such as medical applications and radiation hardness tests [1,2]. In Korea multi-purpose accelerator complex (KOMAC), a 1.7-MV tandem accelerator was developed for applications in various scientific and engineering research works [3], including fast neutron sources with a 300-nm-thick Li layer target on thick Al substrates. Neutrons are generated through ^{7}Li (p,n)^{7}Be reaction at above 1912 keV, and the remaining energy of the proton beam is converted into the kinetic energy of the neutron [4]. Although the scientific properties of the process are well known, there is a need to identify the resulting neutron for reliable usage because unexpected uncertainties arising from the complexity of the system may affect the fidelity of the neutron source.

To characterize the neutron source, we developed a gamma flash-type neutron time-of-flight (nTOF) system. This paper presents the design and fabrication of an electronic beam chopping module and neutron detectors for the nTOF system. The initial experimental results of the identification of neutron energy for two proton energies are presented in this paper.

2. Experimental setup

2.1. 1.7-MV tandem accelerator

In KOMAC, a tandem accelerator moved from Korea Institute of Geoscience and Mineral Resources (KIGAM) is operated to serve various types of ion beam sources for scientific research and industrial applications [3]. The maximum voltage is 1.7 MV, which can accelerate various ions including proton, deuteron, helium, and other heavy ions. Although the accelerator can operate at 3.4-MeV proton energy with 10-μA beam current at maximum, the conventional operation usually employs 3.0-MeV protons at 3 μA in the continuous wave (CW) mode. A schematic diagram of the 1.7-MV tandem accelerator is shown in Fig. 1. Protons are generated at the right end and accelerated to 30 keV by an electrostatic

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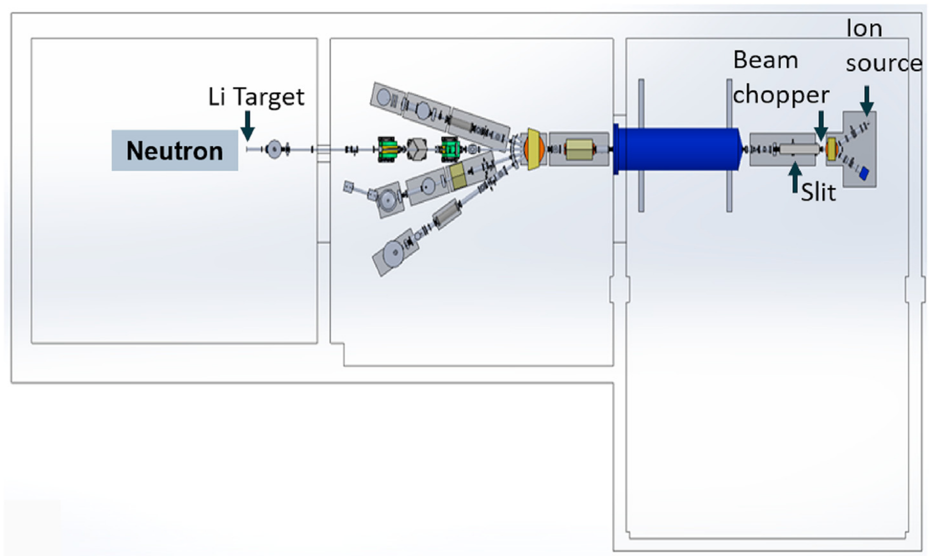

Fig. 1. Schematic diagram of a 1.7-MV tandem accelerator and location of beam chopper and Li target.

acceleration tube through an Einzel lens located behind the beam chopper. Then, the pulsed proton beam is transported to the left direction to hit the Li target, and neutrons are generated.

