

Real-time subcriticality monitoring system based on a highly sensitive optical fiber detector in an accelerator-driven system at the Kyoto University Critical Assembly

Watanabe, Kenichi

Department of Applied Energy, Graduate School of Engineering, Nagoya University

Yamanaka, Masao

Research Center for Safe Nuclear System, Institute for Integrated Radiation and Nuclear Science, Kyoto University

Endo, Tomohiro

Department of Applied Energy, Graduate School of Engineering, Nagoya University

Cheol Ho Pyeon

Research Center for Safe Nuclear System, Institute for Integrated Radiation and Nuclear Science, Kyoto University

<https://hdl.handle.net/2324/7168656>

出版情報 : Journal of Nuclear Science and Technology. 57 (2), pp.136-144, 2019-08-06. Taylor and Francis

バージョン :

権利関係 : This is an Accepted Manuscript of an article published by Taylor & Francis in Journal of Nuclear Science and Technology 06 Aug 2019 on , available online: "See DOI"



Article

Real-time subcriticality monitoring system based on a highly sensitive optical fiber detector in an accelerator-driven system at the Kyoto University Critical Assembly

Kenichi Watanabe^{a*}, Masao Yamanaka^b, Tomohiro Endo^a, Cheol Ho Pyeon^b

^a *Department of Applied Energy, Graduate School of Engineering, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan.*

^b *Research Center for Safe Nuclear System, Institute for Integrated Radiation and Nuclear
Science, Kyoto University, Asashiro-nishi, Kumatori-cho, Sennan-gun, Osaka 590-0494,
Japan.*

Abstract

A real-time subcriticality monitoring system for accelerator-driven system (ADS) is developed at the Kyoto University Critical Assembly (KUCA). The monitoring system consists of a highly sensitive optical fiber-based neutron detector, which combines a large number of small pieces of LiF/Eu:CaF₂ eutectic scintillators with a wavelength-shifting fiber, and a digital signal processing system. The fabricated detector is sufficiently small for insertion into slight gaps between the fuel assemblies of the KUCA core and clearly reveals a peak shape indicating neutron signals in the pulse height spectrum. As subcriticality determination procedures, the system employs the Rossi- α , α -fitting, and area ratio methods. The subcriticality experimental results and their related parameters are compared with numerical results. Although the area ratio method slightly underestimates the parameters, overall, the estimated parameters agree well with the calculated ones. Finally, the developed system is found to evaluate the subcriticality within an accuracy of approximately 20% for the effective neutron multiplication factor k_{eff} ranges between 0.97 and 0.93, which are used in typical ADS

*Corresponding author. Email: k-watanabe@energy.nagoya-u.ac.jp

1 experiments.

2

3 ***Keywords: real-time monitoring system; ADS; subcriticality; prompt neutron decay constant;***

4 ***KUCA; optical fiber detector;***

5

6

1. Introduction

The accelerator-driven system (ADS) was proposed as an energy amplifier and nuclear transmutation method for minor actinides and long-lived fission products [1-4]. Experimental ADS research is being conducted on these applications at the Kyoto University Critical Assembly (KUCA) [5-7]. The subcriticality ($-\rho$) is defined as

$$-\rho = \frac{1 - k_{eff}}{k_{eff}}, \quad (1)$$

where k_{eff} is the effective neutron multiplication factor, whose monitoring is required to determine the subcriticality within a specific margin. ADS experiments are conducted with effective neutron multiplication factors k_{eff} ranging from 0.97 to 0.93. A real-time subcriticality monitoring technique needs to be established to ensure the safety in ADS experiments. Additionally, even in fundamental experiments, the real-time subcriticality monitoring system is important to consider transient response of a reactor. Although ADSs are always operated under a subcritical condition, the subcriticality cannot be directly determined from the reactivity difference from the critical state ($k_{eff} = 1$) using methods such as the rod drop and negative period method.

Because ADS experiments are conducted by using a pulsed neutron source (PNS), the PNS method is suitable for the real-time subcriticality monitoring of ADS experiments [8]. Iwamoto et al. already demonstrated real-time subcriticality monitoring for ADS experiments, in which they used the PNS method [9]. However, multiple methods should be used to ensure the validity of the measurements. In this study, we demonstrated the simultaneous use of a reactor noise analysis-based method and the PNS method. As a subcriticality measurement algorithm based on reactor noise analysis, the Rossi- α method was applied to determine the subcriticality from information for a relatively short time period [10].

To determine the subcriticality by the PNS and/or the reactor noise method, the time-dependent neutron count data are required. To observe the time dependence, the neutron count

data are divided into multiple time bins and the measurement time is generally required to be relatively long. To minimize the statistical uncertainty of the short time period measurements, a highly sensitive detector is desired. In addition, because the correlation between neutron signals is strong in a fuel region, an in-core measurement is preferable for reactor noise analysis. Because the core region of the KUCA has little free space, only a small detector can be inserted into it without changing the reactor configuration. In this study, a novel small and highly sensitive optical fiber-based neutron detector was designed and fabricated and a high-speed digital signal processing system based on a field-programmable gate array (FPGA) was applied to measure the subcriticality in real time.

The objective of this study was to measure the subcriticality in ADS experiments in real-time using the fabricated detector and the digital signal processing system at the KUCA. The experimental results of the subcriticality obtained with the PNS and Rossi- α methods were compared, and the differences and applicable ranges of these methods were discussed.

2. Real-time monitoring system

2.1 Highly sensitive optical fiber detector

An optical fiber-based neutron detector small enough to be inserted into the KUCA core region was designed and fabricated, as shown in **Figure 1**. The neutron detection medium was a LiF/Eu:CaF₂ eutectic scintillator [11]. In this scintillator, the LiF phase works as a converter of neutrons into highly energetic charged particles, which are tritons and α particles, generated by ${}^6\text{Li}(n,t)\alpha$ reactions. The Eu:CaF₂ phase emits scintillation photons when it absorbs the energy of the charged particles. The two phases are alternated with a few-micrometers pitch. Because both phases have similar refractive indices, this eutectic scintillator is translucent. The neutron scintillator performs better when it is structured in small pieces with a few hundred micrometers size. The scintillation photons can easily escape from a small translucent

scintillator, which can therefore show peaks corresponding to neutron events in the pulse height spectrum. In addition, gamma rays can only generate small pulse height signals, because fast electrons generated by gamma rays have a relatively long range of millimeter order and can therefore easily escape out from the scintillator before full energy deposition. In previous works, optical fiber-based neutron detectors were developed using a piece of a small and transparent or translucent scintillator material [12-13]. These types of detectors show a clear neutron peak in the pulse height spectrum, which is advantageous when determining a discrimination level and/or detecting an error in the detector. Here, a small piece of the neutron scintillator has quite low sensitivity. Then, a number of small pieces of the scintillator have to be used to increase the sensitivity. To uniformly collect scintillation photons from a number of the small scintillators, a wavelength-shifting fiber (WLSF) was applied. A large number of small pieces of the scintillators were attached on the side surface of the WLSF (Kurary, Y-11) with a diameter of 0.5 mm, as shown in **Fig. 1**. The scintillators were attached to 150 mm of fiber, which formed the neutron sensitive region. A Teflon tape was wrapped around the scintillator region as a photon reflector. The WLSF was connected to a quartz optical fiber to transmit the scintillation photons to a photomultiplier tube (PMT, Hamamatsu, R9880U-210). To prevent ambient photons from entering the optical fiber, the outer surface of the quartz fiber was covered with a black shrinking tube and the scintillator probe region was covered with a thin aluminum tube. The outer diameter of the probe region was 2.5 mm, which allows the detector to insert into slight gaps between the fuel assemblies of the KUCA core described later.

The signal of the PMT was directly fed into a digital multichannel analyzer (MCA, ANSeeN, HSDMCA). Yagi *et al.* also developed a similar type of optical fiber-based detector using a neutron sensitive scintillator and a WLSF [14]. As the scintillator material, they used a mixed powder of LiF and Ag:ZnS, which had a white color. Because this scintillator is opaque, the effective thickness is limited. This limitation is mitigated with the use of the translucent

LiF/Eu:CaF₂ scintillator. Consequently, our detector has a relatively high sensitivity and can show a neutron peak in the pulse height spectrum.

<Figure 1>

Figure 2 shows the pulse height spectrum obtained from the fabricated optical fiber-based neutron detector. The detector was irradiated by neutrons from a ²⁵²Cf source surrounded by polyethylene reflectors. A clear peak caused by neutron detection events can be seen, from which a discrimination level for neutron detection can be easily determined. The fabricated detector can be inserted into a gap between the fuel assemblies of the KUCA core, and it has relatively high sensitivity and can show a clear peak component in the pulse height spectrum. From these results, the fabricated detector was considered to be ideal for the real-time subcriticality monitoring in ADS experiments at the KUCA.

<Figure 2>

2.2 High-speed digital signal processing system

In addition to the detector, a signal processing system was developed for the real-time subcriticality monitoring. **Figure 3** shows the real-time subcriticality monitoring system. A digital MCA (ANSeeN, HSDMCA) was selected as the signal processing module. In the first stage of this module, a current pulse signal from the PMT is converted into a voltage pulse through an RC integrator. This analog signal is digitized by an analog-to-digital converter (ADC), and the digitalized data are processed in the FPGA. The FPGA processes the PMT signals digitally and extracts information on the pulse height, pulse rise time, and detection timing. The pulse height and rise time can be used for discrimination between neutron and gamma-ray events. The WLSF can also generate signals by reactions with gamma rays. However, these signals have a faster decay time (a few nanoseconds) than those of the LiF/Eu:CaF₂ (a few hundreds of nanoseconds). Because this digital MCA has an integrator in

the first stage, the difference in scintillator decay time can be distinguished as a difference in the signal rise time. This system allows the pulse shape discrimination to reject signals generated by reaction with gamma rays in the WLSF based on the rise time.

The extracted and selected information, such as the pulse height, rise time, and detection timing, was transferred to the control PC. This information was recorded every second into the PC as list-mode files. The neutron detection timing distribution was applied using an analysis software to determine the subcriticality and related parameters, and the estimated parameters were displayed in real time by the software.

<Figure 3>

3. Experimental settings

3.1 Core configuration

The ADS experiments were conducted in the solid-moderated and -reflected core (A-core) at KUCA. **Figure 4** shows the top view of core configurations in the ADS experiments carried out in this study. The fuel assemblies were composed of 60 fuel unit cells, each consisting of 1/8 inch-thick fuel and 1/8 inch-thick polyethylene regions with 2×2 inch squares. Each fuel region was composed of two 1/16 inch-thick highly enriched uranium-aluminum alloy (HEU) plates. The total number of 1/16 inch HEU plates was employed for definition of the core configurations, i.e. EE1-2760, in **Fig. 4**. The subcriticality was varied by changing the total number of HEU plates and inserting control rods, which were located at position shown in **Fig. 4**. The subcriticality and the related parameters of these core configurations were calculated by the Monte-Carlo simulation code MCNP6.1 [15] with JENDL-4.0 [16]. The calculation method was well validated in the previous work [17]. The results of the simulation are listed in **Table 1**. In this calculation, the total histories, histories per cycle, and skip cycle were 5×10^8 , 10^5 , and 300, respectively. The effective neutron multiplication factor k_{eff} ranged from 0.91 to 0.98. An

FFAG proton accelerator-based source was employed as a pulsed neutron source and spallation neutrons were generated by bombarding a Pb-Bi target with 100-MeV protons from the FFAG accelerator. The pulsed source was operated with a repetition rate of 30 Hz and a proton beam current ranging from 50 to 850 pA. The optical fiber-based neutron detector was placed at the center of the core region, as shown in **Fig. 4**. Because the detector was surrounded by the fuel and was placed far from the target, it mainly responded to fission-related neutrons in the core.

<Figure 4>

<Table 1>

3.2 Subcriticality determination procedures

The subcriticality ($-\rho$) is defined as the reactivity difference from the critical state. Because methods that directly determine the reactivity difference from the critical state, such as the rod drop and the negative period methods, cannot be applied, the PNS method and the reactor noise analysis-based method were applied in the developed system.

When an ADS experiment is conducted using a pulsed neutron source, the PNS method is considered to be suitable. In subcritical states, the neutron flux decreases just after the end of pulsed period of neutron injection. The subcriticality can be determined from the time evolution of the flux. When the reactor is operated, prompt and delayed neutrons are generated in the reactor core. The prompt neutrons decrease exponentially when the reactor is in a subcritical state. However, because the lifetime of the delayed neutrons is much longer than a pulse cycle, the generation and disappearance of delayed neutrons reach equilibrium. Then, the delayed neutrons appear to be constant in pulse operation. Consequently, the time evaluation of the neutron flux is given as

$$n(t) = C \exp(-\alpha t) + B \quad , \quad (2)$$

where α is the prompt neutron decay constant, and B and C are constants. **Figure 5** shows an example of a detection timing profile from neutron pulse trigger signals. Using the point kinetic model, the prompt neutron decay constant α can be obtained as follows:

$$\alpha = \frac{\beta_{eff}}{\Lambda} \left(\frac{(-\rho)}{\beta_{eff}} + 1 \right) , \quad (3)$$

where β_{eff} is the effective delayed neutron fraction, and Λ is the neutron generation time. α can be determined by fitting this function to the measured data. For this non-linear least-squares fitting, the Levenberg–Marquardt algorithm was applied [18]. To eliminate higher harmonics from the prompt component, data points of a few percent from pulsed neutron injection were not used for the fitting process. As a result, the subcriticality can be derived using the β_{eff} and Λ , which are determined by the reactor simulation analysis using MCNP6.1. This method is referred to as the α -fitting method [19].

<Figure 5>

In the PNS experiments, the area ratio method can also be applied to determine the subcriticality experimentally [20]. If the pulsed neutron intensity is S , the number of prompt neutrons A_p and delayed neutrons A_d are calculated as follows:

$$A_p = \frac{S}{1 - (1 - \beta_{eff})k_{eff}} , \quad (4)$$

$$A_p + A_d = \frac{S}{1 - k_{eff}} . \quad (5)$$

The area ratio between the prompt and delayed neutrons is finally given as

$$\frac{A_p}{A_d} = \frac{1 - k}{\beta_{eff}k} = \frac{(-\rho)}{\beta_{eff}} = \$, \quad (6)$$

where $\$$ is the subcriticality in dollar units.

The reactor noise analysis-based methods can also be used to determine the subcriticality in ADS experiments. As a reactor noise analysis-based method, the Rossi- α method was applied

in this study because it can determine the prompt neutron decay constant α from information for a relatively short time period. In this method, a histogram of detection time intervals between two arbitrary events is created, as shown in **Fig. 6**. Using the one-point reactor approximation model and neglecting the thermal neutron contribution [10], the probability of two neutron events occurring within the time interval t_{int} is

$$P(t_{int})dt_{int} = (A\exp(-\alpha t_{int}) + B)dt_{int} \quad (7).$$

The first term is related to the correlation between the prompt neutrons, and decreases exponentially. The second term is related to the non-correlation component. In this study, two events occurring across the injection of the external neutron source were not considered. Then, the probability occurring events with large time intervals decreases. We can determine the prompt neutron decay constant α by fitting this function to the measured data.

The histograms shown in Figs. 5 and 6 were created at every time step. Although the time step can be selected arbitrarily, in this study, we applied steps of 1, 2, and 5 s, which define the time resolution of our subcriticality monitoring system.

<Figure 6>

4. Results and discussion

4.1 Real-time monitoring

Figure 7 shows an example of the trends of the measured neutron counts, estimated prompt neutron decay constant α , and subcriticality in dollar units $\$$ with time. The discrimination level of neutron events was set to approximately the value of the peak channel in the pulse height spectrum. This time trend was obtained from the EE1-2760 core with a time step of 1 s. When starting up the reactor, all the control rods were pulled up. Then, some rods were inserted individually shown in Fig. 7. Finally, the center core unit was fallen down and the proton beam was shut down. When inserting a control rod, the subcriticality variation can be observed clearly

in the prompt neutron decay constant α and the subcriticality in dollar units. The fabricated system responded even after falling down the center core unit. Although the area ratio method slightly underestimates the $(-\rho)/\beta_{eff}$ values, overall, the estimated parameters agree well with the calculated ones. In Fig. 7, the proton beam accidentally tripped shortly after approximately 600 s. However, α was estimated accurately immediately after beam recovery, although the beam intensity was not fully recovered. On the other hand, the area ratio method showed a typical transient response. In this case, it was overestimated because the delayed neutrons had not reached the equilibrium condition. Even after the center core was fallen down and

<Figure 7>

4.2 Uncertainty and accuracy of the measurements

The uncertainty of the estimated subcriticality and kinetic parameters is considered to depend on the statistical fluctuation of the histogram of the detection timing profile or the detection time intervals. Thus, the uncertainty is expected to depend directly on the neutron counts recorded in the time step, which is the product of the neutron count rate and the time step width. **Figure 8** shows the relation between the relative standard deviation of the estimated parameters and the neutron count at each time step. Generally, the standard deviation decreases with increasing neutron counts. The subcriticality in dollar units determined by the area ratio method had a larger standard deviation than the prompt neutron decay constant α . When more than 1,000 neutrons were accumulated, the uncertainties on α and $\$$ were less than 5 and 10%, respectively.