2.2. Electrical beam chopper

A gamma flash-type nTOF system requires a beam pulse that is sufficiently short compared with the time taken by generated neutrons to reach the detector. However, a tandem accelerator is innately a continuous beam generator; hence, a beam pulsing module is installed behind the Einzel lens for beam chopping using the electrical beam deflection method. Fig. 2 shows the schematic diagram of the electrical beam chopper. In the design, the distance between the deflection electrodes and the beam slit (Ls) is fixed at 2 m, and the applied voltage (V_d) and slit width (Y_m) are determined so that only the desired protons can pass through the slit. For 30 keV of incoming protons under 80-mm electrode length (L), approximately 7-mm deflection is achieved with a 200-V potential difference between the electrodes. Therefore, the slit opening (Y_m) is maintained at 4 mm to ensure that any proton passing through it at V2 is between 120 and 280 V. A square wave with 50-ns pulse width at a repetition rate of 20 kHz is generated by a high-speed switch so that when V2 approaches 200 V, the incoming proton, previously accelerated to 30 keV before the Einzel lens, is allowed to pass through at the moment.

The typical pulse waveform for the AC electrode, V2(t), is plotted in Fig. 3. The top plateau of the pulse is maintained at approximately 200 V for 50 ns, and the dashed horizontal lines indicate the slit opening through which protons are guided into the next stage. Therefore, the pulse plateau reaching the dashed line implies that the electrical slit is open; the proton beam is then injected into the tandem acceleration tube. Simultaneously, a trigger pulse is created with the start of the pulse and input to a digitizer with a 1.4-μs delay relative to the transport time for which protons are delivered to the Li target. The average proton beam current delivered to the target is 0.5 nA, which is very less than the current of 3 μA for

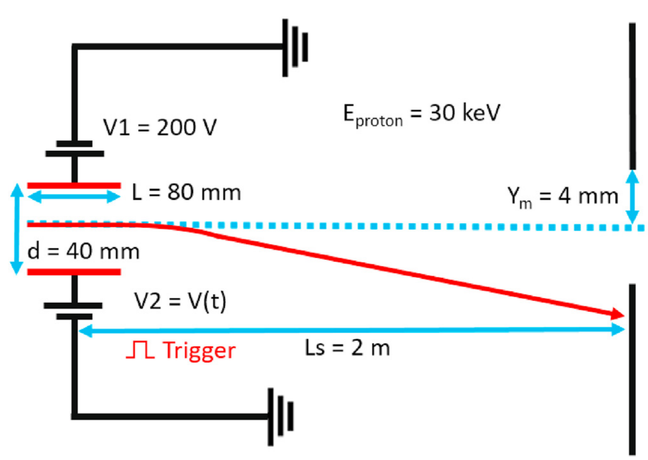

Fig. 2. Simplified diagram of the electrical beam chopper.

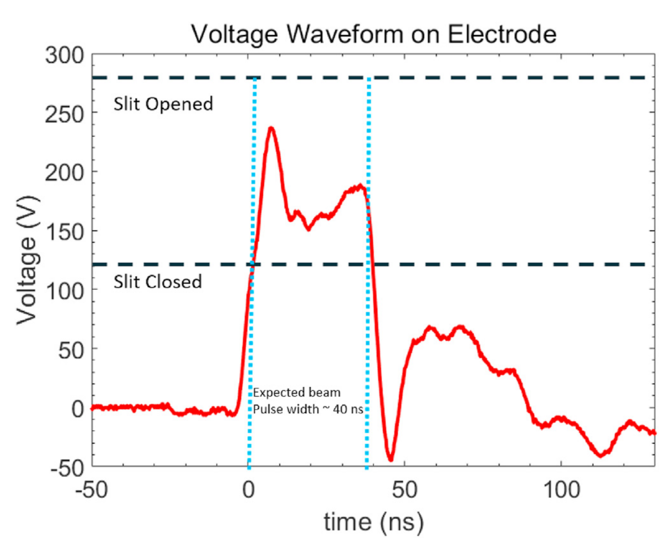

Fig. 3. Typical voltage waveform V2(t) on the AC electrode.

normal CW operations. Considering the shape of the voltage waveform, the width of the beam pulse passing through the chopper is approximately 40 ns, which enables nTOF measurements in the configuration at an energy broadening of 15%. This is discussed in section 3.

2.3. nTOF measurement setup

Five scintillation detectors are employed for the gamma flash-type nTOF measurement. A 3″ NaI(Tl) scintillation detector is used as the gamma-flash detector for the incident beam indicator when gamma radiation is produced by proton incident on the target. Four stilbene detectors are placed at two locations to cross-check the timing with reference to each other, to compare the flight times of neutrons with the same energy traveling different distances. Fig. 4 depicts the configuration of the nTOF measurement setup and a picture of the on-site measurement setup.

As shown in Fig. 4, the 3″ NaI(Tl) detector is placed at the closest possible distance to the Li target, and the four stilbene detectors, labeled A, B, C, and D, are placed in two positions: 2.4 m from the target at 25° to the vertical direction and 2 m from the target at 20° to the axis of the beam propagation. All detectors are connected via a 20-m BNC cable to a Caen dt5730 digitizer with a sampling rate of 500 MHz. The recording time between the channels is synchronized, and the maximum time difference is < 2 ns [5].

2.4. nTOF measurement method

The neutron time-of-flight is measured by subtracting the time at which a neutron reaches one of the stilbene detectors from the gamma-flash peak created by the collection of time coincidence between the triggered time and the first incoming signals in the pulse acquisition. The coincidence-time window is set to 1500 ns to safely include every possible energy at which a neutron can create a signal to the stilbene detectors. The expected time of arrival to neutron detectors from the Li target is approximately 180 ns at 1.1 MeV, which is equivalent to the proton energy of 3 MeV. The gamma incident time is demonstrated by the peak of the coincidence-time plot, as shown in Fig. 5. The proton incident time is determined by a time correction of the signal rise time of the NaI(Tl) scintillator and gamma flight time to the detector.

The stilbene scintillators detect neutrons by discriminating neutron and gamma signals via pulse shape discrimination (PSD) method. PSD values are determined by obtaining the pulse tail ratio to its total area, as expressed below [7]:

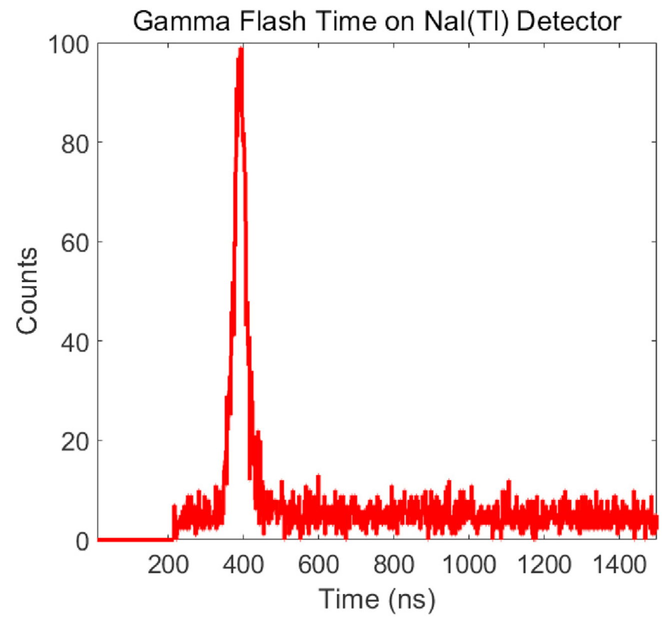

Fig. 5. Time coincidence plot of NaI(Tl) detector for gamma flash time identification.

$$\text{PSD Value} = \frac{\int_{pulsestart}^{longgate} Vdt - \int_{pulsestart}^{shortgate} Vdt}{\int_{pulsestart}^{longgate} Vdt} \quad (1)$$

In Eq. (1), the long and short gates are determined and adjusted with each detector so that incident neutrons are recorded on the PSD value range of 0.18–0.3. Fig. 6 shows a set of two-dimensional (2D) histograms acquired by each neutron detector with the proton beam energy of 2.6 MeV in CW mode. The regions created by neutrons and gamma rays are clearly separated; thus, any signals residing on the neutron PSD value regions are considered as neutron signals.