The accuracy of the determined parameters is also very important. As an index of accuracy, we evaluated the ratios of the experimentally estimated parameters to the calculated ones E/C. **Figure 9** shows the relation between the E/C and the neutron count rate. Overall, the experimental values were underestimated. In particular, the α values determined by the Rossi-

α and the area ratio decrease in the high-count-rate region. These parameters were severely influenced by the effect of the counting loss.

4.3 Subcriticality

The subcriticality $(-\rho)$ can be determined from the experimentally determined α value and calculated β_{eff} and Λ , whose calculated values are listed in **Table 1**, by using equation (3). The $(-\rho)$ can also be determined from the experimentally determined β value and calculated β_{eff} by using equation (6). **Figure 10** shows the relation between the calculated subcriticality $(-\rho)_{cal}$ and the experimentally determined one $(-\rho)_{exp}$, as well as the plot of E/C. As shown in the figure, the experimentally determined values were underestimated. This tendency is considered to be partially caused by background counts. If there is a constant background component in the histogram of the detection timing profile, the the area ratio of the prompt to the delayed neutrons could be estimated to be lower. In deep subcritical states or large α value situation, the prompt neutron component rapidly decreases. This means that the exponential slope is determined only by the first small number of data points, in which the counting loss effect is often severe. Consequently, the exponential slope might be estimated to be lower.

It is possible that the optical fiber-based detector counts the beta particles from the surface of the fuel assembly, because the aluminum detector cover is too thin to shield against the beta particles. The fuel assembly's sheath was made of aluminum (Al), which often contains manganese (Mn) as an impurity. Activated Al-28 ($T_{1/2}$: 2.2 m) and Mn-56 ($T_{1/2}$: 2.6 h) could be sources of beta particles. Because the background contribution becomes high at a deep subcritical state, the experimentally determined subcriticality is underestimated. Because beta particles induce smaller pulse height signals than neutron events, contribution of beta particles can be suppressed by increasing the discrimination level. **Figure 11** shows the relation between the calculated and experimentally determined subcriticality, when increasing the discrimination level by 40% compared with **Fig. 10**. The E/C was improved by eliminating the background

counts. Of course, the detection efficiency and the detected neutron counts decrease with increasing discrimination level. The discrimination level should be set considering the balance between the detection efficiency and discrimination ability of beta- and gamma-ray events, because a sufficient neutron count is required to obtain good statistics of the histograms. However, we can adjust these performances independently from each other. For example, the detector sensitivity can be adjusted by controlling the length or volume of the scintillator region. Moreover, the beta- and gamma-ray discrimination ability can be improved by controlling the size of the small scintillator pieces. In addition, dead time effects can be important in the reactor noise analysis. Some dead time correction methods were proposed [21]. These methods might improve reliability of the estimated subcriticality.

4.4 Discussion

In this section, we discuss the minimum required time step, the suitable count rate, and the measurable range of the subcriticality of our monitoring system. The minimum required time step should be determined from the viewpoint of the uncertainty of the estimated parameters. In the measurements with 1-s time steps, a count rate of at least 1 kcps was obtained with a proton current of 50 pA. In this condition, the uncertainty of the estimated parameters was less than 5% for the α -fitting method and the Rossi- α method and less than 10% for the area ratio method. Therefore, if an uncertainty of 10% is acceptable, a time step of 1 s can be selected.

From the viewpoint of the count rate, the counting loss effect should be considered. From the results in **Fig. 9**, because the E/C of the estimated parameters systematically decreased at the count rate of more than 20 kcps, the count rate should be maintained at less than 20 kcps, by adjusting the sensitive length or volume of the detector. Although the area ratio method occasionally shows severely low values, the E/C of the subcriticality shown in **Fig. 10** indicates that the estimated subcriticality is consistent with the calculation results within an accuracy of approximately 20% for an effective neutron multiplication factor k_{eff} between 0.97 and 0.93,

corresponding to a subcriticality ($-\rho$) between 0.03 and 0.075. As shown in **Fig. 11**, if the background count can be reduced, the E/C can be improved. Consequently, the monitoring system was concluded to have a subcriticality accuracy of approximately 20% for a typical operating mode of ADS experiments, in which the effective neutron multiplication factor k_{eff} ranges between 0.97 and 0.93.

5. Conclusion

A real-time subcriticality monitoring system consisting of an optical fiber-based neutron detector and a digital signal processing system was developed. The highly sensitive optical fiber-based neutron detector combines a large number of small pieces of LiF/Eu:CaF₂ eutectic scintillators and a WLSF. The data acquisition system was based on a digital signal processing system. The real-time monitoring system implemented three different subcriticality determination methods, namely the Rossi- α method, and α -fitting and area ratio methods based on the PNS method.

The measuring range of the monitoring system was experimentally evaluated. With 1-s time step measurements the uncertainties of the estimated parameters were less than 5% for the α -fitting and Rossi- α methods and less than 10% for the area ratio method. The E/C of the subcriticality was consistent with the calculation results within an accuracy of approximately 20% for an effective neutron multiplication factor k_{eff} from 0.97 to 0.93, which corresponds to the typical operating mode of ADS experiments.

By installing the proposed subcriticality monitor into experimental critical assemblies such as the KUCA, we can obtain transient information on subcriticality. This information is expected to be valuable for fundamental ADS researches.

1 In future works, the detector sensitivity needs to be adjusted to a suitable level to match the
2 count rate. In addition, background counts in the detector, which distort the subcriticality-
3 related parameters, should be reduced by optimizing the size of the small pieces of scintillator.

6 **Acknowledgments**

7 The authors are grateful to all the staff at KUCA and to the FFAG accelerator group for
8 their assistance during the experiments.

References

1. Carminati F, Klapisch R, Revol JP, et al. An energy amplifier for cleaner and inexhaustible nuclear energy production driven by a particle beam accelerator. CERN; 1993. (CERN/AT/93-47).
2. Rubbia C. A high gain energy amplifier operated with fast neutrons. AIP conference proceedings. 1995; 346: 44–53.
3. Accelerator driven systems: Energy generation and transmutation of nuclear waste; Status report. International Atomic Energy Agency; 1997. (IAEA-TECDOC–0985).
4. Bowman CD. Accelerator-driven systems for nuclear waste transmutation. Annu. Rev. Nucl. Part. Sci. 1998; 48: 505–56.
5. Pyeon CH, Misawa T, Lim JY, et al. First injection of spallation neutrons generated by high-energy protons into the Kyoto University Critical Assembly. J. Nucl. Sci. Technol. 2009; 46: 1091–1093.
6. Pyeon CH, Yamanaka M, Kim SH, et al. Benchmarks of sub-criticality in accelerator-driven system at Kyoto University Critical Assembly. Nucl. Eng. Technol. 2017; 49: 1234–1239.
7. Pyeon CH, Vu TM, Yamanaka M, et al. Reaction rate analyses of accelerator-driven system experiments with 100 MeV protons at Kyoto University Critical Assembly. J. Nucl. Sci. Technol. 2018; 55: 190–198.
8. Kosaly G, Fischer A. On integral-versions of the area-ratio method of pulsed neutron reactivity measurements. J. Nucl. Energy. 1972; 26: 17–26.
9. Iwamoto H, Nishihara K, Yagi T, et al. On-line subcriticality measurement using a pulsed spallation neutron source. J. Nucl. Sci. Technol. 2017; 54: 432–443.
10. Orndoff JD. Prompt neutron period of metal critical assemblies, Nucl. Sci. Eng. 1957; 2: 450–460.
11. Kawano N, Kawaguchi N, Fukuda K, et al. Scintillation and dosimeter properties of

- ⁶LiF/CaF₂:Eu eutectic composites. J. Mater. Sci. Mater. Electron. 2018; 29: 8964–8969.
12. Watanabe K, Kawabata Y, Yamazaki A, et al. Development of an optical fiber type detector using a Eu:LiCaAlF₆ scintillator for neutron monitoring in boron neutron capture therapy. Nucl. Instrum. Methods Phys. Res. Sec. A 2015; 802: 1–4.
13. Ishikawa A, Yamazaki A, Watanabe K, et al. Sensitivity and linearity of optical fiber-based neutron detectors using small ⁶Li-based scintillators. Nucl. Instrum. Methods Phys. Res. Sec. A. 2019; in press: <https://doi.org/10.1016/j.nima.2018.11.120>
14. Yagi T, Misawa T, Pyeon CH, et al. A small high sensitivity neutron detector using a wavelength shifting fiber. Appl. Radiat. Isotopes. 2011; 69: 176–179.
15. Goorley JT, James MR, Booth TE, et al. Initial MCNP6 release overview-MCNP6 version 1.0. Los Alamos National Laboratory; 2013. (LA-UR-13-22934).
16. Shibata K, Iwamoto O, Nakagawa T, et al. JENDL-4.0: A new library for nuclear science and technology. J. Nucl. Sci. Technol. 2011; 48: 1–30.
17. Yamanaka M, Pyeon CH, Misawa T. Monte Carlo Approach of Effective Delayed Neutron Fraction by k-Ratio Method with External Neutron Source. Nucl. Sci. Eng. 2016; 184: 551-560.
18. Galassi M, Davies J, Theiler J, et al. GNU Scientific Library Reference Manual (3rd Ed.). ISBN 0954612078.
19. Simmons BE, King JS. A pulsed neutron technique for reactivity determination. Nucl. Sci. Eng. 1958; 3(5): 595–608.
20. Sjöstrand NG. Measurements on a subcritical reactor using a pulsed neutron source. Arkiv för Fysik. 1956; 11: 233–246.
21. Gilad E, Dubi C, Geslot B, et al. Dead time corrections using the backward extrapolation method. Nucl. Instrum. Methods Phys. Res. Sec. A 2017; 854: 53-60.

1 **Table Captions**

2

3 **Table 1** Results of the effective neutron multiplication factor k_{eff} , effective delayed
4 neutron ratio β_{eff} , neutron generation time Λ , prompt neutron decay constant α ,
5 and subcriticality ($-\rho$) obtained by a Monte-Carlo simulation. The values of α
6 were derived from Eq. (3) using β_{eff} and Λ .

7

Table 1 Results of the effective neutron multiplication factor k_{eff} , effective delayed neutron ratio β_{eff} , neutron generation time Λ , prompt neutron decay constant α , and subcriticality ($-\rho$) obtained by a Monte-Carlo simulation. The values of α were derived from Eq. (3) using β_{eff} and Λ .

Core	Inserted rod pattern	k_{eff}	β_{eff}	Λ (μ s)	α (1/s)	$-\rho/\beta_{eff}$ (\$)	$(-\rho) (\Delta k/k)$
EE1-2760	-	0.98400 $\pm$ 0.00004	0.0080 $\pm$ 0.0001	32.10 $\pm$ 0.08	710.27	1.8391	1.477 $\times 10^{-2}$
	C1	0.97527 $\pm$ 0.00004			993.69	2.9720	2.386 $\times 10^{-2}$
	C1, C2	0.97263 $\pm$ 0.00004			1080.4	3.3186	2.665 $\times 10^{-2}$
	C1, C2, C3	0.97104 $\pm$ 0.00004			1132.8	3.5282	2.833 $\times 10^{-2}$
EE1-2520	-	0.96876 $\pm$ 0.00004	0.0083 $\pm$ 0.0001	33.08 $\pm$ 0.08	1180.5	3.7054	3.076 $\times 10^{-2}$
	C1	0.96136 $\pm$ 0.00004			1420.7	4.6628	3.870 $\times 10^{-2}$
	C1, C2	0.95850 $\pm$ 0.00004			1514.5	5.0367	4.180 $\times 10^{-2}$
	C1, C2, C3	0.95812 $\pm$ 0.00004			1527.0	5.0866	4.222 $\times 10^{-2}$
EE1-2280	-	0.94715 $\pm$ 0.00004	0.0083 $\pm$ 0.0001	35.30 $\pm$ 0.08	1772.8	6.5667	5.431 $\times 10^{-2}$
	C1	0.93988 $\pm$ 0.00004			2004.2	7.5542	6.247 $\times 10^{-2}$
	C1, C2	0.93880 $\pm$ 0.00004			2038.9	7.7022	6.370 $\times 10^{-2}$
	C1, C2, C3	0.93833 $\pm$ 0.00004			2054.0	7.7667	6.423 $\times 10^{-2}$
EE1-2040	-	0.91747 $\pm$ 0.00004	0.0083 $\pm$ 0.0001	38.53 $\pm$ 0.09	2511.1	10.658	8.846 $\times 10^{-2}$
	C1	0.91184 $\pm$ 0.00004			2685.7	11.469	9.519 $\times 10^{-2}$
	C1, C2, C3	0.91074 $\pm$ 0.00004			2720.1	11.628	9.652 $\times 10^{-2}$

Figure Captions

- Figure 1** The fabricated optical fiber-based neutron detector. a) Photograph of the wavelength-shifting fiber (WLSF) coated with small pieces of LiF/Eu:CaF₂ eutectics scintillators. b) Photograph of the fiber wrapped with reflective Teflon tape. c) Detailed configuration of the detector probe region.
- Figure 2** Pulse height spectrum obtained from the fabricated optical fiber-based neutron detector. The detector was irradiated with neutrons from a ²⁵²Cf source surrounded by polyethylene bricks.
- Figure 3** Real-time subcriticality monitoring system.
- Figure 4** Top view of the core configuration in the ADS experiments. The experiments were conducted at the A-core of the KUCA. A pulsed neutron source, in which a Pb-Bi target was bombarded with 100-MeV protons from the FFGA accelerator, was applied.
- Figure 5** An example of a detection timing profile from neutron pulse trigger signals. In this case, the repetition rate of the neutron pulses was 30 Hz and the data acquisition time was 1 s. The fitted curve is also plotted.
- Figure 6** An example of a histogram of detection time intervals between two arbitrary events. In this case, two events occurring across the pulsed neutron were not considered. The data acquisition time was 1 s. The fitted curve is also plotted.
- Figure 7** Neutron detector count, prompt neutron decay constant α , and area ratio $\$$ as a function of time. The core type was EE1-2760. The proton current from the FFAG was 60 pA and the time step width was 1 s. Calculation results are also plotted as dashed lines. Calculation uncertainty is quite small compared with the dashed line width.
- Figure 8** Relation between the relative standard deviation of the estimated parameters and

the neutron counts in each time step. The parameters α and β were determined with time steps of 1, 2, and 5 s.

Figure 9 Relation between the ratios of the experimentally estimated parameters to the calculated values, E/C, and the neutron count rate.

Figure 10 Relation between the experimentally determined subcriticality $(-\rho)_{\text{exp}}$ (top) and E/C (bottom) and the experimentally calculated subcriticality $(-\rho)_{\text{cal}}$. The discrimination level was set as the peak channel in the pulse height spectrum and the time step was 5 s.

Figure 11 Relation between the experimentally determined subcriticality $(-\rho)_{\text{exp}}$ (top) and E/C (bottom) and the experimentally calculated subcriticality $(-\rho)_{\text{cal}}$ with discrimination level 40% higher than the neutron peak. The time step was 1 s.