3. Results and discussion

The nTOF measurements were conducted at two proton incident energies: 2.6 and 3.0 MeV. According to the calculations, the measurement result must demonstrate an energy shift of 0.4 MeV for each acquisition near 0.7 and 1.1 MeV with a 13-keV broadening, considering the Li layer thickness [6]. Fig. 7(a) depicts the time

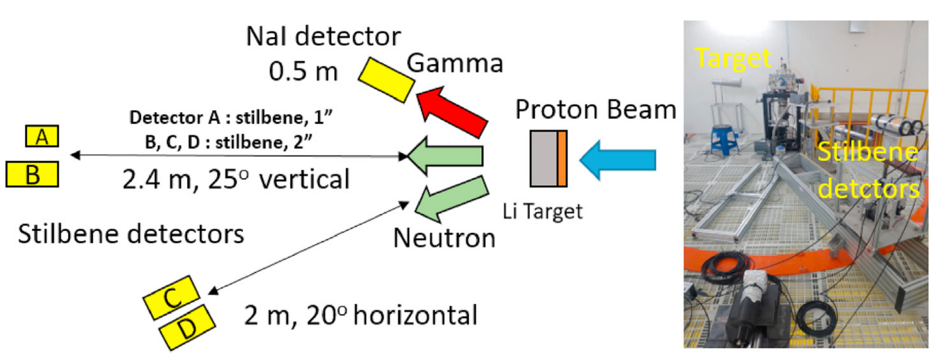

Fig. 4. Simplified configuration (left) and picture (right) of scintillation detector setup for nTOF measurement.

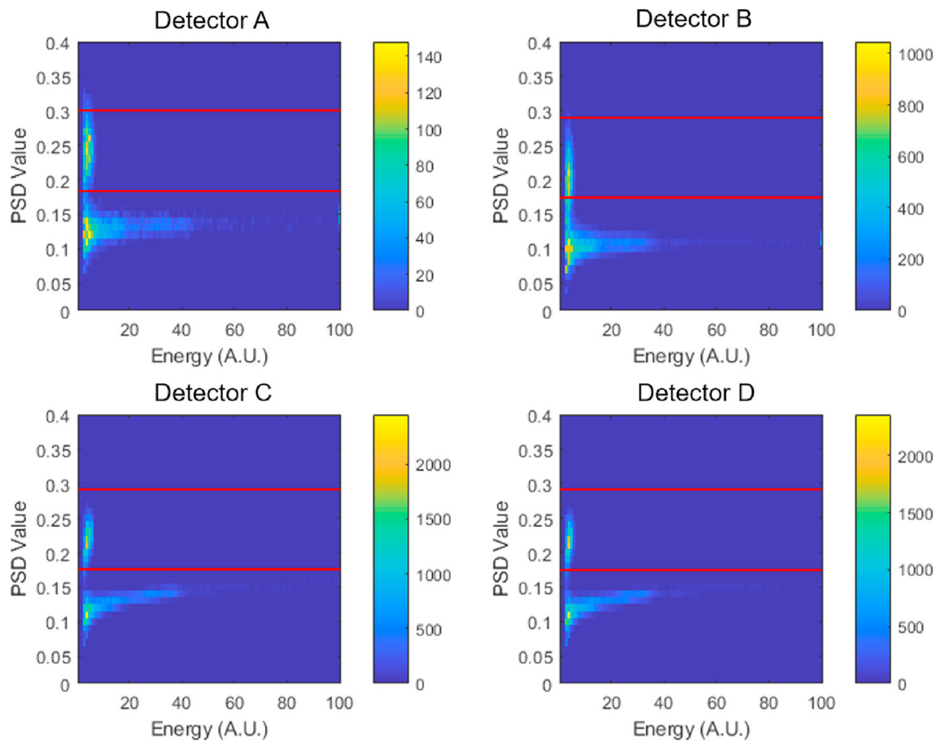

Fig. 6. 2D PSD histogram for stilbene detectors. Signals inside red lines are considered as neutrons. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