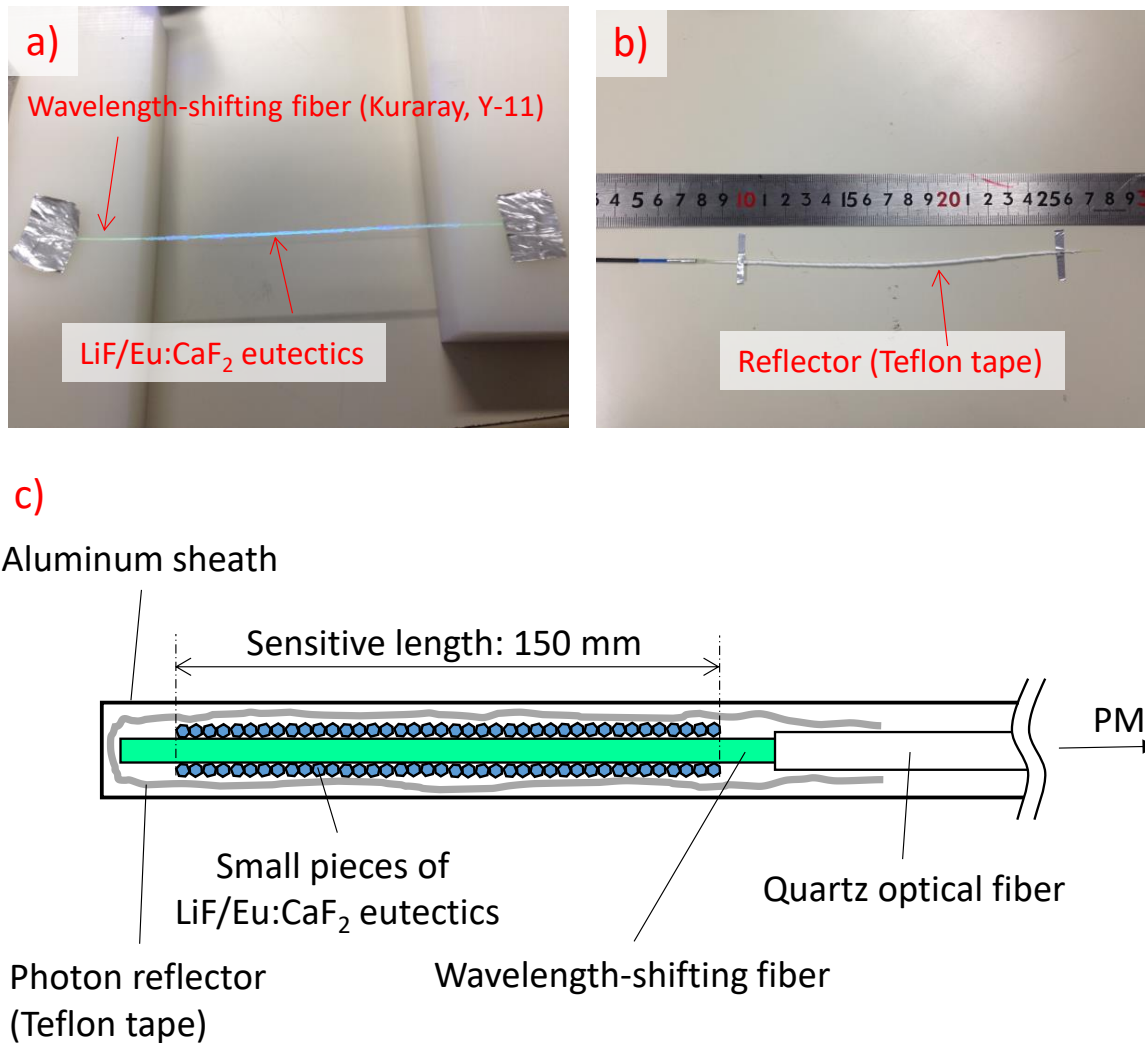
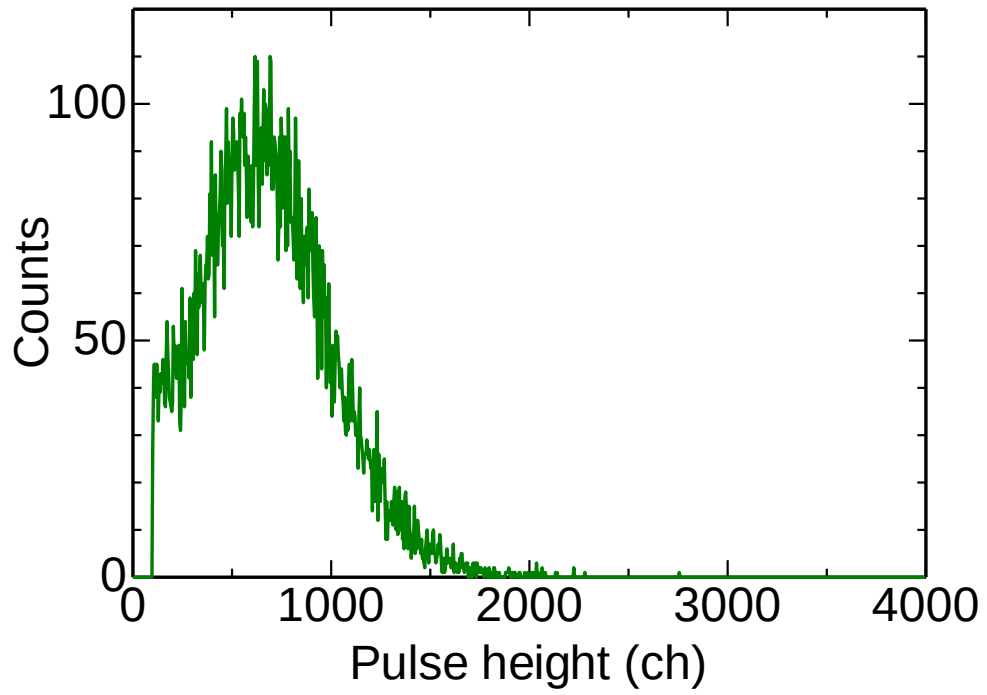


Figure 1 The fabricated optical fiber-based neutron detector. a) Photograph of the wavelength-shifting fiber (WLSF) coated with small pieces of LiF/Eu:CaF₂ eutectics scintillators. b) Photograph of the fiber wrapped with reflective Teflon tape. c) Detailed configuration of the detector probe region.

1



2

3

4 **Figure 2** Pulse height spectrum obtained from the fabricated optical fiber-based neutron
5 detector. The detector was irradiated with neutrons from a ^{252}Cf source
6 surrounded by polyethylene bricks.

7

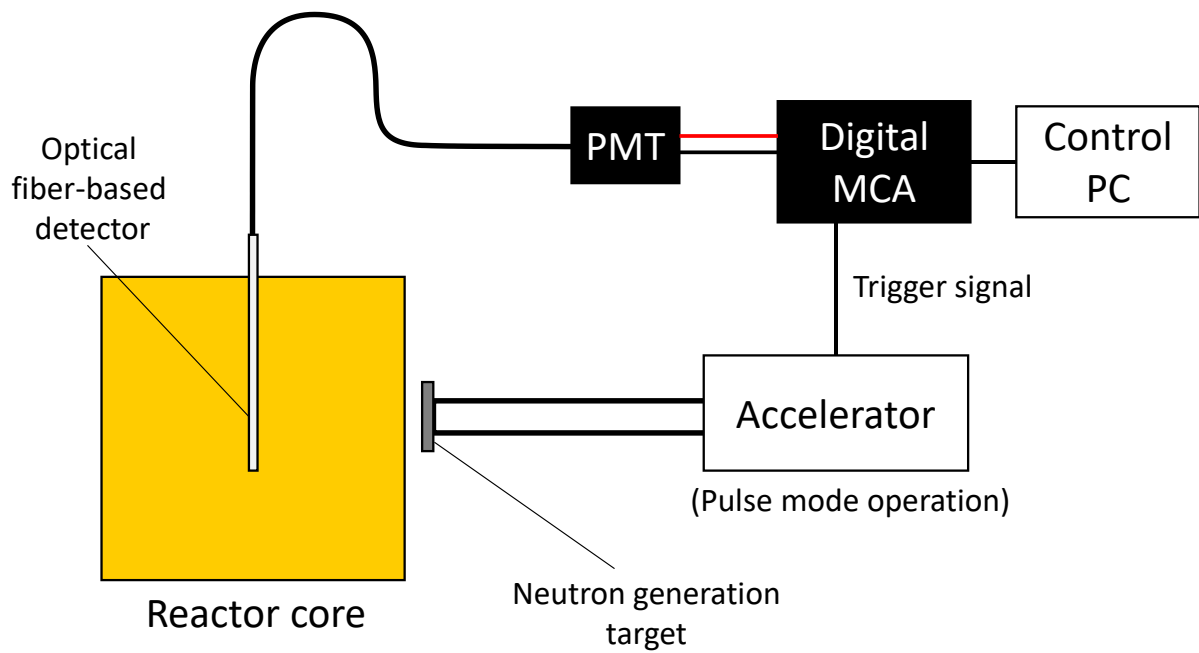
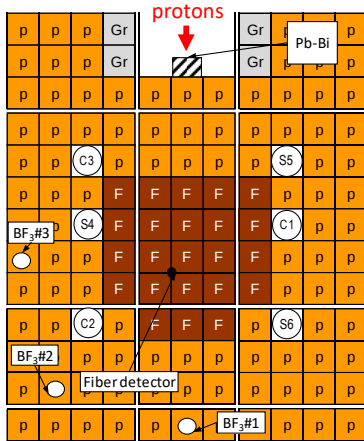
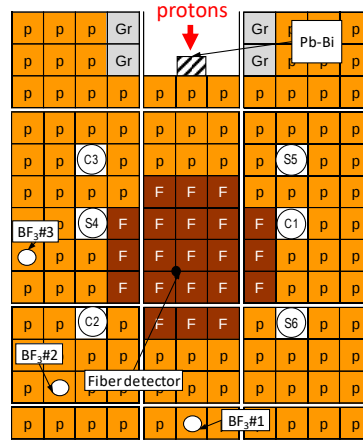


Figure 3 Real-time subcriticality monitoring system.

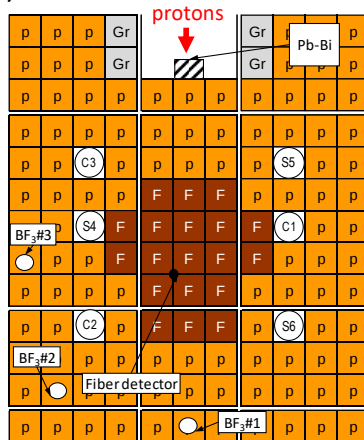
a) EE1-2760



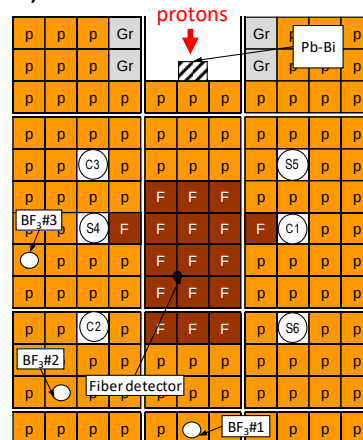
b) EE1-2520



c) EE1-2280



d) EE1-2040



- Normal fuel (1/8"p60EUEU)
- Polyethylene moderator
- Control rod
- Safety rod

Figure 4 Top view of the core configuration in the ADS experiments. The experiments were conducted at the A-core of the KUCA. A pulsed neutron source, in which a Pb-Bi target was bombarded with 100-MeV protons from the FFGA accelerator, was applied.

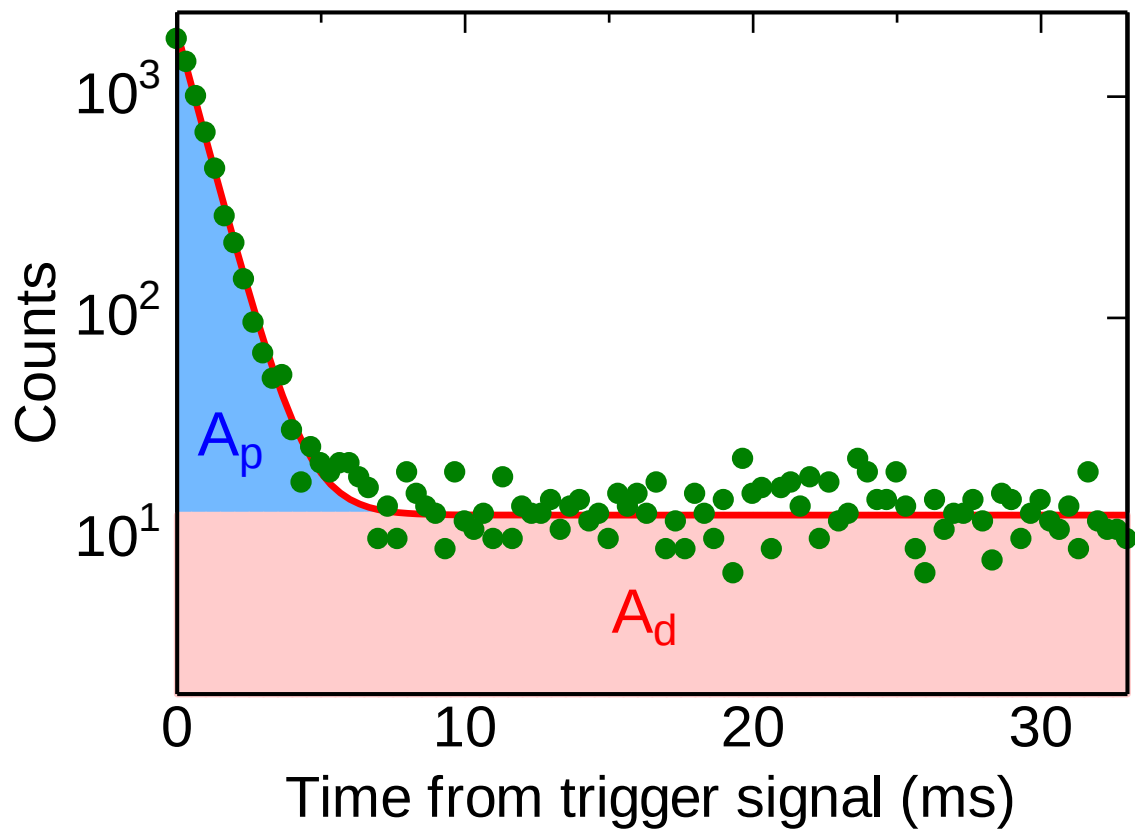


Figure 5 An example of a detection timing profile from neutron pulse trigger signals. In this case, the repetition rate of the neutron pulses was 30 Hz and the data acquisition time was 1 s. The fitted curve is also plotted.

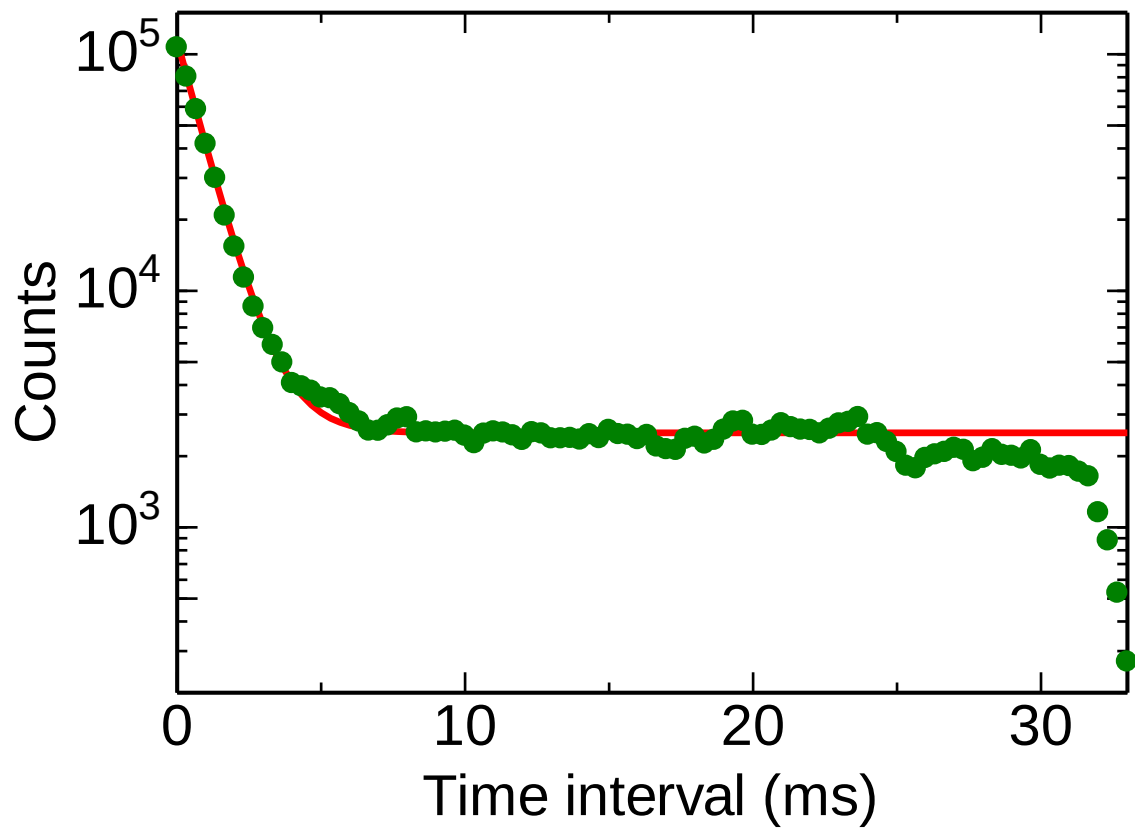


Figure 6 An example of a histogram of detection time intervals between two arbitrary events. In this case, two events occurring across the pulsed neutron were not considered. The data acquisition time was 1 s. The fitted curve is also plotted.