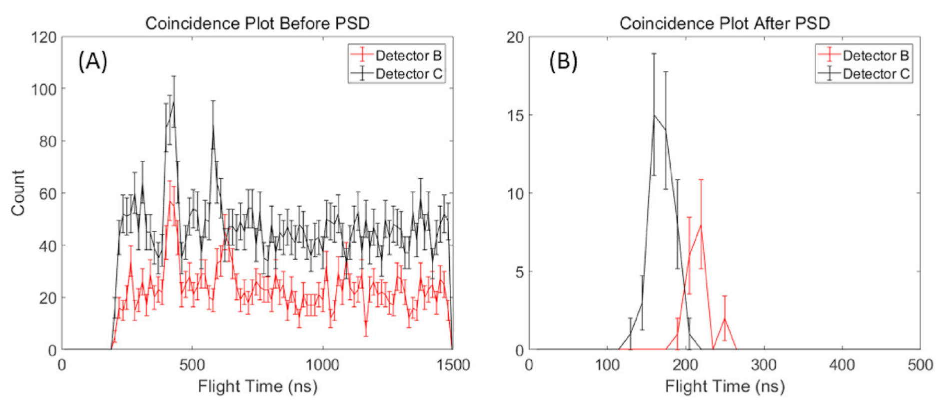

Fig. 7. Raw time coincidence plots with (a) both gamma and neutron and (b) neutron signals only for a 2.6-MeV proton beam. Detector B signal is acquired from the detector at 2.4 m away and detector C signal is acquired from the detector 2.0 m away.

coincidence plot for neutron detectors B and C without gamma–neutron separation by PSD, and Fig. 7 (b) depicts the signals with only neutrons. Neutrons are observed to reach the detector C at approximately 160 ns after its external trigger time. At the same time, a flight time difference is observed between the two locations of neutron detectors.

The neutron energy is obtained from the measured neutron flight time using the nonrelativistic kinetic energy equation, as plotted in Fig. 8. Dots with error bars represents the neutron energy measured by nTOF at the proton energies of 2.6 and 3.0 MeV. Resulting neutron energy from the protons are measured as 0.56 and 0.94 MeV. Vertical error bars represent statistical uncertainty of the value, and horizontal bars signifies possible energy shift due to uncertainty of neutron generation time due to the proton beam pulse width. For the 300-nm-thick Li target, a maximum of 13-keV broadening is expected in the neutron energy [6]. The nTOF system yields a 15% energy broadening at full width at half maximum (FWHM) and an average energy shift of 0.15 MeV. The energy shift from the measurement is assumed to be caused by an integrated time delay of the detector system. The time delays observed from the two measurement are obtained and applied to the system for the time correction.

4. Conclusion

In this study, we developed a gamma flash-type nTOF system to characterize neutron sources using a 1.7-MV tandem accelerator with a Li target. Initial experiments on the nTOF system with two

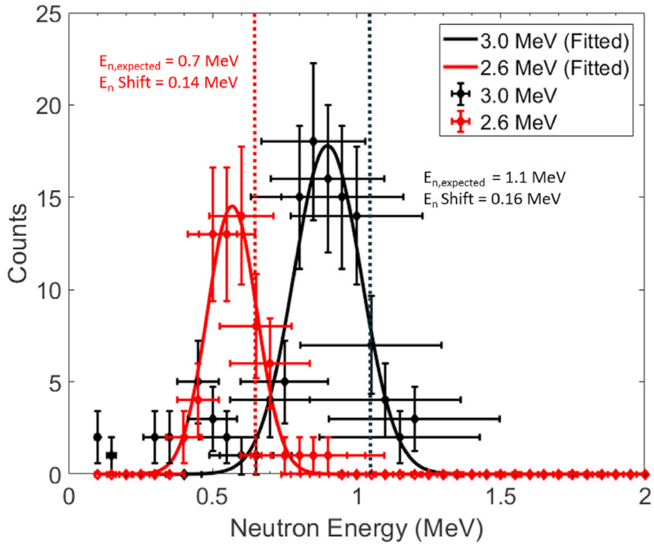

Fig. 8. Neutron energy acquired from nTOF measurements. Dots indicate raw data and solid lines represent their Gaussian-fitted result. Dashed lines indicate their expected neutron energy.

proton energies showed successful identification of neutron energy with an energy broadening of 15% at FWHM and an energy shift of 0.15 MeV. The energy resolution could be improved by upgrading the performance of the electric chopper such that it generates a sharp beam pulse <20 ns to achieve an energy broadening <10%. Moreover, statistical errors could be improved by increasing the repetition rate of the electric beam chopper and increasing the data acquisition time. In the future, the developed nTOF technique would be used in neutron energy measurements for higher-energy neutron sources in KOMAC [8].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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