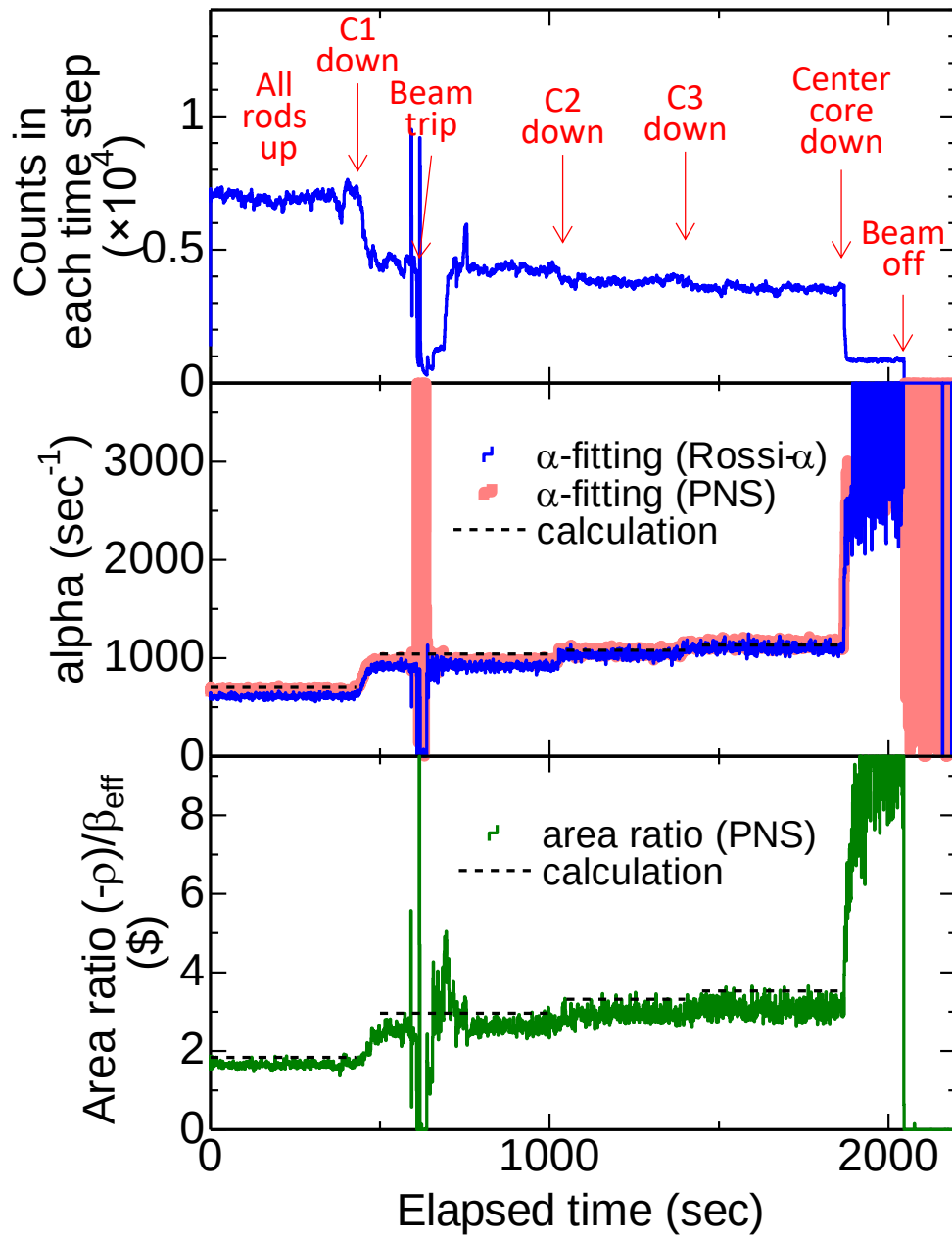
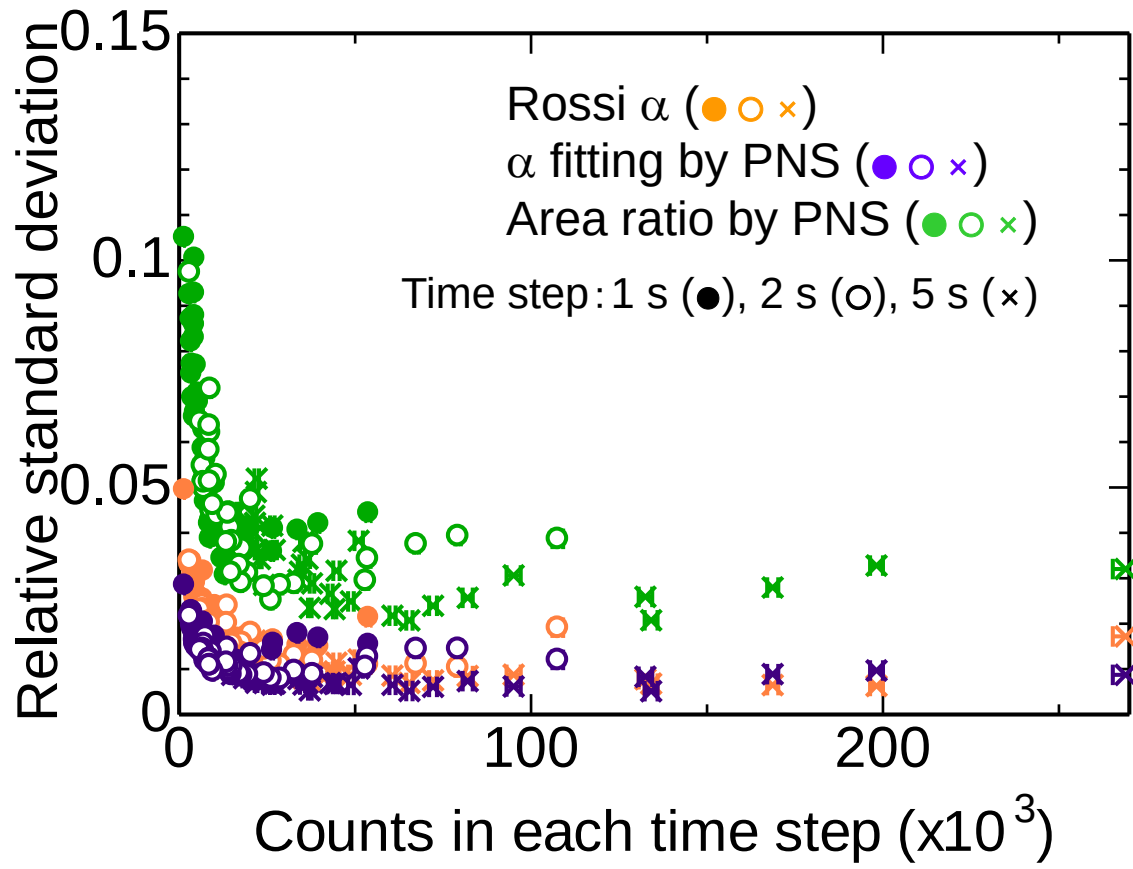


Figure 7 Neutron detector count, prompt neutron decay constant α , and area ratio $\$$ as a function of time. The core type was EE1-2760. The proton current from the FFAG was 60 pA and the time step width was 1 s. Calculation results are also plotted as dashed lines. Calculation uncertainty is quite small compared with the dashed line width.

1



2

3

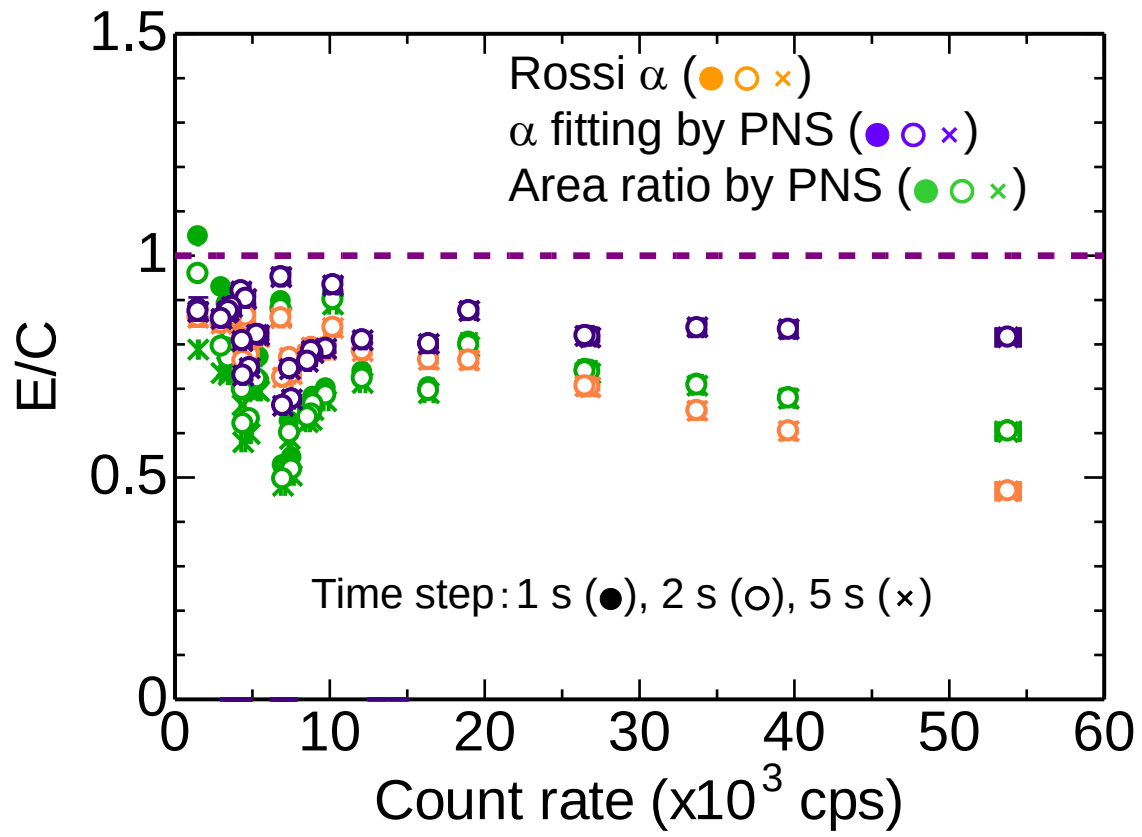
4 **Figure 8** Relation between the relative standard deviation of the estimated parameters and
 5 the neutron counts in each time step. The parameters α and $\$$ were determined
 6 with time steps of 1, 2, and 5 s.

7

8

9

1



2

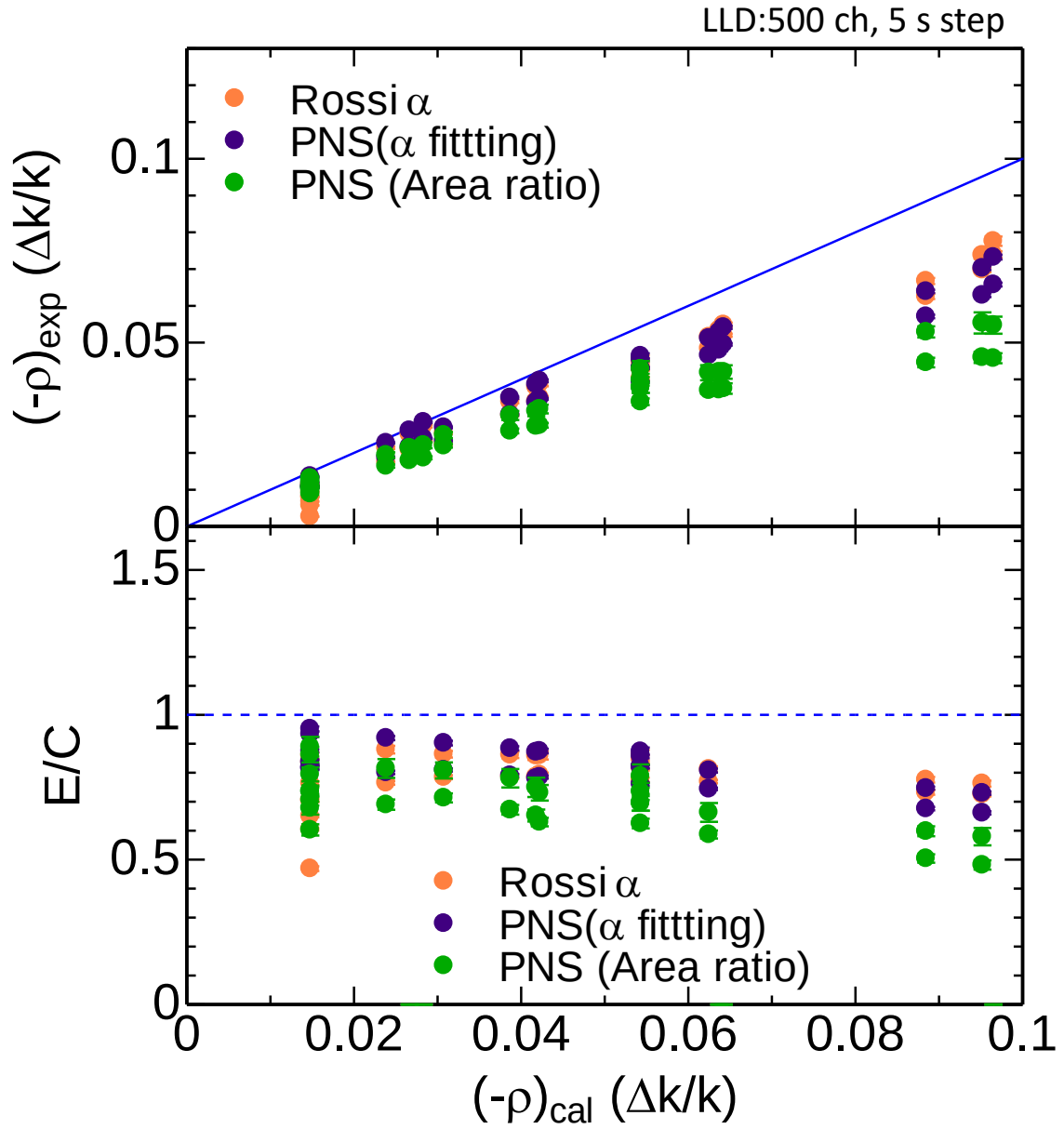
3

4 **Figure 9** Relation between the ratios of the experimentally estimated parameters to the
 5 calculated values, E/C, and the neutron count rate.

6

7

1



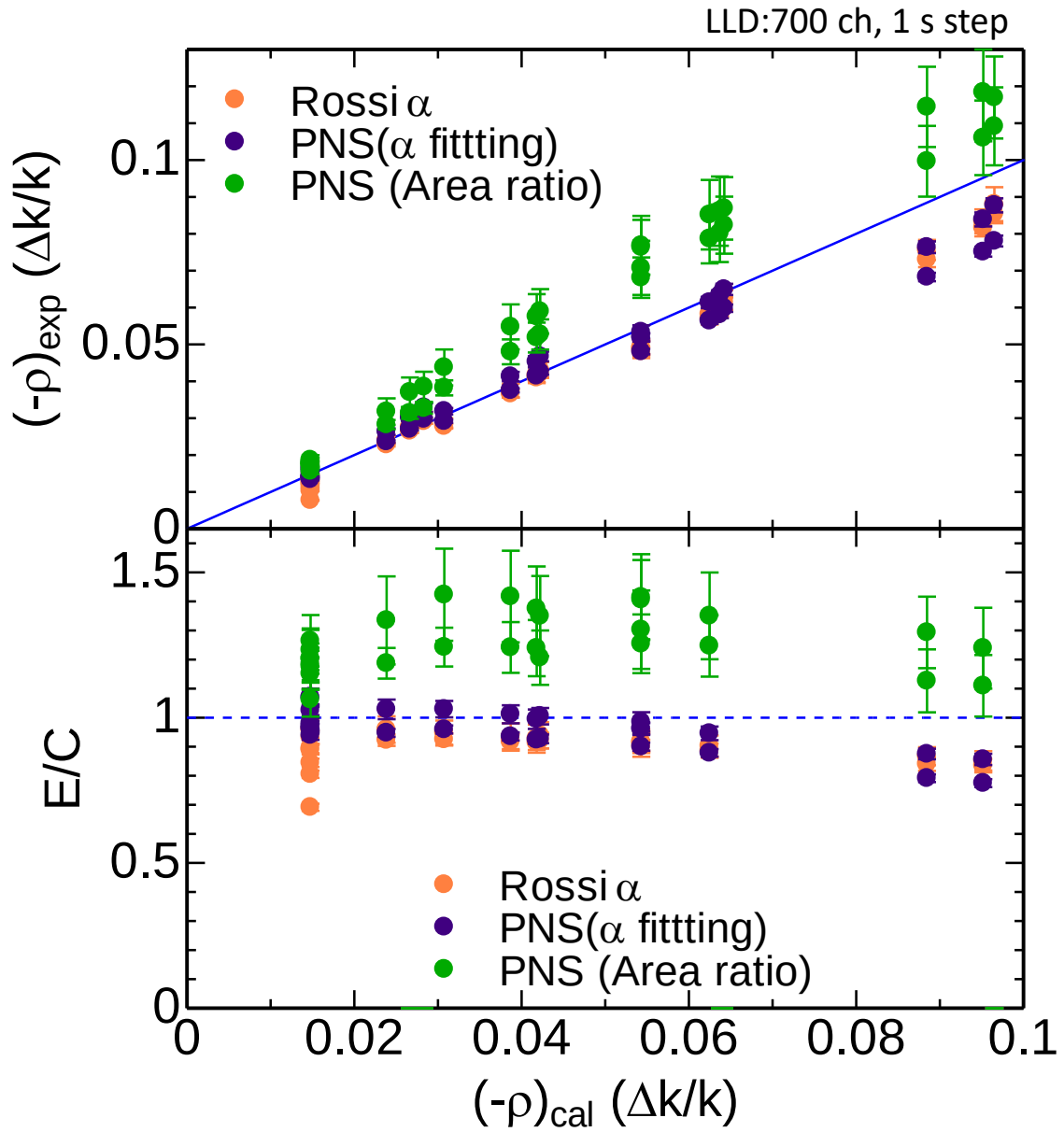
2

3

Figure 10 Relation between the experimentally determined subcriticality $(-\rho)_{\text{exp}}$ (top) and E/C (bottom) and the experimentally calculated subcriticality $(-\rho)_{\text{cal}}$. The discrimination level was set as the peak channel in the pulse height spectrum and the time step was 5 s.

8

1



2

Figure 11 Relation between the experimentally determined subcriticality $(-\rho)_{\text{exp}}$ (top) and E/C (bottom) and the experimentally calculated subcriticality $(-\rho)_{\text{cal}}$ with discrimination level 40% higher than the neutron peak. The time step was 1 s.

6

7